Society of Fire Protection Engineers

Guidelines for Designing Fire Safety in Very Tall Buildings

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PART I

1 Introduction

Scope

This Guide provides information on the special topics that affect the fire safety performance of very tall buildings and their occupants during a fire. This guide addresses these topics as part of the overall building design process using performance-based fire protection engineering concepts. It is not intended to be a recommended practice or a document that is suitable for adoption as a code.

The Guide pertains to "super tall," "very tall" and tall buildings. They are characterized by heights that impose fire protection challenges. They require special attention beyond the protection features typically provided by traditional fire protection methods. This guide does not establish a threshold of what constitutes a building that falls within its scope. It directs the user to perform a risk analysis to achieve a reasonable and adequate solution for the specific building. A description of the elements of a risk analysis is presented in chapter six.

Additionally, while this guide primarily addresses new construction, designers of existing tall buildings that are undergoing fire safety upgrades can benefit from the topics discussed here, provided appropriate risk analysis is performed.

PURPOSE

The purpose of the Guide is to identify issues unique to "super tall" buildings and provide the professionals engaged in the design of these buildings with sufficient information on the topics that affect the performance of tall buildings and their occupants during a fire. By considering these topics, the professional can prepare a fire protection design report or Fire Protection Engineering Design Brief for the project. Further information on this topic is described in chapter six. The Guide expects that the professional will have a fundamental understanding of fire dynamics and is competent in the application of scientific and engineering principles to the evaluation and design of systems and methods to protect people and their environment from the unwanted consequences of fire. The topics identified in this guide are intended to be addressed using performance-based fire protection and engineering concepts and the lessons learned from the experience of current tall buildings.

Background

This Guide is a joint effort of the Society of Fire Protection Engineers (SFPE) and the International Code Council (ICC). The impetus for this guide was a boom in the design and construction of many very tall buildings in a multitude of countries. These buildings were being constructed to a variety of regulations, codes and standards, many of which did not contemplate buildings of the heights that were being built.

The World Trade Center attack in 2001 caused enhanced interest in the challenges of tall buildings. Among those challenges are:

a. Egress and evacuation
b. Emergency access
c. Communications / situation awareness
d. Fire resistance / resiliency
e. Reliability of water supply and active fire protection systems

Another factor is the increased number of “super tall” buildings, resulting from improvements in design technology in areas such as structural design. Building codes address high-rise buildings, but may not adequately address “super tall” buildings. This guide is written to emphasize the importance of taking a systematic approach to the design of fire safety in buildings. A systematic approach looks beyond merely complying with the code and considers how the various fire safety systems in the building complement each other to achieve the fire safety goals for the building. Rather than attempt to define or categorize a building by its height, this Guide identifies the physical factors and principles affecting buildings’ fire safety, some of which vary by a building’s height, in order that the users of this Guide can apply the principles and define the necessary fire protection features for a specific case.

2 History

Tall buildings are not recognized as special buildings in all codes and standards. "High-rise buildings," which are defined by codes as those approximately 75 ft. (23 meters) or greater in height from the lowest level of fire department access, were not recognized as special buildings in codes and standards until the 1970s. It wasn't until the 13th Edition of the NFPA *Fire Protection Handbook* that was published in 1969 that "high-rise" was mentioned in the index, and only in the context of standpipe systems.

The experience of fires in high-rise buildings contributed to the development of high-rise fire safety provisions in codes and standards. A number of fires in the 1960s and 1970s brought attention to the fire safety risk presented by high-rise buildings. The World Trade Center attack has caused newly-focused attention on very tall buildings.

Among the significant tall building incidents are fires at the following buildings:

1. One New York Plaza - August 15, 1970[1]
2. MGM Grand - November 21, 1980[2]
3. First Interstate Bank - May 4, 1988[3]
4. One Meridian Plaza – February 23, 1991[4]
5. World Trade Center Explosion and Fire – February 26, 1993[5]
6. World Trade Center Buildings 1 & 2 – September 11, 2001[6]
7. World Trade Center Building 7 (WTC 7) – September 11, 2001[7]
8. Cook County Administration Building – 2003[8]
9. Caracas Tower Fire - October 17, 2004[9]
10. Windsor Tower, Madrid, Spain – February 12, 2005[10]
11. The Beijing Mandarin Oriental Hotel Fire - February 9, 2009[11]

The following paragraphs describe some of these incidents. The buildings involved may not have met the requirements applicable to them at the time of the fire for new construction. Details of these fires and associated buildings are contained in the references.

ONE NEW YORK PLAZA - AUGUST 15, 1970

One New York Plaza was a 50-story office building. A fire occurred on the 33rd floor on August 15, 1970. Workers from the 32nd floor discovered the fire. Two guards and a telephone company employee took an elevator to the 39th floor with the intention of notifying the occupants of the fire. Because the elevator was called to the fire floor by the fire, the elevator stopped at the 33rd floor. The two guards died, but the telephone company employee survived. The supply air fans had been shut down early in the fire, but the return fans continued to run.

Lessons Learned

The consequences of this fire led to improvements in the elevator code, specifically

1. Automatic elevator recall
2. Elevator call buttons should not be activated by fire or smoke

3. "Fireman's service." Fireman's service allows elevators to be recalled to the "home" floor manually by a key-operated switch and also to be operated by a firefighter from within the car with a key-operated switch
4. Protection of steel members should be accomplished with a durable material

MGM GRAND HOTEL – NOVEMBER 21, 1980

A fire at the MGM Grand Hotel on November 21, 1980, resulted in the deaths of 85 guests and hotel employees. About 600 others were injured and approximately 35 fire fighters sought medical attention during and after the fire. The high-rise building, constructed in the early 1970s, consisted of twenty-one stories of guest rooms situated above a large, ground-level complex comprised of a casino, showrooms, convention facilities, jai alai fronton, and mercantile complex. The hotel was partially sprinklered, but major areas including the Main Casino and The Deli, the area of fire origin, were not sprinklered. About 3,400 registered guests were in the hotel at the time of the fire. The most probable cause of the fire was heat produced by an electrical ground fault within a combustible concealed space in a waitresses' serving station of The Deli.[2]

LESSONS LEARNED

1. Automatic elevator recall is needed.
2. Seismic joints need to be protected against fire and smoke spread between floors.
3. Concealed spaces in fire resistive and noncombustible buildings should have few combustibles.
4. Vertical openings, including stairways and elevator shafts, need to be protected to limit smoke and fire spread between floors.
5. HVAC systems should be protected to avoid distributing fire and smoke during a fire.
6. Large assembly buildings need a pre-fire emergency plan.
7. Stairway doors should allow reentry to floors at no more than five floor intervals.

FIRST INTERSTATE BANK - MAY 4, 1988

The First Interstate Bank building was located in Los Angeles, California. It was 62 stories high and was in the process of being retrofitted with automatic sprinkler protection at the time of the fire. The sprinkler system was, however, not operational at that time. The fire began at 10:25 p.m. on May 4, 1988 on the 12th floor. A maintenance worker took an elevator to the floor of origin and was confronted with intense heat when the doors opened. He subsequently died. Flames spread vertically in the building through a return air-shaft and in the space in between the exterior curtain walls and the edges of the floors.

Lessons Learned

1. Los Angeles Building Code was changed to require the installation of sprinklers in all high-rise buildings, including existing buildings.
2. Curtain walls should be protected to limit fire and smoke spread at the exterior wall

between floors.
3. Automatic elevator recall is needed.
4. Fire alarm systems should be connected to a supervisory service or directly to the Fire Brigade
5. All stairway doors should be fire rated doors.
6. Stairway doors should allow reentry to floors at no more than five floor intervals.
7. High rise buildings need a pre-fire emergency plan..

ONE MERIDIAN PLAZA – FEBRUARY 23, 1991

One Meridian Plaza was a 38 story office building in Philadelphia, Pennsylvania. The building had a partial automatic sprinkler system, but no sprinklers were installed on the floor of fire origin. The fire began on the 22nd floor due to spontaneous combustion of rags left by painters. Because the fire department feared that the building could collapse, they evacuated it and suspended firefighting operations. The fire continued to spread from floor to floor until it reached the 30th floor where it was extinguished by 10 sprinklers fed by the fire department connection.

Lessons Learned

1. High rise building need sprinkler protection having redundant water supply
2. Curtain walls should be protected to limit fire and smoke spread at the exterior wall between floors.
3. Combined sprinkler and standpipe risers should be zoned so that pressure reducing valves (PRVs) are not needed at standpipe hose valves. Annual inspection and testing of the PRVs is needed to achieve reliable operation.
4. Fire alarm systems for high rise buildings should be connected to a supervisory service or directly to the Fire Brigade
5. Primary and secondary power should be routed independently.

WORLD TRADE CENTER EXPLOSION AND FIRE – FEBRUARY 26, 1993

On February 26, 1993 a truck bomb was detonated in the garage beneath World Trade Center (WTC) buildings 1 and 2. The explosion caused a fire and did damage to the below grade spaces. Smoke permeated the 7 towers that composed the WTC complex. Evacuation of the buildings ensued, requiring occupants to encounter smoke for the descent through the stairways. The explosion disabled the fire protection systems and the emergency generators supplying back-up power to the complex.

Lessons Learned

1. Battery pack emergency lighting may provide greater likelihood of functioning during a power failure than lighting supplied from an emergency generator
2. Key fire safety systems need redundancy and separation of redundant systems.

WORLD TRADE CENTER BUILDINGS 1 & 2 – SEPTEMBER 11, 2001

On September 11, 2001, aircraft impacted the North and South Towers of the World Trade Center complex (buildings 1 & 2, respectively). The impacts and subsequent damage resulted in localized loss of structural integrity, loss of exit compartmentation, loss of fire fighting water and loss of water to fire suppression systems. While each building withstood the resulting fires for a period of time, each tower ultimately collapsed, killing nearly 3000 occupants and emergency personnel who were unable to evacuate the buildings.

Two significant investigations were conducted, one led by the Federal Emergency Management Agency (FEMA) and the Structural Engineering Institute of the American Society of Civil Engineers (SEI/ASCE),[12] and the other by the National Institute of Standards and Technology (NIST),[6] in association with other government agencies, professional organizations, researchers, engineers, and various agencies within New York City.

Lessons Learned

While official investigation reports provide much more detail, key observations from the reports include:

1. Structural framing needs redundancy
2. Fireproofing needs to adhere under impact and fire conditions
3. Connection performance under impact and fire loads need to be analytically understood and quantified
4. Fire resistance ratings that are based on the use of sprinklers need a reliable and redundant water supply
5. Egress systems should be evaluated for redundancy and robustness
6. Fire protection ratings and safety factors for structural transfer should be evaluated for adequacy.

WORLD TRADE CENTER BUILDING 7 (WTC 7) – SEPTEMBER 11, 2001

WTC 7 was a 47 story building in the World Trade Center complex. Debris from WTC 1 caused structural damage to WTC 7 with resulting fires on multiple floors. Because of the structural damage and because the collapse of WTC 1 & 2 interrupted the public water supply to WTC 7, automatic sprinklers in the building were rendered inoperable. Fires burned in the building for nearly seven hours before it collapsed.

Lessons Learned

1. Structural building design should anticipate multiple, simultaneous fires.

2. Structural fireproofing needs to be durable and robust so as to withstand impact and fire effects.
3. Structural system connections need to have fire resistance at least equal to the members to which it is attached.

COOK COUNTY ADMINISTRATION BUILDING (69 WEST WASHINGTON STREET) - 2003

A fire started in a storage room on the 12th floor, spreading through the suite of origin. Firefighters accessing the fire from a stairway opened doors, which allowed hot smoke and gases to flow into the stairway. For security reasons, the stairway doors were locked from within the stairway, preventing escape except from the stairway exit at the ground floor. Six people died in the stairway, being trapped above the 12th floor.

Lessons Learned

1. Doors need to unlock to allow re-entry from stairways that may become compromised
2. Effective communication and training is important

CARACAS TOWER FIRE - OCTOBER 17, 2004

The tallest building in Caracas, Venezuela is a 56 story, 730 feet (220 meter) tall office tower. A fire started on the 34th floor around midnight on October 17, 2004 and spread to more than 26 floors. It burned for more than 17 hours. Investigation determined that fire pumps malfunctioned, exits were blocked and elevators were not accessible. The fire was finally brought under control by a combination of military helicopters dropping water on the building and firefighters, who laid 40 stories of fire hose.

Lessons Learned

1. Fire protection systems must be maintained to be effective.
2. Codes and standards must be enforced to be effective.

WINDSOR TOWER, MADRID, SPAIN – FEBRUARY 12, 2005

The Windsor Tower was a 32-storey concrete building with a reinforced concrete core. Originally, the perimeter columns and internal steel beams were left unprotected and vertical openings were not protected. There was no firestopping between the floor slabs and the exterior wall. At the time of the fire, the building was undergoing a multi-year fire protection improvement program consisting of protecting steel structural members, upgrading the curtain wall and installing automatic sprinklers. When the fire started, most of the improvements had been completed below the 17th floor. Some of the curtain wall firestopping and vertical opening protection had not been completed. The fire started on the 21st floor and spread rapidly throughout the entire building.

Lessons Learned

1. High rise buildings need sprinkler protection having redundant water supply.
2. Curtain walls should be protected to limit fire and smoke spread at the exterior wall between floors.
3. Vertical openings, including stairways and elevator shafts, need to be protected to limit smoke and fire spread between floors.

From: *www.mace.manchester.ac.uk*

THE BEIJING MANDARIN ORIENTAL HOTEL FIRE - FEBRUARY 9, 2009

The nearly-completed 520-foot (160 meter) tall skyscraper in Beijing caught fire around 8:00 pm, was engulfed within 20 minutes, and burned for at least 3 hours until midnight. The fire was started by fireworks from an adjacent display or from illegal fireworks ignited in the building. Despite the fact that the fire extended across all of the floors for a period of time and burned out of control for hours, no large portion of the structure collapsed.

Lessons Learned

1. Fireworks displays should be controlled. NFPA 1123,[13] *Code for Fireworks Disp*lay provides guidance.
2. Buildings using combustible components in the construction of a tall buildings facade can pose unreasonble risks for significant fire spread along the exterior of a building. Facade fire spread characteristics need to be understood and may need to be substantiated by large scale tests.

From: *www.911research.wtc7.net*

PERFORMANCE-BASED APPROACH TO BUILDING FIRE SAFETY

During the 1960s, high-rise fires, notably at One New York Plaza and at 919 Third Avenue (New York), contributed to a growing awareness of the special fire safety challenges of high-rise buildings. This lead to a qualitative approach embodied in the NFPA Firesafety Concepts Tree, NFPA 550,[14] and a quantitative approach described in the General Services Administration, Appendix D, Interim Guide for Goal Oriented Systems Approach to Building Fire Safety.[15] A thorough analysis of the GSA system is contained in an NBS report, “A Theoretical Rationalization of a Goal-Oriented Systems Approach to Building Fire Safety.”[16] References in the report provide an excellent history of the early development of performance-based approaches to building fire safety.

3 International Practices

There currently exists no unified global codes and standards for high-rise fire safety design. Most developed economies have local or national codes and standards that, for the most part, address the fundamentals of high rise construction: fire resistive construction, active suppression and alarm systems, egress, and smoke management. These local requirements are often crafted around local and national design and construction practices, previous local experience of incidents and local materials and products.

Regulation of high rise construction in emerging economies varies from North American norms based on local customs and practices. China, for example, has a highly developed set of regulations for high rise construction, including many provisions not found in U.S. codes. Other emerging economies have little or no regulations specific to high rises.

The increasing complexity of building design, the desire of emerging economies to produce "world class" facilities and the globalization of building design and construction industries has introduced new approaches to high rise design, including high rise fire safety. Typically, these new approaches blend international design practices based on developed countries' standards with local codes, construction practices and products. Most local codes favor local materials and products that may not be designed to meet North American standards or have not been evaluated to these standards. Similarly, local products, system designs, and maintenance standards are likely not the same as in North America and may need to be evaluated to see that they provide adequate protection.

INTERNATIONAL DESIGN ELEMENTS

One variable in international high rise construction is the availability of building materials and products appropriate for the design. Many locations are not able to source recognized fire protection products locally and may recognize only locally-tested products and not products tested to developed countries' standards. In some cases, products or systems must be tested and designed to local requirements to meet statutory requirements and to developed countries' standards to meet corporate or insurance requirements. This can be tricky because some requirements can be mutually exclusive.

A second element of international high rise design is the public infrastructure. In many developing economies, designers may not be able to rely on public utilities and might, therefore, design elements such as fire protection water supply and emergency power to be self-contained within the building.

A final element of international high rise design is that, in many locations, the level of building maintenance may not meet developed countries' standards or practices. Designers must take this into consideration and design system that are simple, reliable and robust.

POST WORLD TRADE CENTER ATTACK HIGH RISE FEATURES IN INTERNATIONAL PROJECTS

Perhaps the most significant lesson learned from the World Trade Center attack for high rise designers is that the threat from fire may not be the most critical threat to the building and that a broad range of emergency scenarios must be considered. Most of the high rise construction that has occurred since the World Trade Center attack has been outside of North America. None the less, many of the lessons learned from the World Trade Center attack have been quickly incorporated into the high rise design practice. This has occurred in four key areas:

Structural hardening. Some buildings are currently being designed with hardened cores that contain emergency system risers and stairways. Structural fire resistance is being evaluated in these buildings to evaluate their ability to withstand full burnout.

Robust and Redundant Life Safety Systems. Current high rise design typically incorporates more robust and redundant life safety systems including redundant system risers for power, alarm and fire suppression systems. All of the features are intended to allow the building to function and to maintain a high level of life safety even in the event of partial system failure.

Egress. The World Trade Center attack has made clear the need for some incidents to facilitate full building evacuation of high rise buildings. In current international high rise design, this may include the use of an increased number of exit stairways, the use of safe areas or refuge floors within the building and the use of elevators to facilitate emergency evacuation of building occupants.

Fire fighter access. Some codes require a dedicated elevator for fire fighters, accessed through a vestibule. Other codes that require all elevators to have fire fighter emergency controls also require all elevators to be accessed from a vestibule.

4 Goals and Objectives

GOALS

Project goals identify the desired fire safety performance of a building in qualitative terms. There are generally four types of goals: life safety, property protection, mission continuity and environmental protection.

Life safety goals relate to protection of the building occupants, and members of the public in the event a fire occurs in the building. Life safety would almost certainly be a goal in any very tall building. Firefighter and first responder safety also need to be considered.

Property protection relates to minimizing damage to the building and building contents from fire. Additionally, limiting damage to exposed buildings would fit into this category.

Mission continuity goals address the impact on the building and its tenants from fire. Some building codes do not address mission continuity in very tall buildings, although mission continuity might be addressed for tenants who perform vital roles in the community, such as hospitals and public safety buildings. In most cases, the building owners, tenants or their insurers will provide mission continuity goals.

Environmental protection goals consider the permissible impact on the environment from fire or fire protection. Environmental protection goals might address limitations on the types of fire protection agents that can be used in a building and the environmental consequences of a fire in a facility which might release toxic products into the atmosphere, ground water or bodies of water. Additionally, some "green building" codes may address environmental protection related fire safety goals. Environmental issues are beyond the scope of this Guide, so are not further discussed herein.

The fire protection engineer should work with the other project stakeholders to identify the goals for the project. For most very tall buildings, all four of the aforementioned goals would apply to some degree. The SFPE *Engineering Guide to Performance-Based Protection*[17] should be consulted in establishing the goals and objectives for the project.

OBJECTIVES

Objectives are established to provide more detail about the intended fire safety performance. There are two types of objectives: stakeholder objectives and design objectives.

Stakeholder objectives define how much loss is tolerable in the event of fire. Like goals, stakeholder objectives are written in language that is easily understood by people who are not engineers. However, stakeholder objectives are more quantitative in their description of tolerable losses. These tolerable losses might be stated in terms of life loss, property loss, downtime, or other measures.

For life safety goals, stakeholder objectives will usually come from a code – either directly or, more typically, by inference. For other types of goals, stakeholder objectives will generally be developed by the engineer in consultation with the project stakeholders. It is important to secure the agreement of the project stakeholders about the stakeholder objectives before proceeding with the design so that everyone has a clear understanding about the desired fire safety performance of the building.

Design objectives are developed by the engineer based on the agreed stakeholder objectives. Design objectives describe the conditions at the "target" being protected that are necessary to achieve the stakeholder objectives. Ultimately, the design objectives will be further quantified into performance criteria that are used to determine if a design strategy is acceptable. This approach is appropriate whenever no code is applicable. A common objective is to prevent unwanted fires. Applying a risk analysis, one realizes that this objective is unlikely to be achieved a reasonable cost. The systems suggested to mitigate the unwanted fire would be evaluated to determine their interaction so as to achieve the objective.

FIRE PROTECTION DESIGN REPORT

The goals and objectives for the project are intended to be documented in a Fire Protection Design Report or Fire Protection Engineering Design Brief. This document would be referred to as the project proceeds to measure achievement of system performance against the goals and objectives. The document would be refined during the project.

Tall buildings are frequently centers of commerce or serve important community functions. Accordingly, the economic and/or societal value of the building should be considered when fire protection requirements are being developed.

5 Unique features of Tall Buildings

Tall buildings have attributes which can adversely affect the fire safety of a building. These features include:

- **Height beyond available resources of fire department ladders.** Typical fire department aerial ladders have the capability to have an effective reach (recognizing a setback distance from a building). Some building sites provide multiple levels of street access to a building. Therefore, many codes have defined "high-rise" buildings as those having an occupied floor level a defined height above the lowest level of fire department vehicle access. Buildings beyond the reach of exterior fire department ladders, then, must have additional protection features because exterior rescue and fire fighting capabilities will be limited or unavailable for portions of the building above that height.

  Furthermore, the lack of ability to use an exterior access requires fire fighters to access the upper floors of the building by interior means, frequently involving the use of stairways and sometimes using elevators if deemed appropriate under the circumstances. This interior access results in additional physical demands upon the fire fighters and extended time to reach the fire floor.

- **Extended evacuation time**. The time necessary for full building evacuation increases with building height. (See the SFPE *Handbook of Fire Protection Engineering*[18] and *Engineering Guide to Human Behavior in Fire*[19] for more information.) In the case of very tall buildings, full building evacuation via stairways might be impractical. A "defend-in-place" strategy has been employed in many building designs by (1) designing compartments allowing people to remain in place, *e.g.*, residential units; (2) temporarily evacuating people to areas of refuge on a floor; or, (3) moving people to dedicated refuge floors elsewhere in the building. Recently, times for full building evacuation have been reduced by employing elevators specifically designed to supplement the egress system of a building. Buildings employing assembly occupancies with large occupant loads on the upper floors of a tall building require special consideration.

- **Pronounced Stack effect.** Stack effect is a natural physical phenomenon which occurs in high rise buildings which experience a pressure difference throughout their height as a result of temperature differentials between outside air temperature and inside building temperatures. (See the SFPE *Handbook of Fire Protection Engineering*[20] for more information.) The effect is pronounced in tall buildings because of their greater height. Stack effect causes air to move vertically, either upward or downward in a building. It can cause smoke from a fire to spread in the building if it is not controlled. As a result, tall buildings include features such as automatic sprinkler protection to limit the size of fires and the resulting quantity and energy of smoke which can spread throughout the building, and smoke control means such as openable panels and mechanical systems to either vent, exhaust or limit the spread of smoke throughout the building.

- **Water supply limitations.** The water supply needs in tall buildings can be beyond water supply capability of public mains and fire department pumpers. Public water supplies have pressures which will require supplemental pumps in the building to boost the pressure to a usable level on the upper floors of a building. The building's fire department connection allows the fire department to supply water to the sprinkler and standpipe systems in the event the building's water supply is out of service or inadequate. Above the height achievable by the local fire authority pumps, buildings must have the capability to supply its water independent of the fire department appliances. Therefore, multiple levels of pumps and water storage tanks are provided. Also, because of this potential loss of an external water supply, additional protection features may be considered necessary for such buildings.

- **Greater challenges of mixed occupancies.** Many tall buildings contain mixed occupancies, involving various combinations of occupancies such as retail, residential, automobile parking, business, public assembly (*e.g.*, restaurant), transportation facilities, health care, educational, correctional and storage. The fire protection challenges presented by mixed occupancies – such as means of egress and the integration of protection systems – are even greater when they are housed in tall buildings.

- **Iconic nature**. Although a building need not be tall to be iconic, tall buildings generally are considered iconic because they are generally unusual in height, design or other feature. They are recognizable as unique.

6 Hazard, Risk and Decision Analysis in Very Tall Building Design

Although fire hazards in very tall buildings are essentially the same as in low-rise buildings of similar uses (*e.g*., business, residential, mixed-use), the consequences of a fire have a potential to be more severe given the large numbers of occupants, the inherent limitations in egress and access, and the physical aspects of the structure which can affect the hazard (*e.g.*, stack effect). This is not a new concept: it is why many existing regulations for tall (high-rise) buildings include more provisions for fire and life safety than those for low-rise buildings of a similar use. While such a defense-in-depth approach has resulted in a predominately good fire record for tall buildings, there are sufficient examples of what can go wrong (*e.g.*, see Section 2, History) to highlight the benefits of applying appropriate levels of hazard, risk and decision analysis to the design of very tall buildings in order to try and achieve a high degree of fire safety performance while meeting other project objectives (*e.g.*, operational, financial, etc).

There is a wide variety of hazard, risk and decision analysis tools and techniques that can be applied to very tall buildings, starting at the feasibility or conceptual planning phase, at various stages of design and construction, and throughout the life of the building. The basic risk assessment process is outlined below.[21] The aim of this chapter is to identify aspects of very tall buildings which may warrant application of hazard, risk or decision analysis at various stages of design, construction and operation.

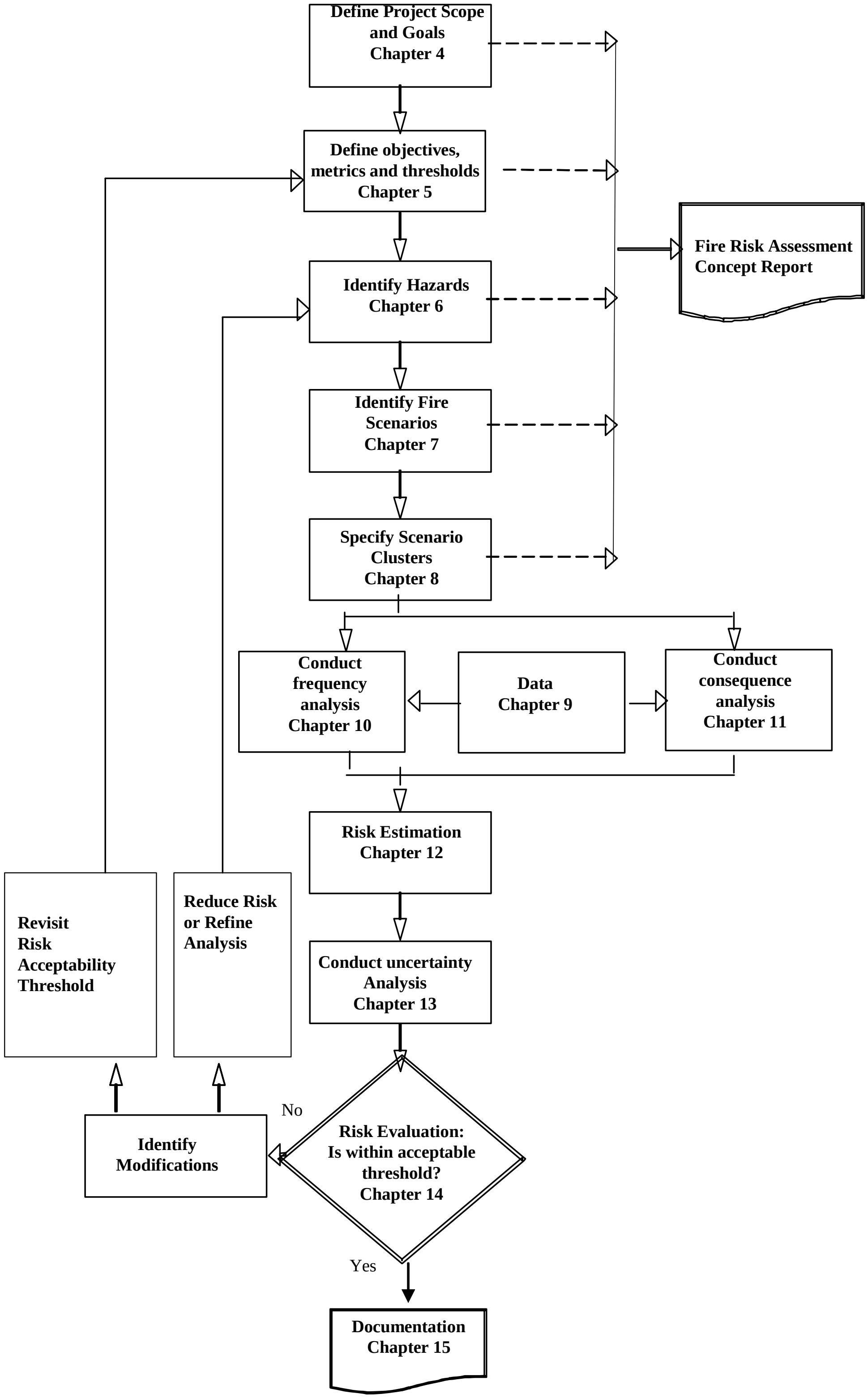


Fig 6.1 Fire Risk Assessment Flow Chart[21]
(Chapters identified in this figure refer to chapters in the SFPE Engineering Guide to Fire Risk Assessment)

HAZARDS

Fire

During the design of very tall buildings, there may be cases where hazards are introduced or somehow enhanced. For example, with a focus on sustainability, there may be additional hazards of concern associated with new materials that may be introduced to address energy performance or other objectives, include façade material, new thermal insulating materials, fuel cells, photovoltaics, and other such materials. Fires in Busan South Korea[22] (October 2010 - See figure 6.2) and Shanghai, PRC[23] (see figure 6.3) associated with combustible façade material installed, or being installed, for energy efficiency upgrades point to one concern. As noted in the Korean media[22] regarding the Busan fire, "it took just 20 minutes for the blaze that started at a trash collection site on the fourth floor to travel up to the 38th floor. The building's concrete body was covered with aluminum panels for aesthetic effect, filled with glass fiber for insulation and coated with flammable paint causing the flames to spread upward quickly."

Likewise, as reported in the media following the Shanghai fire, [23] to meet energy efficiency targets by adding insulation to the outside of existing buildings - the project the welders were working on when the fire broke out. Although the insulation meant for such work is supposed to be treated with fire retardant, it is nonetheless flammable. Many are now questioning if the energy savings are worth the risk."

While new materials for energy efficiency are not unique to tall buildings, it is likely that energy efficiency will be a significant objective for very tall buildings, and fire hazard assessment should be extended to include these new materials and the expected in-use application.

	
Figure 6.2 - Fire in Busan http://blog.daum.net/tobfreeman Permission to use image pending	Figure 6.3 - Fire in Shanghai http://www.bbc.co.uk/news/world-asia-pacific-11760467 Permission to use image pending

Tools and methods for fire hazard analysis, as outlined in the SFPE Engineering Guide to Performance-Based Fire Protection,[17] the SFPE Engineering Guide to Predicting Room of Origin Fire Hazards[24] and elsewhere, can be used as for any other fire hazard. Simple 'what if?" analysis can help identify issues (*e.g.*, if the façade is combustible, what happens if it becomes ignited?). More structured approaches such as failure modes and effects analysis (FMEA) or fault tree analysis (FTA) can help identify specific failure (*e.g.*, how the façade might become ignited). Fire effects and other modeling can help assess development of fire hazards to occupants, contents, the building, *etc.* The main point here is to expand the scope of hazards considered, including fuels, ignition sources, and related factors, seeking appropriate data on the new materials, systems and hazards to support the assessment.

Technological Events

System failures occur every day. Air-conditioning systems malfunction. Power might be lost for a few minutes to a room or floor of a building. A lift is out of service. In most cases the interruptions are brief and result in little, if any, detrimental outcomes. However, in a vertical city that is a very tall building, interruptions to critical systems can have significant impacts on the building and its occupants. Loss of a lift servicing the 100th-140th floor of a building is more than a minor inconvenience, especially if the lift is intended to serve as part of the egress plan as an occupant self-evacuation lift. Likewise, loss of fire suppression water at the 100th floor is more severe than a similar loss at the 1st floor, which can be more readily reached by responding fire brigade personnel and equipment. Extended power outages can have major implications. Gas explosions can result in fire and partial or total building collapse.

Extreme Natural Events

Extreme natural hazard events, such as earthquakes, tsunami, drought and high wind events, pose an additional challenge. In these situations, one needs to consider both the primary event (natural hazard) and the secondary event (fire), given the potential for any damage resulting from the primary event. This is particularly important for assessing fire and life safety systems availability and efficacy following the natural hazard event.

For many of these assessments, the FPE will likely work closely with structural engineers or others focused on the natural hazards evaluation. However, in addition to a focus on structural performance, it is critical to include the nonstructural systems performance, including power, lighting, piping, HVAC, communication, nonstructural compartment integrity internally (passive protection, including walls, ceilings, dampers, doors, etc) and at the exterior boundaries (façade, window or door openings, etc). The aim is to estimate the functionality or damage states of the building and systems – post initial event – for assessing post-event fire performance.

For example, fire protection systems can suffer significant damage in seismic events. Reports published following the Northridge and Kobe earthquakes provide some examples.[25, 26, 27, 28]
While not all details are yet available regarding the impact of the March 11, 2011 tsunami in Japan (see figures 6.4 and 6.5), the fire and explosions at the Fukushima nuclear power plant, Cosmo oil refinery, and industrial areas of Sendai illustrate the potential for post-earthquake and tsunami fire and explosion. An additional challenge in such events is that the initiating event (earthquake, tsunami) can take out critical infrastructure needed to support fire fighting operations, including water supply and roadways (for access).

	
Figure 6.4 - Fire Following Tsunami http://www.fxnonstop.com/index.php/component/content/article/121488-myart88860 Permission to use image pending	Figure 6.5 - Fire Following Tsunami http://www.heraldsun.com.au/news/special-reports/gallery-fn7zkbgs-1226020412258?page=12 Permission to use image pending

Different types of challenge are associated with potential climate change. These include rising sea level (flooding), drought (increased risk of wild land fires, decreased water available for suppression), and increased severity of hurricanes/cyclones (increased wind speeds). As with the above, the focus for the fire protection engineer is post-event fire protection performance of the building. In the case of flooding, issues include location of critical equipment and ability of emergency responders to reach the building. The water resource issues with drought may lead to a need to have 100% on-site capacity of expected fire-fighting water for the target duration. High winds could result in damage to the building envelop, resulting in loss of compartmentation.

Terrorism

The World Trade Center attack is a clear indication that very tall buildings may be considered targets for acts of terrorism. As with natural hazard events, a key consideration is operation of the fire and life safety systems following the initiating event. With respect to acts of terrorism, initiating events could include impact, explosion, arson, or chemical, biological or radiological (CBR) release. While assessment of these hazards may not be within the FPE's scope, concerns may include the state of the fire protection systems post event (*e.g.*, the World Trade Center bombing in 1993 took out fire alarm, emergency lighting, communications, and many other systems; the 2001 World Trade Center attack resulted in loss of passive and active fire protection systems, egress systems, and access for emergency responders), as well as consideration for system operation for multiple hazards (*e.g.*, CBR management and smoke management).

RISK ANALYSIS

As defined in the *SFPE Engineering Guide to Fire Risk Assessment*,[21] risk is the potential for realization of unwanted adverse consequences, considering scenarios and their associated frequencies or probabilities and associated consequences. Risk analysis is the in depth evaluation undertaken to understand and quantify the unwanted adverse consequences. In general, risk analysis is aimed at answering three questions: what could go wrong, how likely is that to occur, and what would be the consequences. It involves identification of hazards, identification and specification of scenarios for consideration, estimation and analysis of probability and consequences, combining probability and consequence to obtain an estimate of risk, evaluation of the risk in terms of risk acceptance targets, and taking steps to manage the risk through reducing probability or consequence, transfer the risk via insurance, or avoid the risk. The process is illustrated for fire risk analysis in Figure 6.1 above.

Risk analysis can be qualitative, semi-quantitative, or quantitative. At the qualitative and semi-quantitative level, matrices for probability and consequence, using descriptive language (*e.g.*, low, medium, high) or numerical values might be used to reflect a relative ranking of the risk. This approach is found in various fields, such as system safety analysis,[29] fire protection engineering,[21] and project management.[30] Quantitative risk analysis can take several forms, depending on the type and level of analysis being undertaken. A common approach is through the use of event tree analysis (ETA). An event tree is a graphical logic model that identifies and quantifies possible outcomes following an initiating event. An example of a simple event tree is illustrated in figure 6.6.[31]

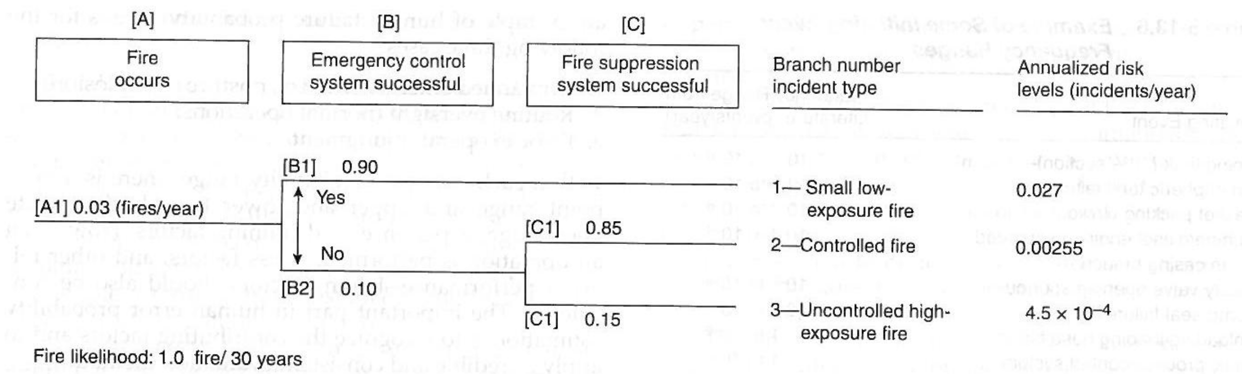


Fig 6.6 Example of a Simple Fire Event Tree[31]

The event tree allows various analyses to be conducted. First, it allows one to identify and assess the number of safety barriers in a system, and what happens if each is successful or fails. By using a logic structure, it allows probabilities to be applied to the successes and failures to develop an estimate of the risk (when combined with the analysis of consequences at each branch termination). It also allows for the analyst to add or remove safety barriers (*e.g.*, detection, suppression, etc), or to increase or decrease the probabilities of success and failure, to assess the risk reduction contribution of different safety barriers in different combinations and with varying degrees of reliability. For estimating the probabilities of success and failure, one can look to statistics available in the literature, collect data, or look to expert judgment. Tools such as FTA can be used for each system to both identify current reliability and to identify how reliability can be increased.

For example, in the simple event tree above, item C is 'fire suppression system successful' with the probability of success 0.85. If the details of the fire suppression system were known, one could construct a fault tree to identify where and how the system might fail (*e.g.*, valve closed, not monitored) and to infer ways to increase the success (*e.g.*, monitor the valve as a constantly staffed location, sound an alarm if closed, etc).

In addition to being tools for estimating risk, given the ability to consider the safety barriers in place to mitigate an initiative event, and the ability to add or modify safety barriers to assess outcomes, event trees can be useful tools for decision-making with respect to fire safety alternatives in a building (other safety measures as well).

A major challenge for any risk analysis is establishing the risk acceptance (tolerance) levels for the design. These are typically set by the owner in consultation with other stakeholders. For any complex process, a full risk characterization process is suggested.[32 33] The aim is not to address the issues of what can go wrong, how likely that is, and what the consequences might be, but more specifically, which consequences, and at what levels, are tolerable. This has to address challenging issues of how big of a fire is tolerable, what extent of loss to people, property and mission can be accepted, and under what circumstances.

Very tall buildings may have large occupant populations who have limited evacuation routes. Setting risk acceptance levels will be the benchmark against which all fire protection system requirements are measured in the risk analysis process. If risk to life values are not set, and surrogates such as extent of fire spread are used, risk thresholds might reflect factors such as to what volume of a compartment or floor does a fire need to be contained and for how long? What probability of horizontal fire spread is acceptable? What probability of one or multiple floor vertical fire spread is acceptable? What levels of toxic products of combustion are acceptable in what parts of the building for what period of time? While fire effects, structural analysis, and evacuation modeling may be used to support such analysis, establishment of the criteria – taking into account associated uncertainty and variability – will be the critical factor in assessing the acceptability of designs.

DECISION ANALYSIS

Decision analysis reflects formal processes for helping individuals and groups reach decisions by structuring decision problems and assisting with the challenges of addressing multiple objectives. Decision support tools can range from qualitative to quantitative, much like hazard and risk assessment. At the qualitative and semi-quantitative end, simple consensus processes can be used, with or without ranking of options. Decision trees, which are much like event trees, can be used to decide between options, using probabilities and consequences (or costs) in combination. More intensive approaches exist for multi-criteria problems.[34 35]

A good starting point for identifying and choosing fire protection measures is the Fire Safety Concepts Tree[14] (FSCT - see figure 6.7). The FSCT provides a structure with which to analyze the potential impact of fire safety strategies against defined fire safety objectives. While it is not a decision tree and cannot incorporate probabilities or be quantified in the same way as a decision tree, it can be used to identify gaps and areas of redundancy in fire protection strategies as an aid in making fire safety decisions.

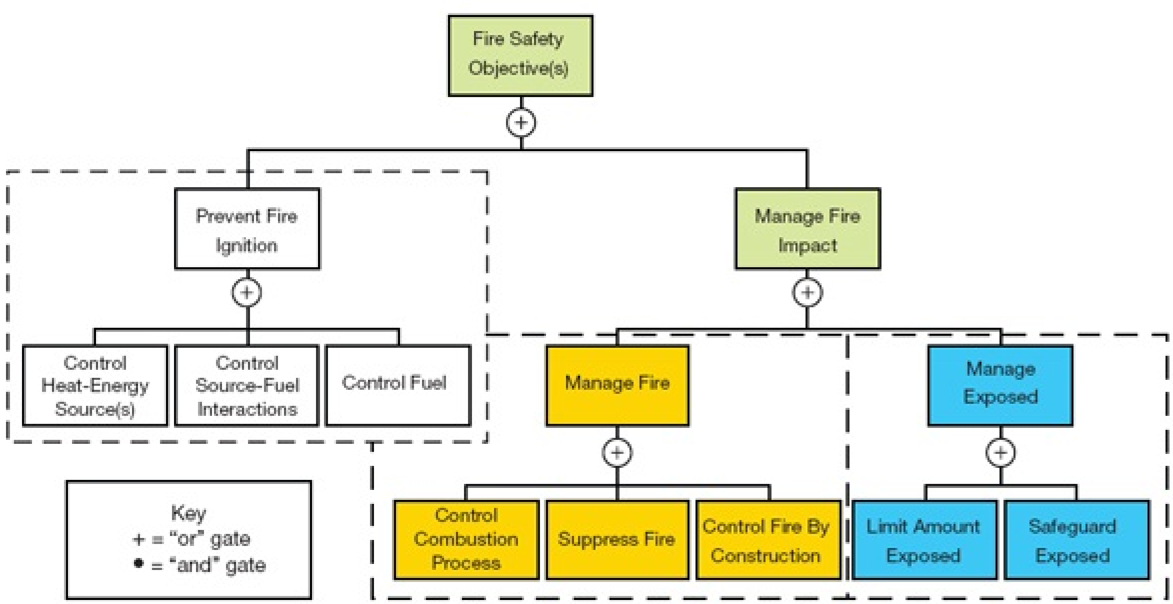


Figure 6.7 - Top Branches of the Fire Safety Concepts Tree[14]

> Reprinted with permission from NFPA 550-2012, *Guide to the Fire Safety Concepts Tree*, Copyright © 2012, National Fire Protection Association, Quincy, MA, This reprinted material is not the complete and official position of the NFPA on the referenced subject, which is represented only by the standard in its entirety.

Regarding costs, several tools may be appropriate, including return on investment analysis, cost-effectiveness analysis, benefit-cost analysis, and life cycle cost analysis.[36] [37] At the end of the day, no building can have protection measures against all risks. Whereas risk analysis aims to help identify what risks and at what levels the stakeholders are willing to tolerate, cost analysis is aimed at helping to identify the costs involved with different protection options – not only at design but as associated with the operation of the building as well.

USES AND APPLICATIONS OF HAZARD, RISK AND DECISION ANALYSIS FOR VERY TALL BUILDINGS

Tools and methods of hazard, risk and decision analysis can be applied at various stages of tall building design, construction and operation.

Fire Strategy (Goals, Objectives, Criteria and Acceptance Targets)

One of the most important stages of a tall building project is establishing the fire and life safety goals and objectives, in conjunction with other objectives for the building, and developing a corresponding set of acceptance and performance criteria that will be used to assess the suitability of the protection design. This information is should be contained in a Fire Protection Design Report or Fire Protection Engineering Design Brief for the project. These provisions are best communicated through a single document which summarizes fire/life safety provisions. The Fire Protection Design Report or Fire Protection Engineering Design Brief should include rationale supporting the selection of pertinent fire protection/life safety features incorporated into the building design. Topics to be addressed in the Fire Strategy can include, but are not limited to, the following:

- Any alternate methods of construction, engineered solutions or performance-based design provisions used in the building design, including documentation of all modeling performed.
- Passive fire-resistance provisions, including structural fire-resistance ratings, fire-resistive rated separations and interior finish requirements.
- Egress system provisions, including the use of horizontal exits, phased evacuation zones and unique exiting configurations.
- Fire suppression system provisions, including sprinkler design densities, unusual fuel loads, special suppression systems and fire pump arrangements.
- Fire alarm system provisions, including zoning, special detection provisions, and emergency communication system configurations.
- Smoke management system provisions, including design approaches, pertinent design calculations and integration with fire suppression and detection systems.

- Facility emergency and standby power provisions.
- Facility hazardous materials.

As noted above, use of the FSCT, application of the risk characterization process and other decision analysis methods can be useful in framing the key issues and developing initial strategies.

Key considerations in developing goals, objectives, criteria and acceptance targets for very tall buildings include the following:

- The building will house a large number of occupants
- Occupants will have limited evacuation options
- The building needs to remain standing for the time necessary to protect occupants in place or safely evacuate them.
- The fire and other emergency responders will have limited access, especially above the reach of local fire-fighting equipment.
- Consideration should be given to a wide range of initiating events (natural hazards, deliberate events, etc) and associated damage
- Consideration should be given to possible accidental or technological failures which could have an impact on fire and life safety

This translates into considerations for fire protection systems availability, reliability, efficacy, redundancy and resilience:

- Systems required to manage fire impacts should have a very low probability of failure, including electrical, mechanical, fire protection (active and passive)
- Redundancy should be considered where the potential for single points of failure are identified
- Consideration should be given to self-supporting of critical systems within the facility (*e.g.*, sufficient emergency power to address all critical functions)
- The structure and systems should have sufficient resiliency to withstand the initiating and fire events identified as a concern for the building

For the above, tools and techniques of hazard and risk analysis, particularly reliability, availability and maintainability analysis, failure modes and effects analysis, fault tree analysis, may be helpful.

Fire and egress scenario development

As outlined in the *SFPE Engineering Guide to Performance-Based Fire Protection,*[17] identifying the hazards, building and occupant characteristics can help inform the mitigation strategies that one might select. A key element of the characterization process involves application of hazard and risk assessment techniques for a range of issues, including the following:

- Identifying the fire hazards and their likelihood of occurrence

- Identification of potential fire scenarios of concern, grouping possible fire scenarios into clusters of reasonably possible scenarios to be used for fire and life safety analysis.
- Characterizing the occupant population in terms of risk factors such as age, ability to evacuate, language, occupant load and distribution, familiarity, whether they will be sleeping in the building, and their perception of risks associated with the environment.
- Characterizing evacuation scenario parameters, such as pre-movement behavior actions and times, movement times, exit selection (*e.g.*, stairway or elevator), and related parameters.

In particular, tools such as fault tree analysis (FTA) event tree analysis (ETA) can be useful in coupling potential fire hazards to event development and response given a range of potential mitigation measures. (In this way, these techniques can be helpful for evaluation of designs as well.) Such analyses can also account for the expected reliability of installed mitigation measures.

Fire size and structural response

Following World Trade Center attack on September 11, 2001, and partial collapses of other high-rise buildings, such as the Windsor Building in Madrid, there has been a focus on structural resilience to fire. As detailed in sections that follow, the potential mitigation approaches are wide ranging, varying from designing for full burnout to increased reliability of suppression systems to keep the fire from becoming a significant structural threat. In helping to assess the potential fire threat (likelihood and severity) and consequences (likelihood and severity), risk assessment techniques are needed, and can be applied within deterministic or probabilistic fire engineering analysis frameworks. In deterministic analyses, risk assessment methods can be useful in helping to quantify likely fire threats for use in structural response modeling. In stochastic analyses, the likelihood of fire threats and unacceptable structural performance can be assessed probabilistically.

Multi-hazard extreme event analysis

In addition to fire, very tall buildings face a number of event-related loads, in some cases dependent upon the building location, including high winds, seismic activity and deliberate (terrorist) attack. For some of these events, fire may be an integral concern, either concurrent with the event or in a post-event damage condition (*e.g.*, post-earthquake or post-blast fire). Where these types of scenarios are of concern, risk assessment techniques can be very helpful, especially considering the low probability, yet high consequence potential of some events or event combinations. Several resources exist for assessing and designing for extreme event considerations, including single and multiple events.[38]

Evaluation of possible mitigation measures

As noted above, there is a wide variety of potential mitigation measures which can be considered in very tall buildings. When considering how the selections of mitigation measures will work together in providing the level of protection desired, risk analysis techniques can be helpful, including event tree analysis (ETA) as mentioned above. The *SFPE Engineering Guide to Performance-Based Fire Protection*[17] outlines how classical risk analysis and risk binning techniques can be used for evaluation of design options. Various other techniques for assessing risk reduction through various fire mitigation strategies, including Bayesian network analysis, are available as well. Risk-cost-benefit analysis techniques can also be useful in weighing options and optimizing the balance of costs and benefits based on likely scenarios and system performance.

Identification and selection of evacuation strategies

There are various strategies one might consider for protection of occupants from fire in very tall buildings, including protect-in-place, phased partial evacuation, phased full evacuation, full simultaneous evacuation, use of refuge floors, occupant self-evacuation elevators, fire fighter assisted elevator evacuation, and combinations thereof. Risk assessment can be helpful in assessing the options available, such as the likelihood of occupants to stay in place or try to evacuate, or to use stairways versus elevators; or the reliability of systems required for achieving the target level of performance for fire and life safety systems.

Emergency response

Risk assessment and management techniques can be helpful for emergency personnel in planning responses and managing fire ground operations. Understanding what mitigation measures are in the building, the availability of those systems within the building, and evacuation systems provided can be crucial in making appropriate first responder response decisions. Based on the type of information required by the emergency organizations for a range of possible events and scenarios, a risk-informed approach to response planning can help to identify types of sensors, camera locations, communication and control equipment, and related resources to be installed in the building to help manage an event.

7 Integration of Building Systems

INTRODUCTION

Proper systems integration is important in any building design but, given the range of challenges associated with very tall buildings, it is crucial that all systems work together as planned. At a high level, the first recognition is that the building, fire and people are interrelated and influence one another. (See Figure 7.1.)

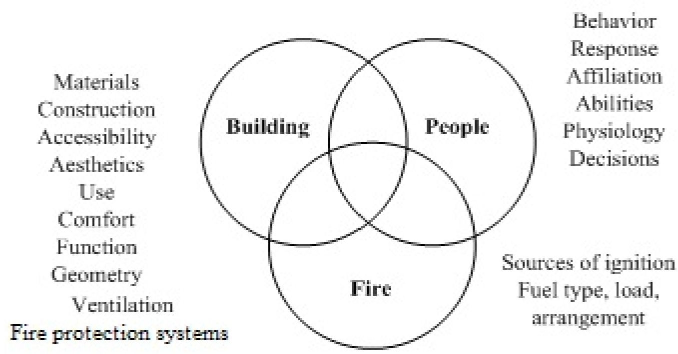


Figure 7.1. Building life safety design framework related to fire event (Alvarez and Meacham, 2010)

Systems will be designed to support the structure, provide necessary environmental conditions for occupants, and provide for acceptable access and use by occupants. These have to be designed giving due consideration to occupant risk perceptions, expected responses and protection desired. Systems should be evaluated to determine that they operate in an integrated manner to provide the intended outcome.

Cultural customs, economic practices, social implications and reliability of operation of systems must be taken into account. Questions such as the following must be asked when developing the protection concepts for the project:

- How long will it take for fire department response?
- How many fire department response personnel will be expected, and with what equipment?
- What is the water supply? How reliable is it?
- What is the maintenance program for the systems in the building?

INTER-RELATIONSHIP OF OPERATION OF SYSTEMS

At a more specific level, combinations of systems required to operate simultaneously need to be designed and tested in that manner. For example, if a strategy is to provide phased evacuation to areas of refuge from which occupants will be evacuated by elevators, the integration of detection, communication, smoke management, elevator control, and related systems need to be designed and tested to determine if the desired outcome is achieved.

Supervision of one system by another, and reporting of system status, may be necessary to demonstrate that performance of the integrated system will be achieved (*e.g.*, detection system causes activation of smoke exhaust, closes doors, pressurizes areas, sends elevators to specified floors, sends appropriate message to occupants in various locations, *etc*). A major aspect of testing system integration is by testing for required functions during systems' commissioning.

If elevators are proposed to be used for vertical egress or for movement to areas of refuge during an emergency condition, it is necessary to consider protected vestibules. This must be coordinated with the fire alarm and voice communication systems to make occupants aware of situations in the building.

EMERGENCY RESPONSE AND CONTROL OF SYSTEMS

In very tall buildings, the control of safety systems is generally from a centralized, staffed control room. Ideally, this control room would normally be located in the vicinity of the primary fire department access point to the building.

There may be a rapid transit system beneath the building and the lower floors of the building may be a large podium, thereby negating the ability of the fire department vehicles from reaching even the lower floors of a tower. As such, the source of fire risks should be addressed regarding the protection methods to be provided.

Given the various uses with these tall buildings, it may necessary to have several fire department response points (*e.g.*, retail entrance, office entrance, hotel entrance, residential entrance, *etc*). The integration and testing of the systems in the control room(s) should be completed prior to partial occupancy of portions of the building.

The cause of unwanted fires and resulting loss is usually due to several factors failing or not operating as designed to mitigate the risks. As seen in the One Meridian Plaza fire, the severity of the fire was due to improper storage of combustibles and the lack of automatic sprinkler protection.

THE BUILDING AS A SYSTEM

Various tools are available to a design team to identify fire risks and to address protection measures to properly mitigate the risks in a very tall building.

It is now time for the fire protection engineer to take a step back and review the objectives (Chapter 4), given the specific risks associated with this specific building (Chapters 5 and 6). It may be beneficial for the design team to review the systems reflected in the Fire Safety Concepts Tree.[14]

While the objectives include complying with all applicable codes and regulations relating to fire safety, it is also necessary for the design team to address the needs of the occupants, environmental regulations, energy conservation requirements, protection against natural risks such as earthquakes and floods, and protection against any specific security threat.

FIRE SAFETY OBJECTIVES

There are many potential means to address the fire safety objectives. The main overall objective of all fire codes and regulations is to reduce the risk of a fire occurring through prevention. Prevention of fires relies on human actions as well as implementing planned maintenance of equipment and systems. As prevention cannot be guaranteed, it is necessary to incorporate active systems (such as automatic sprinkler protection) in conjunction with building elements (exit stairway fire separation, fire rated structure) to limit the effects of a fire, should it occur, while providing options for protection and evacuation of the occupants. Fire fighter safety should be a consideration in this exercise.

The design team – and more specifically the fire protection engineer – will need to concentrate on the interaction of all systems within the building so that incipient fires are limited in size to meet the building's fire safety objectives. In order to achieve this, the fire protection engineer will need to be fully integrated into the design team so that fire safety is taken into consideration from the initial design concept to final delivery of the building and occupancy. The fire protection engineer will also act as a liaison between the design team and authorities having jurisdiction in the field of fire safety and emergency preparedness.

The relationship between building systems and building structure is required to be considered with respect to the fire risk and the capabilities of the occupants. When considering the building as a system, the following is an example of the inter-relationship of the building, the building occupants and the building systems.

At the very start of a project, the occupancies and the fuel loads that can be expected from the occupancies are required to be established. This information is required to be established to determine the fire risk and the type of fire that could be expected within the building. Consideration must also be given to potential future occupancy changes that may be known.

After establishing the occupancies and fuel load types that can be expected, it is necessary to identify the potential ignition sources in the building. While there are obvious sources such as human carelessness or cooking hazards, the building hazards such as poorly maintained equipment, must also be considered. Another significant cause of fires in occupied buildings that must also be addressed is construction and tenant fit up. While standard operating procedures and maintenance programs can be developed and implemented, the causes of ignition must be agreed to by the fire protection engineer and the building official at the start of the project when performance-based design is used in establishing the types and level of fire safety and fire protection to be provided.

Once the fuel load, types of materials and potential ignition sources have been established in a building, the actual structure is to be evaluated. The means by which a fire resistance rating is to be provided to a structure is required to be reviewed. Will the fire resistance rating be integral to the structure by the use of reinforced concrete construction? Alternately, the fire resistance can be achieved by the use of sprayed fireproofing or the use of fire-rated gypsum board.

The fire resistance will be determined either by the local building code regulation as a minimum, or by use of fire modeling in a performance-based design using the expected fuel load and heat release rate of materials expected in the building. When doing this evaluation, it will be necessary to take into account other safety features in the building such as elevator protection, duration of fuel supply for emergency power and voice communication for instructions to occupants. While fire resistance often has units of time, these times do not necessarily correspond to actual building performance in fire.

OCCUPANT NEEDS

In evaluating the evacuation of occupants, it is necessary to keep options open for the emergency responders for methods of evacuating the occupants. In very tall buildings, the emergency responders may choose to evacuate only the floor of alarm or may also evacuate the floors immediately above and below the floor of alarm to remove the occupants in immediate danger of an alarm. The method of evacuation may depend on the source of the alarm, whether an actual fire has been confirmed and the activities occurring in the building. As well, the time of day can play a role in choosing how to evacuate the occupants. If an alarm occurs during night hours when there are few occupants in the building, the emergency responders may choose a partial evacuation or may choose to do a complete evacuation of the building.

If a partial evacuation is chosen, the areas being evacuated may consider the zones used for smoke control systems in the building. As well, these zones for smoke control should consider the zones of the fire alarm system, zones for the voice communication system and the phasing for partial occupancy of the building. These may also coincide with the elevator shafts and the floors being served. In very tall buildings, there will likely be several banks of elevators which serve different floors.

In many very tall buildings, there may be many different uses in the building. There may be condominium floors, above hotel floors, located above office floors which are all located above retail and restaurant floors. Each of these different types of occupancies may have separate mechanical systems, separate elevators and, likely, separate building entrances.

In working with the design team, the fire protection engineer will need to assist the coordination of the stairways, fire alarm zones, sprinkler zones, standpipe zones, voice communication zones, smoke control HVAC zones and elevator zones. The security features in the building will also need to be reviewed. The coordination of these building systems is critical in designing such that in the event of an emergency, the building will work cohesively to maximize the safety of the occupants and the effectiveness of the emergency responders.

On all projects of these types, it is important that the coordination and operation of the fire protection and life safety systems be discussed and reviewed with the local authorities. As these are the people who will review and approve the project and will respond to fire scenarios in the building, it is critical that the local fire brigade be a integral part of the design process. In many cases, numerous entrances, elevator lobbies and fire department connections are required on these buildings for appropriate response and actions when an alarm occurs.

After design and installation, the life safety and fire protection systems should be commissioned to confirm that they operating correctly and will perform their intended function. This will include testing on both normal and emergency power and via actual alarms from the various portions of the building.

In many projects, a record book is retained of the approvals and design concepts used in the construction of a very tall building. This record system is critical when future revisions are being considered so that the life safety systems are not adversely affected. This record system would be in addition to the fire safety plan which provides a description of the systems in a building, the actions to be taken by supervisory staff and the maintenance requirements.

After a building is occupied, it is important that the life safety systems be maintained and the staff be trained on actions to be taken in the event of an alarm. This is required to increase the probability that the systems will continue to operate as intended as well as to minimize the potential for the systems themselves becoming a source of ignition. For these reasons, the operators of the building, the maintenance staff and the security staff become the final part of the project team to ensure the on-going life of the safety systems in the building. Building management can see systems are adequately maintained, and necessary training and procedures are in place so that a prompt and efficient response to fire and other emergencies can occur.

SUMMARY

In conclusion, the systems in a very tall building are required to be coordinated for proper operation in the event of an emergency. In order for this to occur, a qualified and experienced fire protection engineer is an integral member of the team in all phases of the life of a building. The interrelationship of the systems is even more critical in these types of buildings due to the varied uses, interior fire attack and number of persons occupying these structures.

8 Reliability of Systems

System reliability is always important, but it is critical in very tall buildings where access for manual suppression is limited and failure of key systems has the potential to result in trapping occupants or building collapse.

There are different strategies for assessing reliability. One is to include system and component reliability data into a quantitative risk analysis. Another is to consider defense-in-depth, with multiple layers of protection aimed at having back-up measures in case the primary measure fails. Use of redundant or fault tolerant systems could be feasible as well. The specific approach will likely depend on the project aims and the systems used. Chapter 6 describes various approaches to evaluate hazard and risk.

Depending on the systems to be used, there are several approaches that could be taken to provide a high degree of reliability. For electrically-powered systems, measures such as provision of multiple primary power feeds, emergency power, looped and physically protected circuits can increase reliability. For suppression systems, multiple supplies (external to building and dispersed within the building), multiple risers, alternating sprinkler branch lines supplied from separated risers, looped systems, and other such measures might be considered. For passive systems, increased fire resistance ratings of assemblies, fail-safe opening protectives, and related measures could be considered. For certain systems, such as elevators for occupant self-evacuation, additional measures might be needed to protect against water entry or smoke entry into shafts or equipment rooms, redundant controls and displays (such as to waiting occupants), or other measures may be appropriate.

A variety of risk and hazard assessment tools can be applied to help identify potential failure modes (*e.g.*, failure mode and effects analysis), results of component or system failure (*e.g.*, fault tree analysis), and impact of failures on the success of fire protection system performance (*e.g.*, event tree analysis). Reliability, availability and maintainability (RAM) analysis is a helpful tool in assessing the expected in-use performance of systems. As used here, "reliability" is a likelihood of an item working after a predefined time, "availability" refers to the likelihood that at item will be operational at a predefined time, and "maintainability" refers to the analysis of downtime that an item may not be operational due to inspection, testing or maintenance.[39] RAM analysis can help make informed decisions on reliability and redundancy of systems needed to meet targeted performance levels, taking into account downtime that will occur, and informing which systems need to be available when. SPOF analysis aims to identify single points or nodes within a system, which if compromised, result in failure of the complete system. This can then inform the need for increasing reliability or adding redundancy or resiliency into the system. A simple example is having the water supply for the building provided by a single main, where a breach of the main line would result in no fire fighting water for the building.

The reliability, availability and maintainability of systems need to be considered from planning through operation. At the planning stage, factors such as reliability of utilities (power, water, etc.) should be considered. Analysis should consider the appropriateness of the utility infrastructure in supporting the building, especially if the building is to be constructed in a currently underdeveloped area. This will not only affect decisions about the base requirements, but for internal back-up and emergency systems (power, lighting, communications, water, etc.). During operation, the reliability of utilities can affect maintainability and availability of systems. Again, this may have an influence on back-up systems, but also on maintenance and emergency planning.

9 Situation Awareness

Very tall buildings are becoming increasingly complex. These buildings are cities unto themselves, some with overall building populations reaching into the tens of thousands. Providing building occupants accurate information about the situation increases their ability to make more appropriate decisions about providing for their own safety.

Threats to an individual's safety can be either real or perceived. The occupants' perceptions are developed based on available information. In an emergency situation, occupants will make risk-based decisions about how best to provide for their own safety based on the individual's perceptions of the situation. In a very tall building, if those perceptions are not accurate, the decisions may be detrimental to their safety.

Shortly after September 11, the risk perceived by high rise building occupants was that high rise buildings can collapse. Given that news today is transmitted instantaneously via the internet and cell phones, occupants of a building can become aware of a fire occurring in their building before the fire department can arrive and begin to take control of the incident. Lacking any other specific informational input from the building life safety systems, building occupants receiving the outside information will begin to make decisions based on their perceived risks. Those decisions can actually put those occupants into an unsafe situation

Awareness of one's surroundings, and whether the emergent situation has rendered part or all of those surroundings unusable for evacuation, is critical information needed by tall building occupants in order to make appropriate decisions during an emergency. In the circumstance of needing to evacuate a very tall building, not having awareness of the situation or one's surroundings can be catastrophic.

In a recent panel discussion conducted at NRCC,[40] Groner identified that situation awareness in an emergency situation has three distinct components:

1. Determine what information is needed for occupants to make a good decision given the situation.
2. Determine the potential sources from which information can be obtained.
3. Determine the most effective manner to communicate that information.

SITUATIONAL INFORMATION

During an emergency event in a very tall building, building occupants will benefit from information with which to make the critical decisions about how they will respond. Some of this information, such as information about the means of egress plan employed in the building, can be provided in advance of the event. Other information will be specific to a given event and can only be provided during the event.

The risks associated with life safety and fire protection strategies need to be considered, coordinated and balanced as the designs of life safety and fire protection systems are selected so that the fire protection systems work to minimize the risks to occupants given the life safety systems. The means of egress design used in a given building is not necessarily the same as that used in another. In a very tall building, the risk to building occupants increases if one of the egress routes becomes unusable.

There have been a number of variations on the defend-in-place strategy employed in developing the egress systems from very tall buildings throughout the world. Building occupants may or may not be familiar with their surroundings. Regardless, they need to be aware of the designed egress strategy to be able to make good decisions. Chapter 10 provides a detailed discussion on the types of egress strategies that may be used in a building. In non-transient type occupancies, egress strategy information can be shared with occupants at various times throughout the year and emphasized through fire drills. In all occupancies, real-time data regarding the egress strategy used in the design of the specific building can be shared with building occupants during an emergency event through the one-way voice alarm system in combinations with strategically posted evacuation plans. Providing this information can increase the efficiency of evacuation.

For example, some jurisdictions mandate the use of refuge floors periodically throughout the height of all high rise buildings. The intent of this concept is that occupants nearby the floor of origin will evacuate down to the next refuge floor below and harbor in this protected environment. From there, they can take elevators or continue using stairways, if needed, to complete their egress. However, building occupants need to be made aware of this strategy. Providing real-time information about the egress system using the one-way communication system is critical in such a situation.

Recent advances in evacuation technologies make situation awareness even more critical. Historically, building occupants have been directed to not use elevators in a fire emergency, to use only the stairways. As technologies have improved, the design community has used elevators to reduce the amount of time required for evacuation, especially where full building evacuations may be needed. While conducting drills that incorporate all the evacuation systems will help the building occupants to understand how those systems can be used, there will inevitably be occupants in the building whom were not present for the drills.

Other useful information that can be communicated to buildings occupants includes the location of the fire incident and whether the incident has disabled any of the building systems. In buildings that may have only two stairways, it would be important to know if one of those stairways is unusable for egress because the fire department is using that stairway to attack the fire.

INFORMATION SOURCES

People use all their senses to obtain information in an effort to understand the situation they may be facing. However, research indicates that during emergency situations, decisions made will be based largely on past experiences.[19] Since most people have not had the opportunity to face an emergency situation such as a fire in the building they occupy, they will not be able to rely as much upon experience (or intuition) and must rely more upon evaluation of information made available to them. In the absence of information, a good decision becomes less likely.

People receive information from numerous sources.[19] In the case of a fire within a building, systems designed to provide information to the occupants are one potential source of information that are built into the building. In addition, several sources from outside of the building are usually readily available to building occupants in the form of their cell phone. Through their cell phone, they are able to receive phone calls, texts, emails and internet news information, all of which may be more timely than live instructions issued from a one-way voice alarm system. Absent live communication from an authoritative source, such as the fire department on-scene commander, the outside sources of information may gain more credibility that they are due.

Fire drills can be a valuable source of information for building occupants on the means of egress strategies used within the given building. Fire drills can be used to train non-transient building occupants on the locations of primary and alternate egress paths, especially when those may include elevators for evacuation assistance.

Fire detection and alarm systems are a principal source of information during an emergency incident. They are important systems relative to detecting the presence of products of combustion, notifying response teams, and providing information to building occupants. Another source that can provide information about the environment of the building is security cameras, and video can be used for both security and fire detection.

One-way voice communications systems are provided for high rise buildings because in a building such as a high rise, the building occupants need to be made aware of fire situations within the building to facilitate their use of the egress systems provided. Now, with prevalent use of horizontal exiting and the anticipated growth in the use of elevators for evacuation, it will become more critical to be able to notify occupants, and, in very tall buildings, be able to share real time information on the availability of egress system components in a given emergency situation.

Two way communication systems have traditionally been provided in specific locations within very tall buildings. In the past, these systems were specifically intended for fire department use because the radios they carry had operational difficulties in such large buildings. As outlined in Chapter 16, more and more fire departments are mandating the installation of radio signal amplification systems so that the communications tool firefighters typically carry (i.e. portable radios) will work throughout the building. Consequently, the two-way systems may no longer be provided for fire department use. However, given their overall value to building occupants, it is advisable to consider providing such a system for use by building occupants. However, they are only credible tools if they connect the occupants to a constantly attended location staffed by properly trained personnel.

EFFECTIVE INFORMATION DELIVERY

Effective delivery can be divided into two components, the system(s) used to convey the information and the content and presentation of the information itself. Details of design concepts associated with voice systems are fairly well developed and will not be addressed at any length in this Chapter as they can be found in other resources.[41]

However, proper delivery is important. Many voice alarm systems are arranged to operate automatically with pre-recorded or synthesized voice messages. Manual voice announcements are often left up to front desk security guards who are not regularly trained for operating under a stressful condition. In particularly complex structures, the building staff may be better for making live voice announcements to occupants near the emergency since they understand their building. The calm, reassuring voice of the fire department can also have impact upon those having to navigate a complex egress system during an incident.

The level of knowledge and training of building staff can have a significant impact upon the effective delivery of situation specific information. Intended operation of voice alarm signaling systems needs to be determined early in the design process because it may dictate design decisions.

The value of having a pre-defined, rehearsed, emergency management plan cannot be overstated. Persons trained and experienced in emergency situations are shown in research to make quicker, better decisions in crisis situations.[19] Building staff responsible for taking charge during an emergency situation within the building should train with all shifts of the responding fire department, including the shift command personnel, not just the fire inspector who coordinates these activities on behalf of the fire department.

Egress plans can provide significant amounts of information if presented in the proper manner. Making them a part of building wayfinding systems is one way to be able to keep the information in front of building occupants on a regular basis, and can be especially helpful when the building is subject to many transient occupants. An example of such a case is the wayfinding systems that are prevalently in use in the meeting room levels of large hotels and conference centers. Most of these wayfinding systems will identify key egress components and egress paths.

Printed/posted wayfinding systems are giving way to digital diagrams that are easily and remotely changeable. It is reasonable to expect that, at some point in the future, digitally-based wayfinding systems may be used to provide real-time evacuation information and direction in emergency situations based on input from the fire alarm and security systems. Being able to tell building occupants in a live verbal and visual message that an exit may be unusable for evacuation can better inform the occupants and help influence desirable decisions that can have a positive impact on the outcome of an emergency incident.

Part II – Egress

10 Emergency Egress

INTRODUCTION

The development of an appropriate and effective egress strategy is considered one of the key fire safety aspects of any tall building design. As occupants increase their vertical remoteness from the point of discharge to a public right of way, the time taken to evacuate the building will also increase. Above certain heights, the vertical distance to be travelled by an occupant may subject them to additional risks when adopting the traditional method of evacuation using only stairways. In such instances, the proposed egress system may require re-evaluation in order to consider alternative strategies such as relocation or refuge in addition to examining what role and elevators can play in enabling timely occupant egress from very tall buildings.

The acceptability of the egress system design of a within very tall building is an evaluation that must be conducted in collaboration with the building's design team, the project's stakeholders and the local approving authorities. The solution finally adopted will depend upon the building's design, its intended use and its location, amongst many other factors. In many instances, these buildings will require some form of engineering analysis to be conducted to determine the time taken to evacuate the building, either fully or partially, under a series of given scenarios. Guidance on methods to conduct such analysis is provided in a number of sources, including the *SFPE Engineering Guide to Human Behavior in Fire*,[19] the *SFPE Handbook of Fire Protection Engineering*,[42, 18] and others.[43, 44, 45, 68]

The following chapter highlights some of the options available to a building designer/fire safety engineer for decreasing occupant evacuation times or providing building occupants with safe places to rest or seek refuge remote from the fire event. While the building designers/fire safety engineers may not elect, upon consultation with other stakeholders, to implement all of these techniques – this chapter provides descriptions that are intended as 'tools' to be adopted, as appropriate by designers to meet their overall performance goals and objectives of the egress design for their given project.

DESIGN CONSIDERATIONS FOR VERY TALL BUILDINGS

While the design of all buildings must account for a range of egress considerations, several are specific to very tall buildings, and others gain importance as the building height, and consequently its occupant load, increases. These are discussed in greater detail in the following sections:

Egress Goals and Objectives

The primary objective for any fire related egress design is to provide appropriate facilities to allow occupants to move from the area of hazard to a place of relative safety, from which access to a place of ultimate safety can be achieved.

The concept of areas of relative safety is an important one for tall building egress design, because escape to ultimate safety (i.e. a location outside of the confines of the building at street level) could take a considerable amount of time to achieve. As such, stairways, separate fire compartments, areas of refuge, etc. are all examples of places of relative safety. Prior to accessing a designated place of relative safety people are potentially exposed the fire and therefore considered at risk. As a consequence, fire safety features, such as limitations on travel distance, govern within this period and terminate upon entry to the place of relative safety.

When considering a holistic egress plan for a tall building, it is often beneficial to consider the time taken to complete certain actions (such as reaching the entry door to a protected egress stairway) more so than the distance required to complete them - as is traditionally specified within building codes. While this concept is quite commonly accepted, the practice of designing a building’s egress system around a travel time, instead of a travel distance limitation is impractical in most circumstances. As stated previously, travel distance limitations (and hence travel time limitations) are usually taken to terminate upon entry into the buildings protected egress system – typically the stairways. Even if the vertical egress components are efficiently designed, and people descend relatively unhindered within the stairways, the time taken to reach ground level will increase as the building’s height does, and will be further increased due to the onset of fatigue for evacuating occupants of varying fitness levels. In these cases, a time-based approach to egress may be more appropriate than a traditional distance-based approach and this time parameter may form an integral element of the chosen egress goals or objectives for the building under consideration.

As with all buildings, tall or not, the escape objectives for the design should be able to be achieved without the need for external assistance, e.g. Fire Department/building management intervention, whose arrival may be delayed for reasons beyond their control. Such assistance therefore acts as an enhancement to the fire safety design but an acceptable level of safety within the building’s design should not depend upon such external assistance .

It should be noted that the goals and objectives of a building’s egress design are not always complementary with the goals and objectives of other building systems, for instance building security. Collaboration between the project’s fire safety engineer and security consultant early in the planning stages of a project will allow the design team to address any areas of potential conflict such as re-entry to non-fire floors from stairways, lobby security devices such as turnstiles that could impede egress, procedural conflicts or other items that may arise.

Evacuation Scenario Identification

There are a number of ways in which the fire safety egress goals and objectives for a project can be combined into an overall emergency plan that suits the particular use and occupant characteristics of a building. The following will predominately focus on the issues surrounding tall building design.

Besides incidents of fire, there may be a range of conditions or events which warrant the evacuation of a building, either in part or completely to maintain occupant safety – for example; seismic events, explosions, chemical or biological agent releases, power failure, extreme weather conditions, *etc.* While it is not the intent of this guide to address evacuation as a consequence of these non-fire related occurrences, many of which are not mandated by code, the advice and principles contained herein will go some way in assisting in the formation of an appropriate egress plan in such instances. It is therefore important that the fire protection engineer and members of the design team responsible for consideration of such events (security/risk consultant for instance) coordinate their approaches early in the design process since the evacuation provisions for a non-fire threat may conflict with those required for fire safety (not evacuating vs. evacuation for instance). If thought appropriate to consider, those evacuation procedures for fire and non-fire related scenarios should be fully combined and integrated into an overall life safety design in order to provide occupant evacuation procedures that are common to as many circumstances as possible, thus enabling increased levels of familiarity in all emergency conditions for the building's occupants.

Traditional fire safety design usually assumes a single fire source and does not generally take into account the potential for multiple, simultaneous fire locations – an example of where this could occur being arson. The vertical nature and the slender aspect ratio of tall building design gives increased opportunity for single fire locations to pose a threat to multiple egress routes than in other building types. If multiple egress route failures are thought to be an appreciable risk within the building under consideration, then an egress design considering a greater occupant load per stairway maybe an event scenario which is considered. This may be true for buildings adopting a central core design where exit stairways may be on the limit of the minimum width and separation requirements.

While effective design against arson, in terms of space planning of egress arrangements, could be a never ending process, close coordination with a project's security consultant should be initiated to establish an agreed-upon threat level that may warrant more than the standard single fire location approach.

Human Behavior

There have been numerous studies completed of human behavior in fire conditions conducted[42, 18, 46, 19]. A general finding is that occupant and occupancy characteristics can vary significantly among a variety of different building uses –examples of such characteristics are given below;

- Building population and density
- Groups or lone individuals
- Building familiarity
- Distribution and activities

- Alertness
- Physical/cognitive abilities
- Role/responsibilities
- Commitment to task
- Focal point
- Gender
- Culture
- Age
- Prior fire/evacuation experience

These aspects of human behavior affect both occupants' recognition of, and response to, fire cues and their ability to affect an evacuation.[19]

The pre-movement time of any evacuation occurs after fire-related cues have developed, but before occupants have made a decision to begin their evacuation. The psychology processes that influence this pre-movement period is cue validation and is resolved by an overlapping decision-making processes. During cue validation, our brain will process all information as follows:[19]

1. Receiving the cue (sense the cue)
2. Recognizing the cue (identify the cue)
3. Interpreting the cue (give meaning to the cue)

The time delay associated with cue validation will depend on the variety of characteristics of the evacuation scenario, such as the occupancy type, the nature of warning systems, the evacuation procedures and the nature and number of cues given at the time of a fire.

Cues that should be considered and assessed relative to the occupant group(s) in a building include:

- Visual, olfactory, sensory and audible fire cues
- Building signaling or public address systems
- Cues from people alerting others
- Cues from building service disruptions (e.g. shutting down of various building systems, power failure etc.)

The cues for those close to the origin of the fire will likely be different to those in another area of the building. Also, the effectiveness of cues will vary with respect to all the occupant characteristics.

For design purposes, one or several cues may be applicable to an occupant group. Given the selection of appropriate cues, the reaction for the cues and time for validation of the cues must be established using available research data, case histories, decision models or engineering judgment. Various guidance documents on human behavior provide assistance in this area via discussion and reference to many literature sources and case studies that illustrate time delays associated with cue validation.[19] CIBSE Guide: Fire engineering,[47]) four of nine "principals" of human behavior are listed that address the importance and potential impact of the time delay.

- Deaths in large scale fires attributed to "panic" are far more likely to have been caused by delays in people receiving information about a fire.
- Fire alarms cannot always be relied upon to prompt people to move immediately to safety.
- The ‘start-up’ time (i.e. people's response to an alarm) can be more important than the time it takes to physically reach an exit.
- Much of the movement in the early stages of fires is characterized by activities such as investigation, rather than escape.

Closely tied to the cue validation process are the decision-making processes that can contribute further to the delay before evacuation. The pre-movement decisions may occur with or without the validation of cues. The cues may be ambiguous and result in an occupant's decision to seek new information, or simply to decide to ignore the cues which may be based on the inaction or complacency of other occupants. Some engineering guidance documents[42, 47, 48] have published tables of pre-movement times for various occupancies, and context-specific data can be found in other sources. [49, 50, 51]. The sources cited can be useful, but should be used with care because the pre-movement times are generic and based on broadly subjective views. The context specific literature and background sources may serve as the best sources for pre-movement delay times.

Occupant evacuation, unless in the direct vicinity of the fire, can be a slow process with many occupants reluctant to be the first to leave. However, in the aftermath of the World Trade Center attack, there has been an increased focus on occupant evacuation and responses to alarm conditions. An increased level of seriousness, and a heightened level of awareness, to building fire alarms and evacuation drills was experienced by many – more so the occupants of the tallest and most iconic buildings in the world’s major cities.

This increased level of awareness could lead to behavioral factors that influence the egress plan chosen. For instance, the use of refuge floors within buildings (discussed later in this chapter) requires close coordination between building fire wardens/management, fire safety systems and the Fire Department in order to appropriately direct occupants to the refuge. It is possible that not all building occupants will respond in a compliant manner when requested to remain within the building during a fire event – some might attempt to totally evacuate the building irrespective of the instructions given. If an occupant wishes to evacuate, there is little that can be done to prevent them, even if this does compromise the building’s fire strategy and potentially slow the evacuation from floors in the immediate vicinity of the fire. While such actions may not be in the majority, an appreciation of such non-compliant actions may be an appropriate safety factor to include within a tall building’s egress design.

In addition to response to cues, there are aspects of human behavior that can affect their travel time throughout a very tall building. A number of items that should be considered include:[19]

- Occupant mobility
- Occupant mobility as affected by group dynamics
- Number and distribution of occupants
- Nature of floor and wall surfaces

- Egress path geometry (e.g., stair treads, risers)
- Width of path restrictions (doors, stairs, corridors)
- Training or staff guidance

The above factors that affect considerations on distance and speed are defined from a review of either occupant characteristics or building characteristics. The designer or engineer may need to consider each factor explicitly or be prepared to justify why a factor is not relevant to the analysis at hand.

Occupant Physical Condition & Mobility Impairments[19, 42, 18, 44, 46]

When selecting an evacuation strategy for a tall building, the procedures and building features that occupants those with compromised physical condition or disabilities may require consideration. Such impairments may impact the evacuees behavior or require an additional response and behavior of others in the building. Such physical impairments may include, but are not limited to the following:

- Mobility impairments – wheelchair, walking disability
- Temporary impairments – pregnancy, broken limbs, etc.
- Visually impaired and the blind
- Hearing impaired and the deaf
- Physically limited – asthma, heart condition, obesity etc.
- Cognitive disabilities

Within the context of building egress, such impairments or reductions in physical fitness can result in slower moving speeds on stairways or an increased likelihood of frequent rest stops required for the evacuee.

While these impairments should be considered for all buildings, their impact can be compounded when the buildings is very tall. Over a significant number of floors, this has the potential to significantly increase overall evacuation times. Thought should therefore be given to adopting evacuation procedures for occupants of reduced mobility or fitness as would be adopted for those who are more traditionally mobility impaired, e.g. those in wheelchairs.

Security & Fire Safety[52, 68]

By their very nature, tall buildings create landmark structures within cities. This can result in an increase in the property's security risk profile, which subsequently requires unique security solutions to be included within the design and operation to create an acceptable level of risk.

If not given appropriate consideration, standard security strategies such as vehicle standoff and access control can be at odds with fire safety requirements to gain rapid access to buildings for Fire Dept. vehicles and personnel. Given the increased security considerations for many tall buildings, which often contain tenants for which security is a key consideration of their business model, the early collaboration of a project’s fire safety engineer and its security consultant is considered essential.

Such collaboration enables solutions to be developed that can enhance, and not constrain, the overall fire safety design of the project - for instance, the use of combined fire & security control/command centers, the use of CCTV to monitor evacuations etc.

Understanding Evacuation times

To better understand the time taken to evacuate a building, a timed egress analysis can be conducted. Such analyses are typically associated with fire events and are often used as a means to demonstrate that the evacuation by the occupants is completed before conditions become hazardous to the occupants. The analysis typically undertaken compares a Required Safe Egress Time (RSET) versus the Available Safe Egress Time (ASET).[19, 68]

Why a Timed Egress Analysis?

Generally speaking, the taller the building the more occupants it can accommodate, thereby resulting in an increased time to evacuate. Ooccupancies contained in tall buildings are the same occupancies that can be found in lower rise buildings e.g. commercial offices, residential apartments, assembly occupancies, etc. In low rise building,s the time to evacuate may not be considered critical. Placing these same occupancies further from the level of exit discharge increases the time for evacuation. The question is: when is a timed egress analysis necessary? Should it be undertaken for all tall buildings? If one is completed, what is an acceptable result? The answer to these questions may depend upon various factors. Further discussion of this is provided within the Full/Total Evacuation Section.

Egress Plan and Timed Egress Analysis

The evacuation strategies in tall buildings for events such as fire often rely upon some form of partial evacuation. Partial evacuation means that only those people immediately threatened will be evacuated at one time, thus the evacuation process will be relatively quick. During such evacuations, occupants may be relocated within the building or completely evacuated from the building. In either case, the need for a timed egress analysis for a partial evacuation is generally not critical though, this depends on the type of design fire being addressed. Of greater interest are those evacuations that go beyond the initial 3 to 5 affected floors. They may begin to slow the evacuation process, as typically the stairway width is based on the occupant load of a single floor. Although this approach assumes that the occupants of different floors will arrive at a point in the stairway at different times, this approach breaks down when too many floors evacuate simultaneously. This affect can be studied with a timed egress analysis.

Elevators

A timed egress analysis can be beneficial if elevators are being considered as part of the evacuation process. Elevators can assist in reducing the time for evacuation, and a timed egress analysis will help to quantify this and assist in establishing the number of elevators to be used for such purposes.

Timed Egress Analysis Tools

There are many egress models available on the market, each based around similar person-to-person and person-to-obstruction interactions principles, but each containing varying levels of functionality. An evaluation of many of these software tools has been produced by the National Institute of Science and Technology (NIST) which may prove a useful reference when selecting an appropriate model for a given building project.[53,54]

Such egress models can be used to populate a building with the appropriate design population. These occupants can then be assigned characteristics, either as a group or individually if desired, such as; movement (walking) speed, reaction/pre-movement time, tolerance to queuing etc.

A timed egress analysis can also include the provision of elevators if these are being considered as part of the evacuation process.

EVACUATION STRATEGIES

A variety of evacuation procedures and methodologies are available for use by a building's fire protection engineer. The appropriate selection of such a strategy is one which provides both the required level of safety for the building occupants. A selection of the egress strategies widely used in building design are highlighted below.[68]

It is not possible to definitively state which egress plan should be adopted for all tall building designs, as this can only be derived from the performance objectives identified at the outset of the design. Some strategies are better suited than others to tall building desig,n as is described within the relevant commentary below.

Simultaneous Evacuation

Simultaneous evacuation involves the evacuation of all building occupants on all floors, egressing at the same time upon the receipt of an alarm signal or notification. This strategy is the norm for many building types, particularly those with relatively few floors/occupants, but is not appropriate for all buildings. It might be adopted for tall buildings in non-fire scenarios.

The use of a simultaneous egress strategy does not give any preference to those occupants within the immediate vicinity of the fire and places the maximum demand on the egress system, particularly the stairways, as they are used by the maximum number of people possible. As a consequence of this, egress components designed for simultaneous evacuation generally require greater width than those required for other evacuation strategies. This is considered particularly undesirable in tall buildings where this reduction in leasable floor area is magnified given the large number of floors over which it occurs.

Simultaneous evacuation is not typically adopted for fire evacuations within tall buildings because it causes large-scale disruption for what could be a relatively small fire event or even a false alarm. This form of evacuation also has the potential to cause queuing within both the stairways and on the building floors, which would increase the escape time on the fire floor, where people are directly at risk.

For buildings located within dense urban environments, which represents a large proportion of tall buildings, the use of a simultaneous egress strategy can have an effect beyond the initial evacuation. Occupant dispersion away from a building requires consideration as the simultaneous evacuation of a tall building can create people movement issues within the immediate vicinity when possibly thousands of occupants simultaneously exit the building. This not only has the potential to slow the discharge of evacuees from the building's exits, which has negative impacts on the occupant flows within the stairways, but also has the potential to slow the Fire Department's response to the incident by causing large crowds and blockages within surrounding roads inhibiting vehicle access to the building's designated Fire Service attendance points.

For any building type, the point at which a simultaneous evacuation begins to hinder, and not enhance, the level of safety within a building is difficult to determine and it is left to the judgment of the project's design engineers to assess the benefits and/or drawbacks of this form of evacuation procedure for their specific application.

Phased Evacuation

Typically, most tall buildings will adopt some form of phased evacuation regime (sometimes referred to as 'staged' or 'sequential' evacuation).

Such an approach has the advantage of only evacuating those people in the immediate vicinity of the fire, which allows those people in direct danger to make most efficient use of the egress provisions available to them. Additionally, for small fires or false alarms, the level of disruption to the building can be kept to a minimum, enabling day-to-day operations to resume in the shortest possible time. At the exterior of the building, in a real fire condition, the Fire Department will have clearer approach routes, and less people to manage around the site, which enables them to quickly and efficiently respond to any developing incident.

Those occupants within the zone being evacuated are given an appropriate warning signal while those outside the evacuation zone are either notified of a developing incident and told to remain in place and await further instruction, or are given no warning at all and continue their normal day activities unaware of any incident. The decision upon the extent of occupant warning past the initial evacuation zone is determined on a case-by-case basis by first responders on the scene and their assessment of the severity of the incident.

The typical phased evacuation philosophy adopted within many medium height buildings and above is the initial evacuation of the fire floor + a number of floors above + a number of floors below the fire floor. Local codes of practice and opinion may differ on how many floors below the fire floor require to evacuate in the first phase; however, between 2 and 3 floors (i.e. fire floor + floor above OR fire floor + the floor above and below) seems to be relatively standard practice.

With a large proportion of the building's occupants remaining in place, and potentially unaware of a developing fire incident, the building's fire resistant compartmentation has a greater level of importance in the success of the phased strategy compared to the simultaneous approach. This is because it is important that people located outside the initial evacuation zone are unaffected by the incident until those within the affected zone have evacuated.

While the above 2 or 3 floor phased evacuation approach is reasonable in theory, the reality is that during a emergency situation the evacuation is unlikely to be as orderly as the designated 2 or 3 floors only. With the advent of multiple methods of instant communication (mobile phones, text message, email, real time messaging, social networking apps *etc.*) the ability for information to spread rapidly throughout a building is becoming increasingly simple – particularly in tall buildings where a single tenant may occupy multiple floors and occupants across those floors may be well known to one another. The designer should, if appropriate, consider evacuation scenarios where the baseline 2 or 3 floor evacuation scenario has an appreciation of occupant overflow from floors outside the initial zone of evacuation to account for an increased number of evacuees due to internal communication. It is not possible to prescriptively define how, or to what extent, such an appreciation should be applied, however factors of safety by increasing the total building population per floor may be acceptable under certain circumstances. This could result in exit capacities greater than those required by the governing code.

In residential buildings, phased evacuation is often termed 'defend-in-place' whereby the occupants of the apartment of fire origin evacuate to outside and all other apartments, either on the same level or above/below, remain in place. The defend-in-place approach requires a good level of fire and smoke resistant compartmentation between adjacent evacuation zones, and in the case of an apartment building, this requires each individual residence to be constructed as its own fire compartment.

Progressive Evacuation

Progressive evacuation is of the same as the previously described phased evacuation, except that the occupants of the evacuation zone are evacuated to a safe area within the building remote from the fire location (as opposed to escaping direct to outside). From this safe place, occupants will either remain, or if threatened further, be relocated to an alternative safe area with the building – hence the 'progressive' nature of an occupant's evacuation. People are only evacuated from the building to the exterior as a last resort.

The relocation of occupants can either be horizontal – to an adjacent compartment on the same floor, or it could be vertically to a dedicated region further down the building from the fire floor i.e., a refuge area/floor.

The architecture of tall buildings (relatively small footprints of an open plan nature) is rarely conducive for the use of horizontal relocation, and therefore the vertical form is generally considered the only appropriate method. One notable exception to this is the sky bridge connecting the twin towers of the Petronas building in Kuala Lumpur, Malaysia (see figures 10.1 and 10.2). The sky bridge allows occupants within one tower (during its evacuation sequence) to cross over to the other tower (which is not evacuating) in order to use the egress stairways in the non-evacuating tower. Such an approach is advantageous in a single tower evacuation mode (e.g., in case of a fire event); however it provides little benefit in instances where the simultaneously egress of both towers is warranted, such as in the event of a security threat.

The evacuation of mobility impaired occupants usually adopts this progressive movement approach (by relocating them disabled areas of refuge) even if the remainder of ambulant occupants evacuate in some other manor.

Figure 10.1 – The sky bridge connecting the two towers of the Petronas building in Kuala Lumpur which is used for the horizontal transfer of occupants between the towers in a fire condition
Photo from http://www.kenmac.me.uk

Figure 10.2– Internal view of sky bridge which is used as an egress route between the two towers
http://alohomorra.com/petronas-twin-tower-building-architecture-design-kuala-lumpur-malaysia/petronas-tower-building-design-kuala-lumpur-malaysia_3/
Permission to use image pending

Full/Total Building Evacuation

In tall building design, the horizontal portion of egress is usually relatively short and it is the period of time which people are within the protected stairways which becomes the dominating factor in an occupants time for total evacuation. While people within the stairways are at a significantly reduced level of risk from fire & smoke, the building's ability to structurally resist the developing fire over time plays an increasingly important factor.

It is commonly appreciated among fire professionals that the fire resistance period for a structural element tested under the standard fire exposure tests correlates very little with the reality of how a complete structural system will react, and how long it will survive, in a real fire condition.

An evacuation of Taipei 101 in Taiwan in 2004, prior to the building's official opening, gave a total evacuation time in the region of 2.5hrs when using only the egress stairs. In order to reduce this time, at the direction of the local fire authority, the egress strategy was modified to incorporate the use of elevators from the upper floors which resulted in a reduction in the overall evacuation time to in the region of 1 hr.

Hybrid/Combined Strategies

While on the macro level, a phased evacuation procedure is the predominate strategy for a large proportion of all tall buildings, the likelihood of this being the sole evacuation strategy for the building is unlikely.

Many modern tall buildings contain not just one, but many, occupancy types and therefore a sub-set of the overall phased evacuation procedure may also be present. For instance, a tall mixed use building containing office, residential, hotel, assembly etc. may have a separate evacuation strategy for each individual occupancy; however, this will feed into the wider phased evacuation approach for the entire building.

It is commonly accepted design practice to share the vertical egress components among the various occupancies present - by doing so, egress strategies are also mixed. While the egress design will naturally adopt the requirements of the most onerous occupancy present, other challenges in such instances may still be evident. Particular attention should be given to the interface between adjacent occupancies, and hence adjacent evacuation strategies.

The majority of tall buildings, in some way, often capitalize on the views experienced from their upper levels by the provision of features such as external observation decks or internal/external dining experiences. The provision of a potentially large assembly occupancy (whose occupants may be unfamiliar with the building and may contain a greater age range than a typical office's occupants) at the top most level within the building, from where evacuation will take the longest, requires additional thought within any such fire safety strategy.

TALL BUILDING DESIGN FEATURES WHICH EFFECT EVACUATION TIMES

A number of methods are available for reducing the amount of time required to evacuate a building during a fire event. Some of these methods involve physical systems, whereas some may require management strategies or a combination of both. The selection of such methods requires consideration that each works to appropriately complement one another.[68]

Components of Egress

Exit Discounting

Many fire safety codes determine egress capacity from a floor on the basis that one of the exits available to occupants could become compromised as a consequence of a fire occurring within a close proximity of that exit. In such cases, the remaining exit or exits are then required to serve the total occupant load of the floor (i.e. an n-1 approach).

This approach, adopted by a number of European fire safety codes, offers a level of redundancy should an exit be lost in the event of a fire. While many fire safety codes do not require such an approach it is perhaps a concept that should be considered for certain high rise building designs. Such an approach, while increasing the level of redundancy within the design, may have a detrimental effect on the efficiency of the building's egress system design. If adopted, this efficiency reduction may be offset by deploying additional egress solutions e.g. elevator evacuation (see the section on "Elevator Evacuation".) A risk analysis as described in Chapter Six should be performed to determine whether this approach is adequate or if another strategy is needed.

Horizontal Stair Transfers

The competitive nature of tall building design has necessitated that architects continually push the boundaries of tall building design. One aspect of this is the variation in the vertical nature of many tall buildings. Staggered or offset floors, creating leaning towers, are becoming increasingly common in tall building design.

For the fire safety engineer, the challenge often lies in the fact that compliant travel distances and stairway separation are required on all building levels, but where a floor shifts, with respect to the vertical stairway locations, this can sometimes be challenging.

To maintain cost efficiency, and constructability, inclined or stepped stairways (mirroring the exact geometry of the tower) may not be an appropriate method of addressing such design challenges. Instead a series of straight vertical runs of stairways can be provided which horizontally connect to one another at transfer floors.

At such floors, horizontal transfer corridors (fire passageways) will connect the two stairway portions, allowing evacuees to transfer between the two stairways, in an equivalent level of protection to that of the stairway (in terms of fire resistance and pressurization).

As an evacuee, it may be somewhat of a surprise when evacuating down a stairway to find that it suddenly terminates and leads into a horizontal corridor above the level of exit discharge. In order to prevent potentially confused occupants from exiting the egress system at this point, thought should be given to limiting access points into the transfer corridor. Ideally, the corridor will contain no access points, which maintains its level of protection and prevents occupants from leaving the protection of the corridor. Additional exit signage, reaffirming and reassuring evacuees as to the direction of escape, should also be considered.

Effective Wayfinding/Exit Signage

As with any building, the provision of appropriate fire safety signage is a crucial feature in facilitating a smooth and efficient egress strategy.

Within high rise buildings, with the repetitive nature of the continual downward motion of descending multiple floors, occupants can lose an appreciation of their progress towards safety and be unaware of how many levels they have descended. For this reason, repeated information within the stairway, such as fire safety signage and stairway level identification, can reassure occupants and give people a metric with which to benchmark their progress to safety at ground floor level. Where facilities such as refuge rooms or floors are present, these should be clearly identified by signage to encourage their use. See figure 10.3.

Figure 10.3 – Common signage found within egress stairways

http://www.evacuationsign.com/EVC/Evacuation-Signs-Best-Selling.aspx

http://www.emergencysigns.com/EMS/Roof-Access-Signs.aspx
Permission to use images pending

The ability of occupants to negotiate a building's egress system under power failure scenarios should perhaps be considered with a tall building egress strategy. There are several strategies that can be used to address this. These include redundant power sources or the use of photoluminescent markings. See figure 10.4.

The use of photoluminescent markings in exit stairways is increasing within the US, but perhaps less seen elsewhere in the world. The use of such egress markings became popular following the terrorist attack on the New York World Trade Centers in 1993, where an explosion within the buildings' basement disabled the emergency generators and the building's evacuation took place largely in complete darkness or by flashlight (as the stairways were located within a central core which therefore did not benefit from light from the exterior).

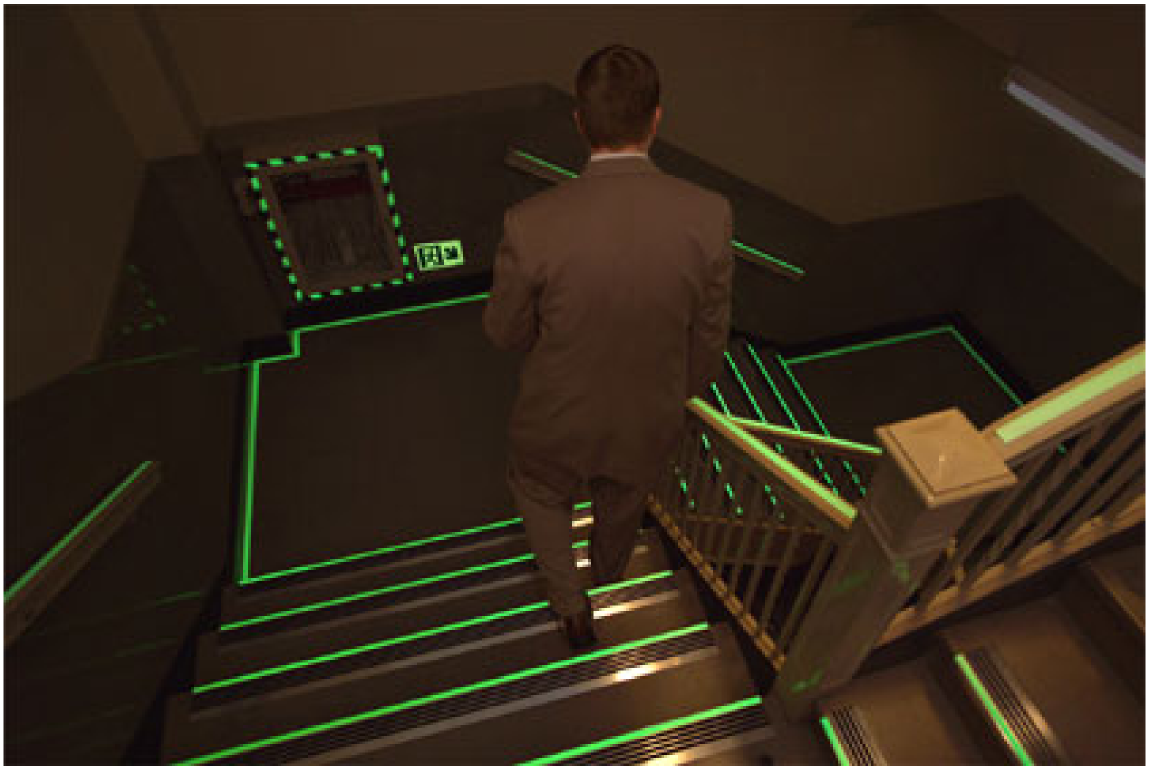


Figure 10.4 – Egress stairway provided with photoluminescent markings
Photo courtesy Balco, Inc.

The provision of photoluminescent markings is a relatively inexpensive, and generally non-architecturally intrusive safety measure. As such, while it is tempting, due to its relative low cost, to include such features within the fire safety design of a tall building, the question that is then raised is that the design considers multiple failures or extreme events which, if a realistic scenario for the building under consideration, has more far reaching consequences for the building's design then simply providing photoluminescent signage.

Egress Discharge Locations

With the large numbers of people potentially evacuating from a tall building, it is essential that people discharge to locations where they are both safe from the effects of a fire and from hazards above, e.g. falling glass etc. Egress discharge also should not interfere with vehicle access routes to the building for the Fire Service. Key to enabling this is the implementation of a building management plan to move evacuees from the perimeter of the building to appropriate assembly areas in locations remote from the building.

While considered fundamental in any fire strategy for the interior of a building, the adequate separation of exterior exit discharge points at the street level, is equally important. While theoretically the discharge of an occupant to the exterior of the building is moving away from the fire threat someway above them, the close proximity of final exits at street level creates the potential for a single point of failure which may, or may not, be fire related e.g. exits blocked by a parked vehicle or large numbers of evacuees for instance.

Some tall buildings are not free standing entities in their own right but are connected in some way to a low rise function e.g. a tower as part of a shopping center, transport interchange or other form of podium accommodation. In such instances, it is conceivable that egress from the tower above may discharge onto these low level functions, e.g. podium/plaza area such that occupants discharge to an area that is not truly at street level. Where this occurs, the important aspect of any such design is that occupants are appropriately protected from any risks below, for instance smoke discharge locations, and that egress from the podium/plaza areas can be readily achieved without affecting the continuing egress within the tower portion of the building.

Elevator Evacuation

Elevators have been recognized by some prescriptive codes as a means to assist with occupant evacuation since at least the 1970's.[55] While the early use of elevator evacuation was typically under the manual control of the Fire Department, in the late 1980's and 1990's, various government and industry groups began to encourage the use of elevators to evacuate building occupants, particularly those with disabilities[56, 57, 58, 59, 68]. A collection of references detailing these early studies in the use of elevators for occupant evacuation were compiled by Bukowski et. al.[60]

Within the US, such a strategy adopted a system of recall, as detailed below. While this terminology is specific to the US, the principle is adaptable to all markets. Currently, many buildings operate elevators under a recall system that involves two phases:

Phase I Recall : Elevators automatically relocate to the pre-defined Fire Department access level.

Phase II Recall : Elevators are placed under the control of the Fire Department, for their use, in performing fire-fighting operations or assisting with occupant evacuation.

As tall buildings continue to be built, and as security concerns drive designers to consider a wider range of emergency scenarios, the use of elevators for the evacuation of building occupants is likely to become more prevalent. A number of tall buildings already use elevators for evacuation in some form , including air traffic control towers,[61] the Stratosphere Tower[62] in Las Vegas, the Petronas Towers in Kuala Lumpur, Taipei 101 in Taiwan and Burj Khalifa in Dubai.

There are several roles that elevators can play in a building's fire safety strategy;

- For use by the fire department in their fire fighting operations. This reduces counter-flow conditions in stairways as fire fighters ascend to the floor of incident without affecting the physical condition of the attending fire department personnel.

- For use by fire-fighters to shuttle equipment from the Fire Department access level to the bridgehead on the level of incident.
- For use by the fire department to assist in rescue operations.
- For use by disabled occupants for evacuation, or others unable to use the stairways.
- For use by all of, or a portion of the general building population for evacuation.

Depending on the needs of a particular building, elevators may be used for several of these roles. No matter what the specific use, there are a number of design considerations that should be considered, including safety and reliability of the elevators, coordination of elevator controls and building safety systems, education of the building population and first responders, and communication to evacuating people during a fire.

Safety

In order to safely use an elevator for evacuation, a number of criteria should be considered. Fire and smoke should be kept out of the elevator system (i.e., elevator shafts, cars, lobbies and any adjacent stairways), water should be kept away from elevator machinery, redundant power supplies should be provided and accommodations should be made for the rescue of occupants of a stalled car in the event that a failure does occur. A number of these items are addressed in Annex B of NFPA 101.[63]

For the purposes of limiting the spread of fire and smoke into an elevator during evacuation, one should consider the entire system, including;

- The elevator shaft/hoistway/car
- The elevator lobbies on any floor connecting to the elevator
- The stairway(s) attached to the elevator lobbies
- The exit area between the elevator at the level of exit discharge and safety

Available literature suggests a range of options for providing a fire separation between the elevator evacuation system and the rest of the building[63, 62, 64]. This could include a fire resistant separation or a combination of a fire resistant separation with automatic sprinklers. In addition to physical separation, measures will be needed to prevent the migration of smoke into the elevator evacuation system. Whether this is accomplished through physical separation, pressurization, smoke exhaust or other means, a component is to have smoke detection installed in elevator cars, at the tops of elevator shafts, in elevator machine rooms and in each elevator lobby. Activation of any of these smoke detectors should recall the affected elevator to the level of exit discharge.

Whatever the means of providing fire and smoke separation from the elevator evacuation system, it is crucial that performance criteria be set such that occupants waiting in the elevator lobbies will be protected from untenable conditions for a period of time long enough to undertake an evacuation. Design of these areas should consider the number of people that may be housed in these areas as well as the needs of disabled building occupants.

Another safety/reliability consideration is the possibility that water from sprinklers or fire department suppression efforts could affect elevator machinery. In order to prevent water infiltration into an elevator evacuation system, the following methods could be considered.[63]

- Construct shaft enclosures and any penetrations in such a way that water accumulating on the inside wall cannot spill over into the elevator shafts/machine rooms (for example by installing a curb).
- Provide drainage sufficient to manage the flow of water from fire department hoses and activated sprinklers.

Controls and Operations

The controls used to operate elevators in high rise buildings are complex and require planning during the design process. Elevator cars should be provided with an emergency call system that will allow riders to call for help if the elevator cars malfunctions. The fire control/command room can be used to monitor the movement of each elevator and respond to any request for assistance.

The controls used to run elevators used in evacuation require interface with the building fire protection systems. As the height and complexity of a building increases, it may be necessary to pre-program automated control responses into the elevator systems. Controls should be programmed differently for emergency situations where the intended use of the elevators has changed. Decisions as to what functions are appropriate in different situations should be informed by a risk analysis, as discussed in Chapter 6. Whereas in normal conditions elevator occupants usually control the elevator to the desired floor (by an elevator control panel within the car), there may be benefit in an emergency scenario of having dedicated egress elevator operators (a trained member of building security staff for instance). While this reduces by one the room for evacuating occupants within the elevator, i the increased efficiency of the evacuation may compensate for this.

A thorough discussion of controls for evacuation elevators is provided by Bukowski et al.,[64] and some of the major concepts are outlined here. Some control functions that should be considered during the design of an elevator evacuation system are:

- When smoke/fire have penetrated to a portion of an elevator system (shaft, lobby, machine room, *etc.*) that elevator should be recalled to the level of exit discharge and taken out of service for egress purposes.
- The fire department should have the ability to route elevators as needed to fit their suppression/rescue plan for the building.
- Consideration should be given to minimizing the number of starts and stops required for an elevator during an evacuation. Certain floors can be designated for elevator evacuation and elevators can be run in an “express” mode.
- First priority should be given to collecting occupants of the fire floor and other adjacent floors. Once the fire zone is emptied of occupants, the elevator evacuation can serve other floors.

- An elevator can be designated for fire department use and remain clear of evacuating occupants.

Training & Communication

Training will be a key requirement to successfully implementing an elevator evacuation system. For decades, people have been told not to use elevators during an emergency, and in most buildings they still should not. The few buildings that do harden their elevator systems for use in an evacuation will need to make their occupants aware that they should (and how they should) use the elevators in an emergency. A major aide to the education of a building population in the use of their elevators is the provision of voice communications and illuminated signs during an emergency event.

The following issues should be considered when developing a training plan for use of elevators in evacuation[61]:

- Building occupants need to practice unconventional procedures. Distribution of the plan to occupants is insufficient by itself.
- The system cannot be expected to work properly in a fire emergency without periodic exit drills.
- Occupants of elevator lobbies should be taught to anticipate long waits.
- A means of receiving feedback from fire drill participants should be implemented.
- Training should not be restricted to a classroom setting; it should include a walkthrough of the steps required of evacuating occupants.
- Separate and more regular training should be provided to employees who staff the control room.
- Voice and text communication to elevator lobbies from a fire command location should be provided

SUPPLEMENTAL ESCAPE EQUIPMENT

Following the events of 9/11,many products began to emerge hat were designed to provide supplemental provisions for escape of tall building occupants without the use of traditional stairways. The use of such devices may be inappropriate for tall building evacuation and they are not recommended as a permanent alternative to the use of stairways or elevators. It is not expected that these would form an integral part of any fire strategy other than in exceptional circumstances.

Helicopters for Egress/Rooftop Helipads

The use of helicopters to assist in tall building fire emergencies is something that seems to divide many fire safety professionals and approving authorities around the world. Requests for the provision of helipads on tall buildings, for the purposes of both occupant evacuation and fire-fighting operations, are often sought by fire authorities.

The use of roof located Photovoltaics (PV) and green roofs are increasingly common, potentially conflicting with traditional helipad design.

Helicopters have been successfully used to assist with building evacuations. For example, during the 1980 MGM Grand Hotel and Casino fire in Las Vegas, occupants were rescued from a building roof top.

Many tall buildings are provided with helipads as part of the building's functional use (e.g. a hospital or a high end residential/hotel/office development for instance) and in such situations, the use of this helipad would be a good additional safety feature, given it will be present regardless. In such instances, or where the specific provision of a helipad for either fire-fighting or evacuation is decided upon, the functional use of helicopters in a fire emergency offers many unknowns.

For the purposes of evacuation, people usually travel in a downward direction when residing on the upper floors of a building – there is a natural instinct in a fire, or any emergency, to get to the ground level and then out the building as opposed to travelling upwards and away from perceived safety. This, combined with the fact that other occupants within the stairway will be travelling downwards, results in very few occupants opting to escape upwards. That said, there have been instances where occupants have made their way to the roof of building. This has usually been because there has been a failure in some other fire safety system which has made upward travel their only option.

Even if evacuees decide to escape to the roof, the number of people that can be evacuated by helicopter in a single trip is usually relatively small. For large groups of evacuees, without careful and rigorous crowd management being implemented, the issue of establishing the priority of evacuees has the potential to escalate into a dangerous situation and therefore such a rescue operation must be carefully planned and executed.

The landing of a helicopter on the roof of a burning building is, in itself, an extremely dangerous operation. Lack of visibility due to smoke or high winds could make it difficult for the helicopter to land.

Because of the unreliability of using helicopters for evacuation purposes, the standard internal facilities of stairways will be required irrespective of the provision of the helipad, i.e., no credit in the egress provision should be sought on the basis of having a helipad because it is not reliable. At best, the provision of a helipad only represents an enhancement to the existing provisions.

METHODS FOR PROTECTING BUILDING OCCUPANTS IN PLACE[68]

Some evacuation strategies make use of safe areas to which building occupants can be relocated. These may be designed to provide temporary refuge/resting locations as people exit the building, or to hold people for the entire duration of an event within the building. A number of methods of achieving these options are discussed below. In order to make use of any of these strategies, it is important that a structural analysis of the building design is also completed to demonstrate that the integrity of the building and its systems can be maintained during design fires/events under consideration.

Evacuation of the Mobility Impaired

Adequate provisions for the evacuation of mobility impaired occupants is a fundamental requirement in all buildings – whether tall or not. In tall buildings, however, where there may be an extended time period before outside support arrives to assist these occupants, special consideration for their protection should be considered.

The traditional view of mobility impairment is that of occupants confined to wheelchairs or similar devices. However, there are a variety of conditions outside of the commonly considered mobility impaired definition that may require an alternative egress plan to be sought, for example, those with temporary disabilities, e.g. broken limbs, sports injuries, pregnancy.

Areas of Refuge/Refuge Floors

During a building evacuation, there will often be people who for a variety of reasons cannot evacuate via stairways. This could be due to disabilities, or in the case of very tall buildings, even an ambulatory population may be unable to make it all the way to the level of exit discharge without resting along the way. In order to accommodate for these considerations, staging areas or areas of refuge can used to create a safe area where building occupants can await assistance, periodically rest as they descend, or wait for an evacuation elevator. Structural considerations should also be noted; Chapter 11 of this document discusses the impact of extended egress on fire resistance, which is applicable to areas of refuge/safe areas, or defend-in-place.

Areas of refuge have typically included protected elevator lobbies or stairway landings that are sized to accommodate a wheelchair. Based on studies that have shown that areas fully protected by sprinklers can maintain tenable conditions in egress corridors[65, 66], many codes allow for the use of any floor in a building protected throughout by an automatic sprinkler system as an area of refuge.

As buildings become taller, and in light of events such as the World Trade Center attacks, areas of refuge have been considered as alternatives, or supplemental to full building evacuations.

Prescriptive fire safety codes in a number of countries such as China, Singapore and India mandate dedicated refuge floors in some very tall buildings, typically separated a specified number of floors from one another. These refuge floors are often created by separating portions of mechanical floors, dedicating their use as refuge floors with openings to the exterior on opposing sides to prevent smoke accumulation.

The *Indian National Building Code* requirement for refuge floors, albeit not whole floors, is at least every 7 floors. The size of the refuge is based upon a percentage of the habitable area of the floors between adjacent refuges. The Indian refuge model is different from those in other parts of the world in that the refuge rooms (to give them a better description) are not a mandatory part of the building's fire strategy (although it is mandatory that they are provided). An evacuation regime is chosen for the building, for example a phased evacuation, and if an evacuee becomes fatigued during that evacuation they can stop and rest in the refuge room (which is directly accessed from the stairway enclosure).

Another alternative to the concept of providing dedicated refuge floors is designing for re-entry of evacuating occupants onto floors that are below the fire floor. If this strategy is employed, stair doors that are available for re-entry should be regularly spaced (for example every 3 to 5 floors) and clearly labeled on the stairway side of the door which can be used for re-entry.

Designs in the United States for areas of refuge in tall buildings have more typically made use of protected elevator lobbies attached to stairways as areas of refuge. NFPA 101[63] suggests that these elevator lobbies be designed to provide a minimum floor area of 3 ft^2 per person, and be able to serve at least 25% of the occupant load of the floor served by the lobby, as well as provide space for occupants in wheelchairs. Another approach to the design of an area of refuge would be to base the size of the area on the occupant load that has been calculated using a timed egress analysis.

Regardless of the exact design of an area of refuge, several accommodations should be considered to increase its effectiveness during times of emergency. These include;

- Provision of two-way communications for contact between occupants and emergency responders and building management
- Windows in doors that allow occupants in the area of refuge to see what conditions are like outside the protected area
- Appropriate signage to allow the area of refuge to be found
- Emergency lighting on standby power
- The ability to maintain a smoke free environment for the duration of the intended use
- Proper integration with building fire safety systems, maintenance procedures, and procedures for evacuation and emergency response
- Contain or have access to an elevator, if above a certain height

Some of these requirements will affect the building power supply system, and are discussed further in Chapter 16.

A study of human behavior related to use of areas of refuge in a number of US government office buildings was conducted by Levin and Groner in the 1990's[67] Among other things, this study found that intended users of areas of refuge would accept the concept if properly implemented. It was found to be important that information be provided to the building occupants regarding the specific hardware features of the areas of refuge (smoke control, communications, etc.), and when areas of refuge are intended for long term staging that some form of seating be provided, and that vision panels should be provided in doors.

A final consideration that may be appropriate for areas of refuge in some buildings is their level of structural isolation. If the building could be subject to threats that could result in partial building collapse, the structure of areas of refuge could be designed to be independent of other portions of the building, or provided with redundant structural reinforcement that could make them more resistant to harm during a partial collapse of a building.

Sky Lobbies

An efficient elevator lifting strategy is one of the most important aspects of tall building design. The design of many modern day tall buildings is governed by its ability to move people from street level to their level of work or accommodation in a reasonable time period. This can be a particular challenge at times of the day when there is a peak flow of people either leaving or entering the building.

Technologies with respect to lifting strategies for tall buildings is advancing to cater for taller building. Double-decker elevators, destination control and express elevators zones are all methods of reducing elevator wait times.

Often integral to this strategy is the use of sky lobbies, areas (or even whole floors) where transfer between various elevator groups can be achieved in order to reach the desired floor. These sky lobby areas may share a level with mechanical equipment and may even have additional occupant facilities to act as a mini destination, e.g. café or light retail facilities.

Given the familiarity of these spaces to the building's population (as people are required to transfer through these spaces on a daily basis) their alternative use in a fire condition would seem an appropriate function, particularly for use as a refuge area.

IMPACT OF EMERGENCY RESPONDERS

In all complex building designs the engineer should consult with the local fire department to understand their operational procedures and how they could impact building evacuation. While the operating procedures/access strategies of any local Fire Department could influence egress performance, some degree of counter flow will occur during Fire Department intervention process, whereby evacuees who egress downward pass fire-fighters traveling upwards.

A Fire Department access strategy which adopts protected fire-fighter elevators can be more efficient because the opportunity for counter flow is vastly compared to an approach where the Fire Department accesses the fire floor purely by the stairways. The use of dedicated fire-fighting elevators is becoming increasingly common within many international codes This strategy allows the rapid vertical movement of fire-fighting equipment and personnel throughout the building.

Within many buildings, Fire Department standpipes and hose reels/hose racks are located within the stairway, either on the full or half landing. When setting up a fire-fighting bridgehead within the stairways, congestion may be experienced. A common method for reducing the effect of equipment within the stairway, which is adopted within a number of countries within Europe, is the location of the standpipe outlets within a protected lobby/vestibule between the stairway and the accommodation – thereby reducing the presence of hose-lines within the stairway. If connected to on the fire floor, this has the advantage that the fire doors into the protected stairway remain closed (as opposed to being held open by a charged fire hose) which assists in the effectiveness of the stairway pressurization system.

The New York Fire Department considers counter flow by defining a single stairway within a building as their attack stairway. If it is necessary to further evacuate occupants above the fire floor following the initial evacuation, fire-fighters direct occupants to the other (non-attack stairways). While this does solve the issue of falls and trips from people evacuating within the attack stairway (not to mention evacuees obstructing fire-fighting operations) the building evacuation time may be increased.

Evacuation Management[68]

Due to the complexity associated with evacuation and relocation of occupants in very tall buildings, creating and implementing an evacuation plan is an essential element of a building's fire safety strategy. Regulations such as building codes typically do not mandate how a building is to be evacuated, but there is often a requirement for certain buildings, such as tall buildings, to develop fire safety and evacuation plans. These types of plans likely include elements such as egress routes, the basic evacuation strategy (phased, simultaneously, defend in place *etc.*), employee procedures, procedures for assisted rescue, and operation procedures for systems such as emergency voice communication.[68] An egress strategy will be developed using a risk as analysis such as described in Chapter Six.

Tall buildings are likely to have large populations, which can be challenging to manage in terms of occupant reaction and the need to respond during a fire or other emergency. Therefore, building owners/managers need to take the lead in such a role and work with the local Fire Department and emergency responders to establish the most efficient regime for the particular building. In certain countries or cities, every tall building is required to have a Fire Safety Director to manage egress planning and associated evacuation training. Even if not mandated by code, this approach can be beneficial for all very tall building projects.

Development of Egress Plan

Egress plans should be documented in the fire protection design report. The building's stakeholders should participate in its development. In the case of a tall building, there may be many stakeholders, such as the owner, property manager, fire safety director, occupant and tenant representatives and building engineers. The emergency responders such as the police and fire department should be involved.

When developing the plan, a number of factors should be considered, for example:

- What are the anticipated credible events?
- How a fire is detected or how it is determined that a hazard exists?
- How are occupants alerted
- How are emergency responders alerted?
- How will occupants and fire department personnel interact? Will they interfere?
- Where will the occupants go when exiting the building – will it affect the fire department?
- How are occupants being accounted for during an evacuation?
- If elevators are used, do the evacuation features automatically activate? Do they need be activated manually, and if so, who makes the decision on site to activate?

These factors may seem straightforward for a single fire in a building; however, other events such as a chemical release may not have automatic detection and notification to the fire department. Being prepared for a variety of events provides more flexibility for the egress plan.

Implementation

Several factors affect the implementation of an egress plan. Much of it comes from the leadership. Building occupants should understand that the senior leadership see planning and implementing egress plans as a priority, and that it is important in order for occupants to take the process seriously. Otherwise, during an event the fire, wardens will not be as effective, and strict adherence to the plan might be seen as optional or unnecessary.

Changes and Absentees

Changes in layout of a building, introduction of new tenants, or changes in fire wardens should all be addressed. Also, fire wardens could be absent during an event, along with people designated to assist those with a disability.

Occupancy Types

Occupant familiarity plays a major role in the execution of a successful egress plan. Office or residential occupants, for instance, are likely to be familiar, to a degree, with a building's escape routes and egress procedures, whereas for a hotel occupant (who is likely to be unfamiliar with their surroundings due to the short duration of their stay), the use of fire wardens providing clear evacuation information to occupants becomes more critical.

Assisted Evacuation

Persons that have disabilities or with some sort of mobility impairment will likely require assistance during evacuation. This assistance may simply be from a fire warden or other assigned staff that makes sure that the occupant gets to a place of safety to await rescue.

11 Fire Resistance

INTRODUCTION

Fire resistance is the ability of a structural element or system to withstand exposure to fire such that load-bearing capacity, integrity and insulation are maintained for a specified duration. Traditionally, the fire resistance of a structure is demonstrated via standardized fire testing where single elements of structure are exposed to an infinitely increasing standard fire curve (*e.g.* ASTM E119,[69] BS 476:20,[70] ISO 834[71]) and assessed against prescribed temperature and integrity limits. While this approach has historically satisfied life-safety objectives, it is unclear whether these objectives, let alone other performance objectives, will be satisfied as buildings become larger, taller, and more complex.

WHY FIRE RESISTANCE FOR VERY TALL BUILDINGS?

While the fire sizes or fire hazards for tall buildings may be no different than in low-rise or medium-rise buildings, the consequences of partial- or global collapse of very tall buildings due to a severe fire event poses a greater risk to a larger number of people, fire fighters, surrounding buildings and the community at large. In addition, by the nature and scale of the projects, tall buildings often contain unique design features (*e.g.* large structural elements/systems, complex atria, innovative and/or complex structural systems, coupled gravity and lateral load-resisting systems) whose role in the structure and real fire response are not easily defined or understood using traditional fire protection methods.

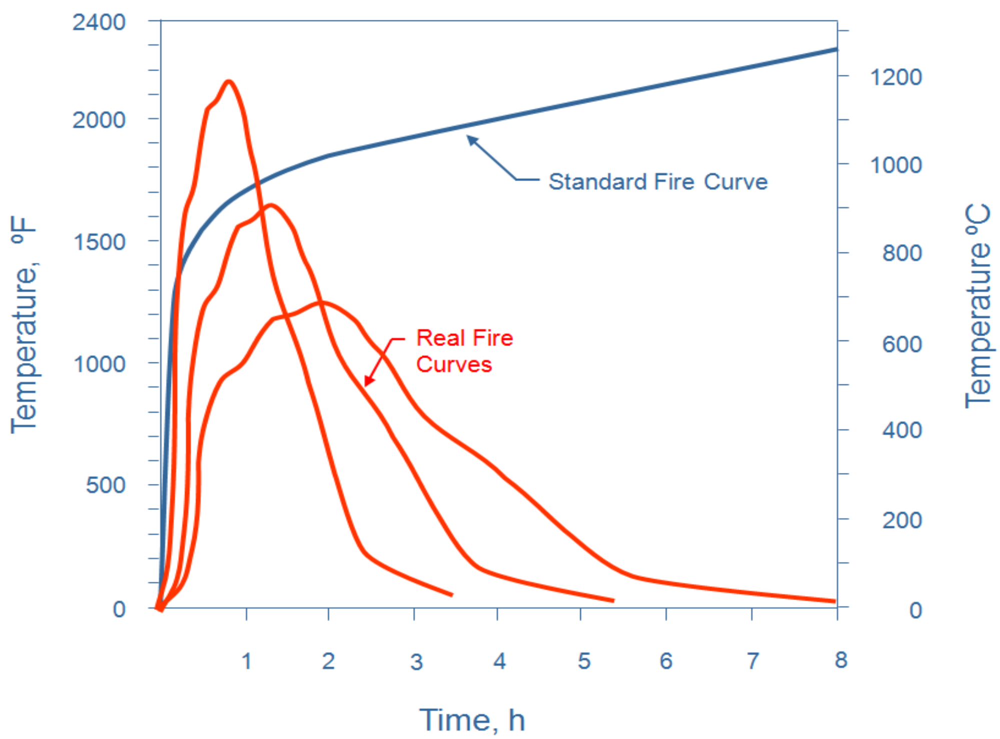
The increased consequences of collapse and unique/complex structural systems may warrant a change in the level of fire resistance required for structural components and the need to adopt advanced structural fire analysis techniques to demonstrate that the performance objectives are satisfied. In some cases, life-safety objectives alone may no longer be appropriate, and additional performance objectives may need to be provided to address such issues as resiliency, business continuity, property protection, community investments and national security.

LIMITATIONS OF STANDARD FIRE TESTS

Historically, the structural response of building elements in fire conditions has been based on standardized fire tests of single elements exposed to a standard temperature-time curve such as ASTM E119,[69] BS 476:20[70] or ISO 834.[71] Depending on the type of structural element (i.e. column, beam, floor system, wall, *etc.*), the test specimen will either be loaded or unloaded. Failure of the element is assessed against standard temperature and integrity limits, and in some cases load bearing function (*e.g.* floor/roof systems). While this approach is a necessary part of the regulatory systems and provides data on the relative performance of materials and small-scale assemblies in a furnace, it may not capture the response of the actual structure in realistic fire conditions. For very tall buildings, this method of assessing structural response in fire conditions may not be acceptable, as the consequences of failure are greater in comparison to low-rise buildings.

The primary concerns with the prescriptive fire resistance ratings relate to the fire exposure and the physical limitations on the size of elements tested.

The standard fire curve used in furnace tests is intended to represent a fully-developed fire in a compartment. By its nature, the standard fire curve is a thermally severe fire due to its constant and infinite temperature increase. Real fires are transient, spatial phenomena with a finite fire load (See figure 11.1). In tall buildings, where large open floors and multiple floor openings (i.e. atria) are common and can be quite complex, a travelling fire could present a more challenging or less challenging fire exposure to the structure, in comparison to, a fully-developed fire. Real fires have a growth period as well as a cooling period. The effect of heating (thermal expansion) and then cooling (thermal contraction) could have significant impact on the performance of the structure in realistic fire conditions. While the unrealistic nature of the standard fire curve is a weakness for assessing performance of structural elements in all buildings, the level of uncertainty in this approach may not be acceptable for very tall buildings where a higher degree of resiliency, robustness and efficiency may be required.



<u>Figure 11.1 - standard fire curve vs. real fire curves</u>

In addition, the structural elements tested in standard fire tests are limited to relatively short spans (*e.g.* 3 meters for columns, 4 meters x 5 meters for floor systems, and 3 meters x 3 meters for walls). In most cases, the elements are not loaded. For tall buildings where structural elements can be significantly larger, the expected fire performance from standardized tests may no longer robustly translate or be acceptable as the basis for design at the scale required.

Real structures are not composed of single elements; they consist of 2D and 3D systems where continuity, connections, alternative load paths, and restraint play a role in performance, both in ambient and in fire conditions. For tall buildings, the interaction of different systems/forms/materials, the coupling of gravity and lateral load-resisting systems, the resiliency of key connections become critical to structural performance and satisfying agreed objectives. These aspects of tall building design are not captured by standard fire tests.

These concerns with the reliance on the standard fire test as a basis for design, particularly as buildings become larger and more complex, should be considered. Appropriate methods of assessing fire resistance of the structure should be considered and agreed with all relevant stakeholders. Those methods are further described below.

PERFORMANCE OBJECTIVES

Because of the increased consequences of structural failure due to fire, additional performance objectives/criteria beyond life-safety may be necessary and appropriate in the fire resistance design of tall buildings. Chapter Six provides an explanation of risk based methods to evaluate the performance.

The designer should consult with all major stakeholders (*e.g.* owner, design team, authorities, insurers, future tenants, *etc.*) to establish performance objectives that may go beyond the minimum for life-safety. Some sample questions or concerns that should be addressed include:

- What are the life safety and insurance criteria for fire in a tall building?
- What is the egress plan for the building, and does this change the performance criteria for the structure during a fire event?
    - Evacuate occupants on the floor of fire origin and the floors adjacent to the floor of fire origin only?
    - Defend in place ?
    - Total building evacuation?
- How are fire fighters activities going to be conducted? And how does this impact the structural fire resistance design?
- What is the surrounding community like? What level of safety needs to be provided for the general public or community in the vicinity of the building ?
- What level of fire damage/loss is acceptable?
- What is an acceptable level of downtime for repair?
- Is partial collapse in a severe fire event acceptable?
- What level of local collapse is acceptable?
- What level of resiliency in fire should be provided?
- What level of analysis is satisfactory to meet the desired performance objectives?
- What is the best approach to understanding the building's real performance in fire?
- What fire scenarios (fire size, severity, location, number of levels affected) are reasonable for design?
- Should multi-hazard scenarios be considered (i.e. post-earthquake fire events)?
- Should a threat and risk assessment be conducted to develop suitable design/mitigation measures?

- Do the building owner and insurers have additional performance objectives beyond the minimum for life-safety (*e.g.* limit damage/deformation, property loss or business disruption)?

STRUCTURAL SYSTEMS TO REDUCE DRIFT AND ACCELERATIONS DUE TO WIND

In general, as buildings go beyond approximately 30 stories, lateral resistance to address drift and accelerations becomes an increasing concern due to wind. Traditional lateral resisting systems, such as moment frames, for low- to medium-rise buildings become less efficient and less economical as the building height increases. Additional structural systems, such as outriggers, tuned mass dampers and/or visco-elastic dampers, are typically required to help address the increased lateral resistance demand. Oftentimes, these systems can influence the demands on the load-resisting systems (both gravity and lateral) of the building, and therefore become an integral part of the overall global stability system of the building. In addition, these systems may consist of combustible materials that may degrade in a fire or contribute to fire severity.

Consideration needs to be given on how fire will affect the material response of these systems locally and globally, and what level of fire resistance or protection is appropriate to maintain global stability and other performance objectives.

COUPLING OF GRAVITY AND LATERAL LOAD RESISTING SYSTEMS

In very tall buildings, the coupling of gravity and lateral load resisting systems also becomes more essential for economy of scale and performance. This results in increased use and reliance on combinations of structural systems (*e.g.* shear-wall frame systems, shear truss-outrigger braced systems, framed tubes, tube-in-tube systems, bundled tubes, truss tubes, mega-braced tube structures, *etc.*) and/or new structural systems (*e.g.* cable stiffened towers) to serve multiple functions and satisfy the unique structural challenges faced by very tall buildings. This may mean that the fire resistance level of a structural system may need to be increased beyond that specified in the code due to its importance in maintaining global stability. For example, some building designs include a mega-floor, which is a floor whose structure is essential for the global stability of the building. The fire resistance level of a mega-floor in a very tall building will likely need to be increased to the same fire resistance level of the main structural frame whereas, an intermediate floor may not.

Oftentimes, the various structural systems that are coupled in very tall buildings consist of different construction materials (*e.g.* steel, concrete, composites) which can have differing material behaviors at elevated temperatures. These differences in material behavior could lead to thermally induced forces, internal stresses, deformations, displacements and other incompatibility issues that the structure may not be designed to resist. For example, a steel - bracing system may be coupled with a concrete core system. In a fire event, the steel bracing elements (which have a high thermal conductivity relative to concrete) will heat rapidly and expand against the cooler concrete core walls. Because concrete does not heat or lose strength/stiffness in fire as rapidly as steel, thermal expansion from the steel will be restrained by the concrete and induce axial forces into the steel brace. In a fire, these thermal expansion forces can be significant and potentially lead to yielding or buckling of the steel brace. Consideration should be given to the effect of differing thermal material properties of gravity and lateral resisting systems that are coupled in tall buildings.

POST-EARTHQUAKE FIRE RISK

The occurrence of fire following an earthquake is a potential concern for all structures, not just very tall buildings. Water supplies, automatic sprinkler systems, emergency power and fire department intervention may be limited or disrupted after a major earthquake. However, for very tall buildings, because of the potential remoteness of the fire floor from grade level, it may take more time for emergency fire fighting activities to occur. This may mean that a fire on the upper floors could go unchecked for several hours and potentially travel to multiple floors. Consideration should be given to the impact of a fire on the performance of the structure post-earthquake. This may consist of a post-earthquake fire risk assessment, structural fire analysis of various fire scenarios (*e.g.* fully-developed post flashover fire over a single floor, multiple floor fires, travelling fires, *etc.*), providing additional fire safety provisions to mitigate fire ignition or spread, *etc.*

POTENTIAL FIRE SCENARIOS TO CONSIDER IN FIRE RESISTANCE DESIGN

Unlike design basis fires for smoke control systems, which are typically governed by the incipient and growth phases of a fire, design basis fires for structural fire resistance is generally concerned with fully-developed post-flashover fires. This is when the fire has moved past the growth phase and all combustible contents in the compartment are burning. It's generally during this phase of the fire and during the cooling phase when a structure can be affected. The peak temperatures, duration of peak conditions, and overall fire severity are a function of combustible fuel load and amount of ventilation (or openings). In tall buildings, the amount of combustibles may be no different to low-rise buildings; however, the ratio of ventilation (i.e. windows) to combustibles is generally higher and can result in higher peak temperatures in a post-flashover fire scenario.

Various methods are available to the designers to determine post-flashover events/conditions, e.g.:[72]

- One Zone Models (SFPE S.01,[73] Pettersson, Magnusson & Thor;[74] Babrauskas & Williamson 1978,[75] Ozone,[76] SFIRE-4[77])
- Standard fire curves (*e.g.* ASTM E119,[69] ISO 834,[71] BS 476:20[70])
- Parametric temperature-time curves (*e.g.* Babrauskas Method,[78] Eurocodes,[79] Lie's Model,[80] Mäkeläinen's Model,[81] *etc.*)

In some cases, adopting a post-flashover fire scenario as the basis for design may not always be the correct approach.[73] For example, in very large open spaces (such as atria, open plan office layouts, enclosed stadia, airport terminals, *etc.*) or where the structure is located external to the internal floorplate, which can often occur in very tall buildings, a post-flashover fire is unlikely.

A severe localized fire, external fire or travelling fire may be more acceptable for design. A number of methods are available to designers to determine these more localized fire events:

- Localized fires (*e.g.* Eurocodes,[79] SFPE S.01[73])
- External fires (*e.g.* Law Method,[82] SFPE Handbook,[83] Eurocodes[79])
- Multi-zone fire models (*e.g.* CFAST,[84] Ozone,[76] Branzfire[85])
- Computational Fluid Dynamics (*e.g.* FDS,[86] SMARTFIRE[87])

Because of the size, scale and unique design aspects found in very tall buildings, the potential fire scenarios may be different than those typically observed in low-rise buildings or assumed in standard fire tests. See figure 11.2. Consideration should be given to conducting a fire risk assessment where unique design features of the tall building could result in a fire scenario that impacts the expected performance criteria for the building. The following table provides some sample fire scenarios that can be unique to tall buildings:

Potential fire scenario	**Unique aspect of very tall buildings**
Travelling fires	Large open floor plates Complex multiple floor openings
Multiple floor fires	Complex atria Complex multiple floor openings Delayed fire fighting due to remoteness of floor
Full-developed post flashover fire over entire floor plate	Large open floor plates Delayed fire fighting due to remoteness of floor

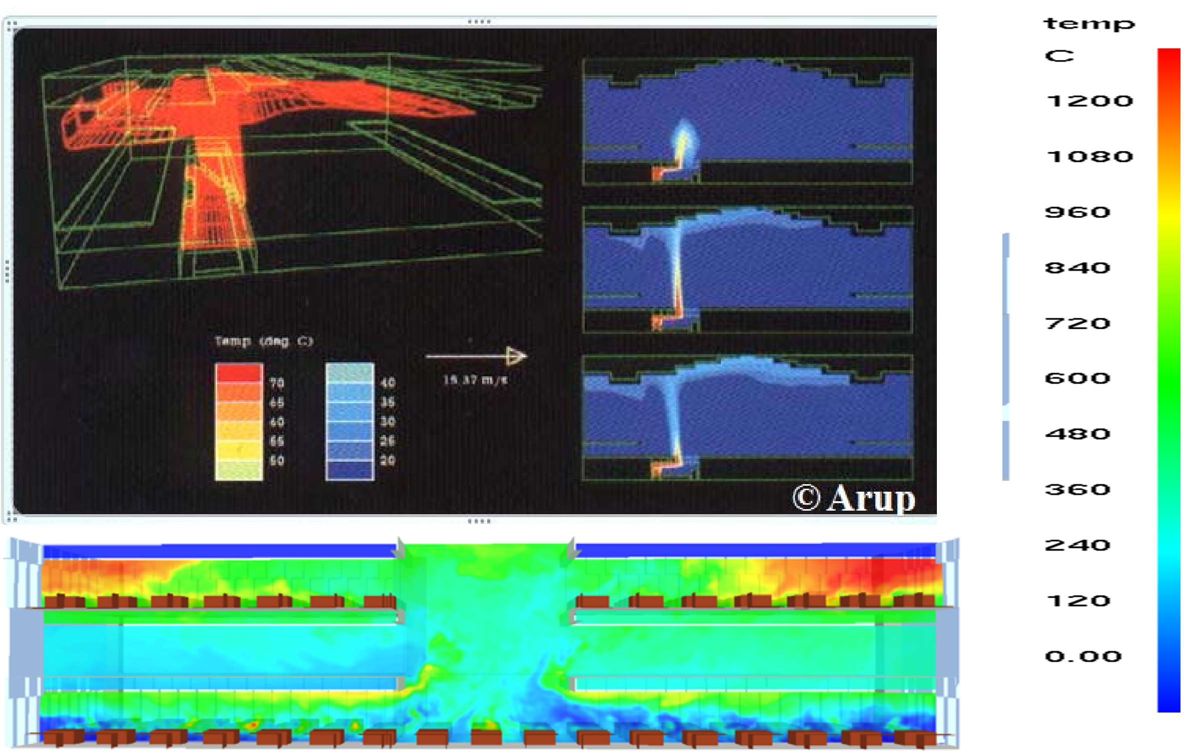


Figure 11.2 - complex fire scenarios (e.g. multistory fire) that may need consideration in tall building design.
Images courtesy ARUP

Consideration of Cooling Phase

The cooling phase of a fire can potentially be a critical period in the response and performance of a structure in fire conditions. During the heating phase of a fire, a structure undergoes thermal expansion, material degradation and material softening that can lead to a range of structural responses (*e.g.* local damage, elastic deformations, plastic deformations, large displacements *etc.*). As the structure cools, it begins to thermally contact and try to return to its original shape. If a joint, for example, has been allowed to freely rotate and expand during heating, it will freely rotate and contract during cooling. However, if a joint has buckled during the heating phase, then during the cooling phase when the structure tries to thermally contract and return to its original position, high tension forces could potentially be generated. In some cases, where a joint is not designed for these forces or sufficient ductility, joint failure can occur. This may be a critical issue in tall buildings where specific connections could be key to the design (*e.g.* nodes of mega braces).

The effects of the cooling phase on the performance of key connections should be considered (*e.g.* provide sufficient ductility or tensile force capacity) in the design.

CONSIDERATION OF SPALLING

At high temperatures, concrete structures can undergo varying degrees of spalling – the deterioration and breakdown of the concrete causing layers of material to separate from the structure. In fire conditions, spalling can be progressive (due to a gradual rise in temperatures) or explosive in nature where there is a sudden loss of large portions of the concrete surface.

This phenomenon can be caused by different mechanisms:[88]

- Increased pore pressure.
  - As a concrete element heats, the free water and physically bound water begins to evaporate. At the surface layers of the concrete structure, this water vapor is generally able to escape via the pore structure in the concrete matrix. However, in deeper layers, water pressure increases, inducing stresses perpendicular to the exposed surface. This pressure is maximum at a critical thickness and drops to zero at the external surface
- Increase in compression forces
  - As the concrete surface increases in temperature, thermal expansion forces that are restrained from moving began to induce restraint forces. This results in higher compression forces near the surface of the concrete element and tension forces further inside.

- Internal cracking due to difference in thermal expansion between aggregate and cement paste
- Cracking due to difference in thermal expansion/deformation between concrete and reinforcement bars;
- Strength loss due to chemical transitions of the concrete matrix during heating.

In general, spalling is rare and/or minimal in normal concrete strengths. However, for high strength concretes (HSC), spalling can be more of an issue. This is due to the dense, low porosity matrix of HSC mixes which limit the free movement of water vapor and steam as the concrete heats. This can lead to high pore pressures that result in explosive spalling and/or the loss of a significant portion of the concrete element.

Where high strength concretes are used, consideration should be given to mitigate the effects of spalling (*e.g.* use of fiber reinforcement, sacrificial concrete layers, thermal barriers, fire resisting concrete, *etc.*)

CONSIDERATION FOR ROBUSTNESS OF FIRE PROTECTION MATERIAL

In tall buildings, a higher level of resiliency and robustness may need to be considered in determining the type of fire resistance materials used to protect the structure. More robust fire protection materials may be warranted due to the increase in consequences of partial or global collapse of the structure, the increase in egress times for building occupants, and the increase in time for fire personnel to conduct fire fighting activities. For example, concrete is a more robust fire protection material with respect to durability, damage, maintenance etc, in comparison to, spray applied fire protection material, which can be more susceptible to physical damage, water damage, maintenance *etc.* The advantages of a more robust fire protection material will need to be weighed against other drivers in the design (*e.g.* weight, cost, aesthetics, sustainability, *etc.*), in order to identify an appropriate solution.

AVAILABLE METHODS TO DETERMINE APPROPRIATE LEVELS OF FIRE RESISTANCE

Once a design fire basis has been determined, an acceptable approach or method to demonstrating the fire resistance of the structure(s) that satisfies the agreed performance objectives should be agreed with the designer and all relevant stakeholders. Two general methods are available for assessing the fire resistance of a structure: standard fire testing or performance-based structural fire analysis.

Standard Fire Tests

The simplest approach to demonstrate fire resistance is to use the prescriptive rules found in building codes where standardized fire tests for varying fire resistance periods are used as the basis for design. The standard fire resistance test (e.g. ASTM E119,[69] ISO 824,[71] BS 476,[70] etc.)

subjects individual elements of structure (columns, beams, floors, walls, etc.) to a standard fire curve. That is, only individual elements of the building are tested and not building systems.

In general, the aim of the standard fire test is to demonstrate the element's ability to maintain stability, integrity, and temperature transmission for a specified duration under furnace conditions. The performance criteria established in the fire test standards are primarily aimed at satisfying objectives of the relevant building codes, and not specifically for additional performance objectives that may potentially be required by the owner. Catalogs of fire tested elements are available (such as the UL Fire Resistance Directory[89]), and it is possible to assemble a complete building from such components.

Due to the limitations of the standard fire tests and the unique aspects that often exist in very tall building designs (i.e. size of elements, unique structural systems/forms/materials), the designer and all relevant stakeholders should determine whether the standard fire tests are an acceptable method of determining the level of required fire resistance for the individual structural elements and the building as a whole to satisfy the agreed performance objectives. Specific consideration should be given to large and/or long span structural elements, new structural systems/forms, coupled gravity and lateral-load resisting systems, and performance objectives beyond those contemplated by the governing codes.

Performance-Based Structural Fire Analysis

Where the agreed performance objectives and/or the unique aspects of the building are outside the relevant application of standard fire tests, consideration should be given to adopting a performance-based structural fire analysis as the basis for the fire resistance design of the structure.

Structural fire engineering is a performance-based approach to design and analyze structural systems under realistic fire conditions and to use this understanding as the basis for the fire resistance design. This type of approach typically involves the evaluation of realistic fire scenarios in and around the building, calculation of the heat transfer from the design fire(s) to the structural elements, and quantification of the structure's response for the duration of the design fire(s). This is in contrast to the prescriptive requirements, where, the actual fire hazards and response of the structure to the fire is not quantified or explicitly understood.

Varying degrees of structural fire analysis are available to the designer that range from simple single element checks to sub-models to advanced finite element models. The design fire(s) basis and the level of analysis should be agreed with the designer, owner, local authority, insurer and any other relevant stakeholders. For very tall buildings, special consideration should be given to assessing the performance of the structure using an advanced finite element model.

- ***Single Element Analyses***
  The analysis of single structural elements in isolation from the rest of the structural frame has formed the basis for structural fire engineering for many years, mainly because it is comparable with standard fire tests and excludes calculations based on nonlinear

response of a whole frame or a subassembly to fire. This approach is a simple, first check of the capacity of a structural element at elevated temperatures.

This type of analysis typically involves an assessment of the load bearing capacity of an element at elevated temperature (considering thermal degradation of material properties) with the applied load at the fire limit state. Single element analyses, by nature, do not consider the effects of restraint on the performance of the structural element. Therefore, thermal expansion is not addressed. The benefits of alternative load carrying mechanisms (*e.g.* catenary action) are neglected.

Design tools for performing single element analyses can vary in complexity and can include empirical correlations, look-up tables, nomograms, hand calculations, or simple computer models. Various single element methods are available in several references such as the SFPE Handbook,[88, 90] ASCE/SFPE/SEI 29[91], Eurocodes,[79] BS 5950-8,[92] BS 8110,[93] AS 4100,[94] NZS 3404[95] *etc.*

- ***Advanced Analysis***
  Since the Cardington tests in the U.K.,[96] research and development worldwide has led to the improved understanding of structures in fire. This has led to the development and use of more advanced performance-based structural fire engineering techniques, as an alternative to the traditional prescriptive approaches and/or single element methods.

  Advanced analysis techniques can include varying degrees of complexity in assessing the design fire(s) and quantifying the performance of the structure in fire conditions. The types of analysis methods can include slab analysis, 2D frame analysis, sub-system analysis, element removal analysis, or whole building finite element analysis. See figures 11.3 and 11.4. Unlike single element methods, advanced analysis can consider the effects of thermal expansion, alternative load paths, secondary load carrying mechanisms, nonlinear material response, large displacement response, and connection performance.

  An advanced structural fire analysis may incorporate the following design aspects:

  - Identify performance criteria and objectives with all relevant stakeholders (see chapter 6).

  - Identify credible worst-case fire scenarios based on building use, geometry, combustible contents, worst-case ventilations conditions for structure, and presence of fire safety systems, *etc.*

  - Identify a representative portion(s) of the structure, as well as, key critical elements/systems and connections.

  - Assess the response of the structure(s) for the duration of the agreed design fire scenario(s) during both heating and cooling phases.

- Include thermal and mechanical properties with elevated temperatures (in particular thermal expansion and material degradation)
- Consider dead and live loads in the fire limit state
- Consider the effects of spalling for concrete structures (if present)
- Assess the structure for stability, fire separation and other performance criteria for the duration of the design fire scenario(s) to satisfy the performance objectives

Guidance of performing advanced structural fire analyses can be found in SFPE Handbook,[97] Eurocodes,[79] ASCE Manual No. 114.,[98] *Structural Design for Fire Safety,*[99] *etc.*

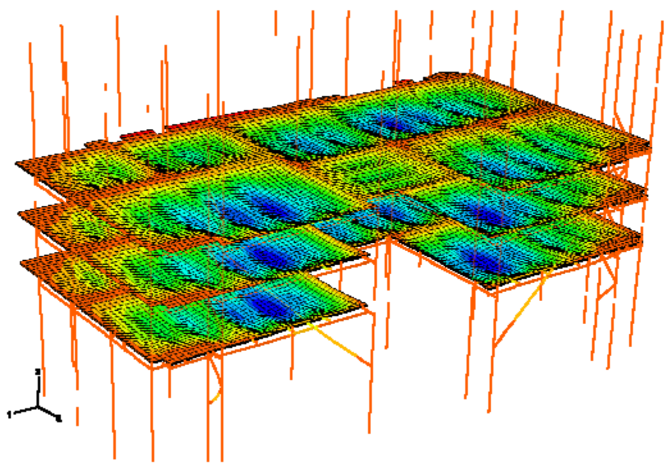


Figure 11.3 - Finite Element Model
Courtesy: Arup

Figure 11.4 - Builing Structure
Kohn Pederson Fox Associates, Inc.
Permission to use image pending

KEY METRICS FOR DEMONSTRATING FIRE RESISTANCE

As a minimum, the fire resistance of a structure should provide stability, integrity and compartmentation throughout the full duration of the agreed design fire scenario(s) such that life-safety objectives are satisfied. The metrics for demonstrating that life-safety objectives are satisfied should be discussed and agreed with all relevant stakeholders.

Sample performance metrics are provided below:

Stability

- The primary structural systems (columns, beams, connections, load-bearing walls, lateral load resisting system) should maintain the applied loads in the fire limit state for the full duration of the fire (including cooling).
- Metrics for stability may include:
  - Limitations on deflections
  - Strains are within reasonable limits for slab reinforcement and structural steel in fire conditions
  - Stresses are within the limit of the relevant material properties at elevated temperatures.
  - Connections forces are within reasonable rotation and ductility limits for fire conditions.

Integrity

- Limit the passage of smoke and flame from floor-to-floor separations, fire separations, fire rated escape routes (stairways, cores, elevator, etc).
- Metrics for integrity may include:
  - Limitations on deflections
  - Strains in slab/fire barriers/fire walls are within acceptable limits for fire conditions
  - Rotations in slab/fire barriers/fire walls near supports and cores are within acceptable limits for fire conditions

Compartmentation

- Fire separations (*e.g.* walls and floor systems) should limit temperature rise
- Thermal bridging is limited.
- Metrics for compartmentation may include:
  - Thermal transmission is limited
  - Strains in slab/fire barriers/fire walls is within acceptable limits for fire conditions
  - Rotations in slab/fire barriers/fire walls near supports and cores are within acceptable limits for fire conditions

IMPACT OF EXTENDED EGRESS ON FIRE RESISTANCE

Very tall high rises may rely on an inherent or dedicated defend in place strategy. See Chapter 10, Emergency Egress for more information. In very tall buildings, occupants may be expected to remain on upper floors for hours. Even if those occupants are directed to use the stairways, total evacuation time may exceed an hour. In some cases where areas of refuge are created as part of the egress system, the building occupants may be located on a floor immediately above or adjacent to the fire floor while awaiting rescue or evacuation assistance. Designers should coordinate the fire resistance of the structure as a whole and specifically for areas of refuge with the anticipated time frame necessary for egress or defend in place strategies.

The structural fire resistance and robustness of the egress path should be designed with a severe fire in mind. The vertical exit enclosures themselves may represent the greatest need for fire resistance in the building from an evacuation standpoint. The fire resistance designer should be able to describe the anticipated range of fires which expose the vertical egress elements, the floors and other compartment walls of areas of refuge. They should also be able to describe scenarios which are outside of the performance based design. As an example, it may not be appropriate to design every building for a terrorist attack. The design should be able to address the following important points:

- Is every floor required as an area of refuge or are certain floors (for instance, every 20th floor) hardened beyond the typical floor from a fire resistance rating standpoint?

- Does the fire resistance of floors and adjacent walls need to be increased for the areas of refuge compared to the floor below?

- Does the fire resistance rely on sprinklers in either the areas of refuge or the floor below?

- Can the structure provide adequate fire resistance without sprinklers?

- Is the material providing thermal installation of sufficient hardness for the anticipated hazards?

- Is the fire proofing prone to be removed for future tenant improvements or to degrade over time?

- Does the fire proofing material offer a significant resistance for non-fire related issues such as water proofing, mold or mildew resistance, rodent or insect resistance?

- Does the structural fire resistance system rely on components that will be changed over the life of the building under normal tenant improvement scenarios? If so, what safeguards are necessary so that future building designers and owners can maintain these systems?

POST-FIRE USE

After a severe fire, post-fire material testing should be conducted to assess structural worthiness. While this is true for most buildings, it is critically important for very tall buildings. A fire analysis may be required to determine the gas temperatures to which the structure was exposed. Consideration should be given to replacing structural elements that were located in severe temperature zones unless material testing deems otherwise.

COMMON DESIGN FEATURES

Individual Hazards

The fire resistance of a building as a whole can depend on the fire resistance surrounding individual hazards. If not properly considered in a performance based structural design, individual hazards could cause failure of a floor to floor separation, perhaps leading to potential structural effects distant from the fire or even progressive collapse.

Areas with high fuel loads should be identified and addressed by the structural fire resistance design approach. Examples include rooms containing diesel or other fuel storage, significant paper storage, rack storage, big box retail spaces and multi-level car stacking mechanical systems.

It may be necessary to provide a greater level of thermal insulation for these areas with high potential fuel load. Alternatively, these areas should be addressed individually within the structural fire model. Designers should be aware that even in a prescriptive based fire resistance design, the fuel load and fire hazard of some of these spaces may exceed that represented by the standard time temperature curves used in standardized testing. More information can be found in Chapter 5, Unique Features of Tall Buildings.

12 Facades

Non-bearing curtain walls are a common, cost effective method of creating an exterior enclosure and weather barrier for tall buildings. In recent decades, the desire for taller structures, and particularly, those that are competing for architectural recognition, are continually implementing creative, new and unique façade or curtain wall designs.

Many of these unique designs veer from the more traditional continuous vertical façade surfaces of the past, often using curved surfaces and rotated floor plates that complicate the facade connections and hidden details of fire barrier assemblies. Double curtain wall systems, with two glazed walls separated by short distances, are being implemented. These twisted façade designs, double skin designs and other new facade creations pose new challenges from a fire protection engineering perspective.

The risk of fire spread through articulated elements of the façade or vertically around the facade via the mechanism of flame leap, poses potential concerns for tall and very tall structures. To address these concerns, several factors that should be considered include the façade design, fire department response capabilities, reliability of sprinkler systems and associated water supplies, and the characteristics of the building and building's occupants.

As architects develop new and creative curtain wall designs, it becomes more critical to consider the risk factors that can impact the tall building's overall level of fire safety. This chapter outlines risk factors that may influence issues of curtain wall fire safety design and discusses what building systems and features can factor into an analysis to validate a curtain wall's design details.

There are two basic ways to structurally support a curtain wall or façade design. One approach is for the curtain wall to be supported directly on the structural floor slab edge, which precludes any gap or joint condition, given that the floor slab is continuous to or extends past the building envelope. This type of installation can result in floor-to-floor glazed curtain wall assemblies as shown in Figure 12.1.

This approach is sometimes observed in high-rise building design, but it is not the most common approach for the installation and support of curtain walls. The most common approach is applicable when the curtain wall assembly is positioned just outside the edge of the structural floor plate. This type of design requires the curtain wall assembly to be supported by structural elements that extend from the structural floor plate to the framing elements of the curtain wall assembly. With this type of curtain wall design, a void space commonly appears between the floor system and the curtain wall assembly as shown in Figure 12.2. In either design, the curtain wall may or may not have operable windows or ventilation openings.

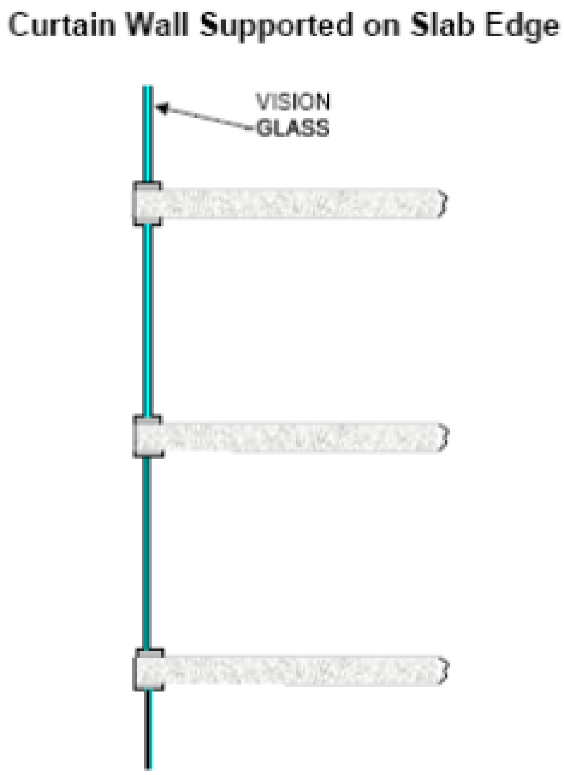


Figure 12.1. Curtain wall supported on slab edge. (Courtesy of Aon Fire Protection Engineering)

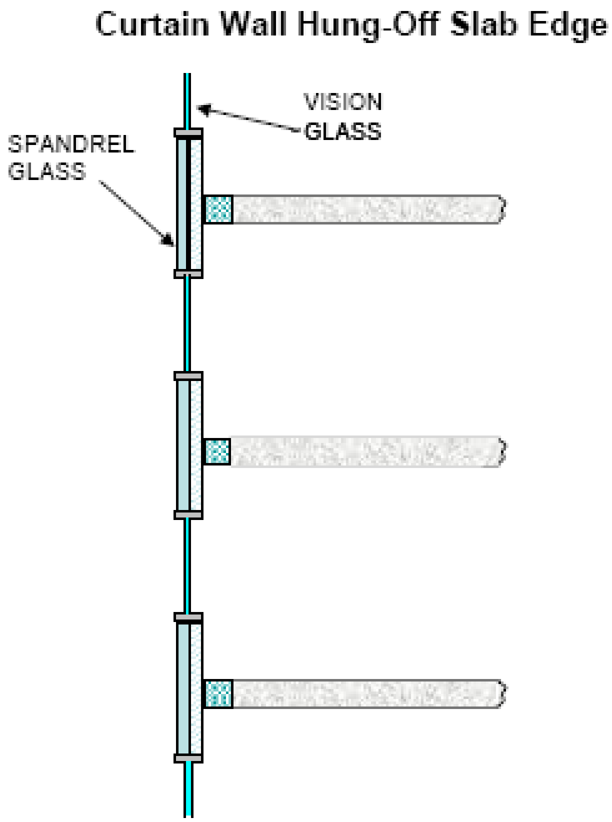


Figure 12.2. Curtain wall hung-off Slab edge. (Courtesy of Aon Fire Protection Engineering)

The void space at the slab edge introduces a risk of fire spread not encountered with curtain wall designs where the curtain wall is supported directly on the structural floor slab edge. Typically, such void space conditions (Figure 12.2) are sealed with a material or system to prevent the interior spread of fire from one to the floor above. This requires some form of a joint system or what today are called “perimeter fire barrier systems.” Such joint or perimeter fire barrier systems can be simple or complex constructions and a variety of materials. Both mechanical and thermal forces can influence the performance of these perimeter fire barrier systems and generally, specific tests or extrapolation of tests are needed to justify any given system's performance.

In recent years, the green building/sustainability movement has resulted in the development of new concepts in façade or curtain wall design that are intended to enhance the energy efficiency of building facades. Double-skin facades are a key development in this area that offers solutions to heating, cooling, sound control and lighting efficiency for high-rise buildings. The basic components of a double-skin façade systems involve the use of an outer glazed curtain wall, usually with ventilation openings; a cavity (usually ventilated) with dimensions of centimeters to meters in depth; and a second inner curtain wall with insulated glazed units.

There are wide variations possible for the design of these double skin facades. Design variables include the ventilation scheme (passive or active), use of louvers, motor operated openings or fans, shading devices, horizontal or vertical partitions within the cavity and operable windows on the inner skin of the double facade.

Depending on the local climate, the double façade concept may be used in different ways. For example, in winter climates, the air cavity can be isolated and the system is used as a triple glazed system with the air in the cavity acting as a transparent insulator. The temperature of the internal glazing is effectively raised, reducing heating costs and increasing human comfort at vicinities close to the glazing. In hot climates, air inlets and outlets may be opened to develop a stack effect (hot air rises) allowing hot air to be released at the top of the cavity and replaced by fresh air from the lower regions of the cavity. Within the air cavity, sun shades can be used to absorb and reflect solar heat energy which can promote an even higher temperature differential for the stack effect to take place within the cavity. As a result, cooling cost for inhabited areas are reduced and human comfort increased.

The double-skin façade concept poses conditions impacting fire spread that previously were not encountered with single skin or more common curtain wall designs. The cavity can act as shaft for fire and smoke spread, but depending on the cavity design and ventilation scheme ,the result may be either an increase or decrease in flame extension and risk of fire spread

The materials used to construct a curtain wall can be a important consideration in the relative risk that the façade poses to fire spread vertically on the building face. Facades are often constructed primarily of metal and glass materials, but it is also common to find facades that use architectural cladding systems comprised, in part, of combustible materials. Examples are aluminum faced sandwich panels with a polyethylene core or combustible Exterior Insulation and Finish Systems (EFIS), among numerous others.

MECHANISMS OF FIRE SPREAD

Ventilation-controlled fires represent the scenario where a fire burning in a building is not controlled by sprinklers and breaks the window glazing, permitting hot gases to flow out the top portion of the opening. A portion of the hot gases are unable to burn inside the room due to limited air (ventilation controlled) but, upon movement to the exterior, encounter sufficient air entrainment, allowing the hot fuel gases to burn outside the building.

The fire flame projection and temperature profile will be a factor of window area and height, room geometry, fuel contents and burning rate, and wind velocity. Building interior areas and curtain walls can be attacked by fire in three principal ways. Figure 12.3 illustrates the potential temperature and heat flux characteristics of a fully developed, compartment fire without the benefit of suppression from an automatic sprinkler system.

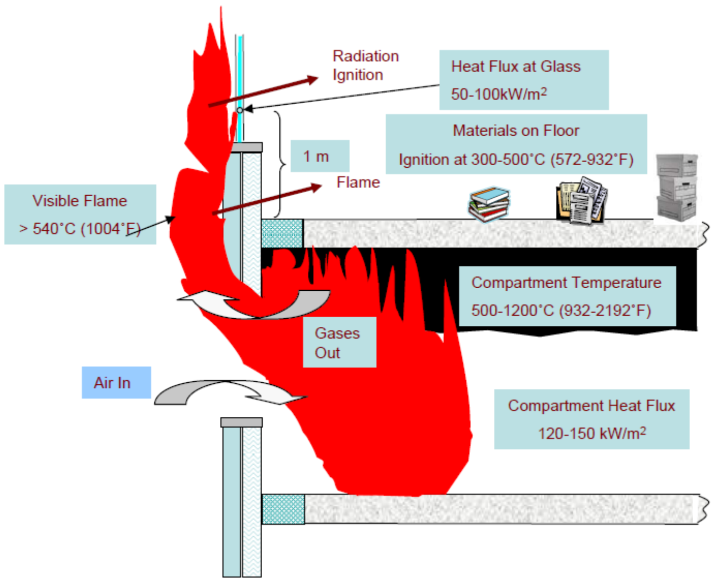


Figure 12.3. Exterior curtain wall and floor fire exposure mechanisms. (Courtesy of Aon Fire Protection Engineering)

The three principal mechanisms at work in Figure 12.3 are as follows:

- Inside – Flames and fire gases in the building attack the interior surfaces and details of the curtain wall and associated perimeter fire barrier materials.
- Outside – Flames and hot gases projecting from fire-broken glazing or other openings directly impinge on the curtain wall exterior face (convection). Flame impingement on the architectural cladding system may ignite combustible components of the cladding system if not appropriately isolated/protected.
- Outside – Flames projecting from fire-broken glazing or other openings radiate heat to and through glazed surfaces or through other openings to building contents and furnishings.

Exterior building detailing or articulations incorporated as elements of the facade or, which perhaps, are due to the structural floor plate changes, can impact the flame projection and associated corrective and radiation heat exposure to the façade. Work done at the National Research Council of Canada[100] showed the extent to which a horizontal projection located above flames issuing from a window can reduce the flame exposure. This work also showed that vertical exterior elements could have a negative impact by increasing the vertical projection of flames along a façade. Figure 12.4 illustrates the change in fire flame position and extension due to a horizontal projection above a window and vertical panels located at each side of a window.

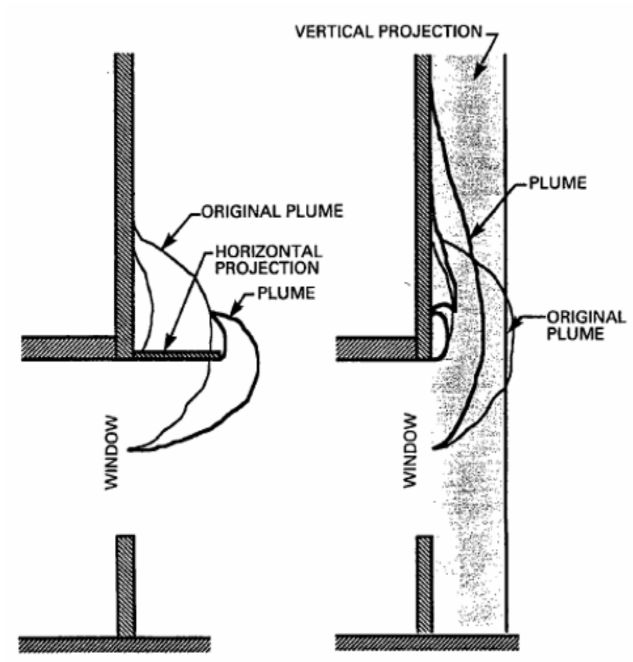


Figure 12.4. Impact of horizontal and vertical projections on window plume.[100]
Permission to use image pending

DESIGN FEATURES IMPACTING FIRE SPREAD

Curtain walls are a relatively complex combination of components that can include aluminum frames, vision glass, spandrel panels of glass, metal or stone, metal back pans, insulation, gaskets, sealants, and anchors or connectors of steel or aluminum. Given a fully developed fire exposure in a room or space (i.e. sprinkler system out of service or failure scenario) bordered by a building's curtain wall system, the vision glass may fail. Once the failure occurs and flames extend to the exterior, the various curtain wall components and any perimeter fire barrier system are then subject to thermal forces and degradation that can result in fire spread to the floor above.

Factors that impact the curtain wall's resistance to vertical fire spread include:

- Full height or partial height (*e.g.* spandrel panel design) vision glass systems
- Nature of the glass used to construct glazing system
- Nature of the curtain wall components (*e.g.* framing, spandrel panels)
- Height of spandrel panels
- Vertical or horizontal projections on the exterior that may deflect or enhance flame behavior
- Building geometry at curtain wall – twisted, staggered, sloped, *etc.*
- Operable windows/openings – size, vertical or horizontal orientation

- Ability of perimeter fire barrier system to remain in place during fire exposure
- Design characteristics of double-skinned facades
- Wind conditions

When full height vision glass systems are used, flame extension and heat fluxes to the window areas above can be greater than that for curtain walls using a spandrel panel design. A spandrel panel design can limit the flame extension and reduce heat flux to the areas above by providing an opaque surface to block the heat transfer. Glass used in curtain wall assemblies may be one of several types – float glass which may be heat strengthened or tempered glass, laminated or wired glass. Vision glass can be single, double or triple glazed, and are typically assembled into an insulating glass unit (IGU). Vision glass may also be tinted to provide a heat absorbing quality, or coated to provide a heat reflective capability. All of these features can impact the performance of glass under fire exposure,[101] however, very little is currently known about the fire performance of the wide variety of IGUs that are possible.

Building geometry and exterior projections of the curtain wall or building structural elements can have a beneficial or negative effect on flame length extension and heat flux exposure to curtain wall elements above the fire compartment. This can be particularly important if operable windows or ventilation openings are used. Of course, any such opening can allow the unrestricted passage of flames and hot gases from a fire on a floor below into the floor above. The position of the window or ventilation opening relative to the expected flame extension is important in assessment of the fire spread risk.

Many articulated curtain wall designs veer from the more traditional continuous vertical façade surfaces of the past, often using curved surfaces and rotated floor plates that complicate the façade connections and hidden details of fire barrier assemblies. Such new designs can result in an orientation that allows for either more direct flame exposure or diminishes the threat of direct flame contact. Regardless of the facade orientation, wind conditions may reduce or exacerbate the flame and temperature exposure.

Double-skinned façade or curtain wall systems, where two glazed walls are separated by distances of less than a meter are being implemented. The risk of fire spread through such double-skinned façades introduces concerns arising from the fact that should flame break through the inner façade, it would then be confined within a long tall shaft-like space. The dynamics of the flame and radiant heat exposure for this case is potentially more severe than a flame freely flowing to the open atmosphere. Other types of double-skinned façades may reduce the risk of fire spread, particularly those using a partitioning scheme within the cavity of the double-skinned façade.

RISK ASSESSMENT FACTORS

Several factors to consider in a risk assessment of fire spread at the building façade include, but may not be limited to, the following:

- Automatic Sprinkler Systems' reliability

- Fire Department/Brigade response capabilities
- Building height
- Building occupancy considerations – *e.g.*, office, residential, hospitals, mercantile
- Building compartmentation features
- Building evacuation strategies
- Fire hazard – fuel loads, continuity of combustibles, compartment sizes
- Security threat assessment scenarios

Sprinklered high-rise buildings have a very successful record of life safety and property protection performance. For this reason, U.S building codes, do not require fire resistance rated spandrels or flame deflectors at the building façade in fully sprinklered buildings.

The relative fire hazard of various occupancies can present varying levels of concern in assessment of vertical fire spread risk. Residential occupancies are generally well compartmented units. In the event of a sprinkler failure and fire spread to a residential unit on the floor above, it should be recognized that the fire would not propagate readily due to the fire-resistive enclosure walls of apartment units. This generally assumes vertical stacking of units. Conversely, in a retail or office occupancy, there is far less subdivision to provide passive fire containment, increasing the risk of fire spread.

13 Suppression

INTRODUCTION

Controlling the growth and spread of a fire in a very tall building is of paramount importance, and there are several systems needed to contribute to this goal. Compartmentation and fire resistive construction are key elements in the ability of a very tall building to limit the impact of a fire, but they can only limit the growth and spread to the amount of fuel contained within the boundary of the fire barriers forming the compartment. Controlling the fuel load within fire compartments is nearly an unmanageable task.

As observed in numerous fire events, one of the most infamous being the One Meridian Plaza fire in Philadelphia, PA (see Chapter 2), fire sprinkler systems are critical in the ability of a very tall building to limit the growth and spread of a fire in a very tall building. Sprinkler design codes and standards used throughout the world provide the designer with guidance in the basics of designing and installing sprinklers within buildings. However, they don’t focus on some of the challenges associated with designing and installing sprinklers, and related systems, in very tall buildings.

RISK ASSESSMENT

The designer will need to consider the risks imposed by the individual project and how those risks may impact the design of the building sprinklers. For example, if the project is being built in a geographical area where the water supply is not reliable, then provisions will likely need to be made in the project to provide a sufficient duration of fire protection water to supply building sprinkler operations for a period of time sufficient to support a fire department operation, permit complete building evacuation, or all of the above.

Today, for most very tall buildings, sprinkler systems are designed based on evaluating the occupancy classification of the intended use of the building and using a prescribed design density that is commensurate with the occupancy classification to determine the overall amount of water needed to suppress a fire in this anticipated occupancy. This is an abridged approach to assessing the fire hazard and designing the suppression systems to control or suppress the potential fires associated with such hazards. The sprinkler designer will need to consider the results of the risk analysis performed early in the life of the project design (see Chapter 6) to identify design parameters that need to be incorporated into the overall project.

FIRE STRATEGY

While normally associated with buildings having high fire challenge contents (which is not typical in common office or residential occupancies), one key strategy to be resolved is whether the sprinklers will be designed for control or suppression of fires. The sprinkler systems for a typical office or residential occupancy are generally intended to only control the fire, anticipating the fire department to be summoned to complete the task. In geographical areas where a robust fire department may be available, the sprinkler system may need to only be designed for control mode operation in anticipation that the fire department will arrive to perform final fire suppression activities.

In this case, the fire sprinklers serve two primary purposes, that of detecting and notifying of the presence of the fire and that of controlling its growth and spread until fire department assistance arrives. On the other hand, if the fire department in the location of the project is expected to be challenged in fighting a fire in such a unique structure, then the designer may consider designing the sprinkler systems for a suppression mode of operation. The key difference between the two modes of operation is the ability of the system to discharge sufficient quantities of water early enough in a fire to actually suppress the incipient fire rather than to merely control it.

Other strategies for controlling fire growth may be developed to address the unique nature of a project, and those strategies likely involve other systems as described in other chapters of this Guide. Coordinating those strategies with the design and arrangement of sprinklers and standpipes may be necessary.

RELIABILITY

Fire sprinklers are known to be remarkably reliable. The five leading reasons for failure of sprinklers in the United States[102] include the following:

- System shut off prior to fire ignition
- Manual intervention that defeated the system
- Discharged water did not reach ignited combustible materials
- Insufficient water discharged to protect the hazard
- Lack of maintenance

Four of these five top reasons were among the top five in a similar 1970 study, indicating the issues have not generally changed in 40 years.

Given the importance of sprinklers in providing protection within very tall buildings, the sprinkler system designer should consider redundancies and system enhancements to directly countermand these reasons for sprinkler system failure. Implementing one or more of these enhancements will increase the reliability of the sprinkler systems. Features to consider to enhance the system reliability may include:

- Multiple points of supply for floor sprinkler systems;
- Alternating floor supplies from different risers;
- Electronic supervision of floor control valves;
- Rigorous, frequent maintenance and inspection programs;
- Gravity source of water supply for sprinklers;
- Cross connecting standpipe/sprinkler risers at multiple points vertically with control valves arranged to permit shut down of one riser without shutting down the other;
- Re-evaluating appropriateness of sprinkler system design and arrangement upon tenant changes.

Using any one, or a combination, of these enhancements will improve the operating reliability of the sprinklers. The designer will need to consult the Fire Strategy to determine the level of improvement is needed for a given project.

SYSTEM DOCUMENTATION

The strategy employed in designing fire protection systems for a given project is unique. Therefore, the design approach to be used in designing the sprinklers for the project needs to be documented so the building owner and future architects and engineers who may be designing modifications and alterations are aware of key sprinkler systems design concepts. The Fire Strategy, as described in Chapter 6, is one potential medium that can be used to document all the decisions going into the design of fire protection water supply, sprinkler and standpipe systems.

KEY ISSUES

Most of the issues surrounding suppression systems in very tall buildings have to do with the water supply, the pressure problems that result from elevating the water to extreme heights and the building's reliance on the need for fire pumps to elevate the water within the building.

WATER SUPPLY

Availability of the municipal water supply will dictate overall on-site storage needs. Some very tall buildings are planned for what will eventually become a city. However, there may be no public utility infrastructure in place. Very tall buildings cannot wait for a water supply of adequate duration to arrive with the rest of the city and therefore appropriate on-site storage needs to be considered.

Primary water supplies may need to consider sprinkler in addition to standpipe demands. In most buildings, the water supply system is generally designed for the larger of either the sprinkler or the standpipe demand. This is predicated on the understanding that the fire department will respond in emergency situations and are able to supplement the water supply for the two systems. However, because fire department apparatus will generally not be capable of reaching the top, fire protection systems in very tall buildings need to be designed to be essentially self-sufficient.

In a very tall building, the designer should consider providing a system capable of meeting the combined demands of sprinklers and standpipes. Discussions with the responding fire departments will provide better understandings of their anticipated tactics for deploying hose streams, which will help the designer to identify necessary flow rates and pressures needed. This will drive the determination of the standpipe system demands.

Reliability of the water supply will also be a key consideration for very tall buildings. Since the fire suppression and standpipe systems will depend upon pumps for moving water up to the top of the building, back-up pumps, gravity based storage supplies, or both may be considered in order to enhance the reliability of the water supply system. Figure 13.1 depicts one approach for providing a gravity based water storage system for building sprinklers:

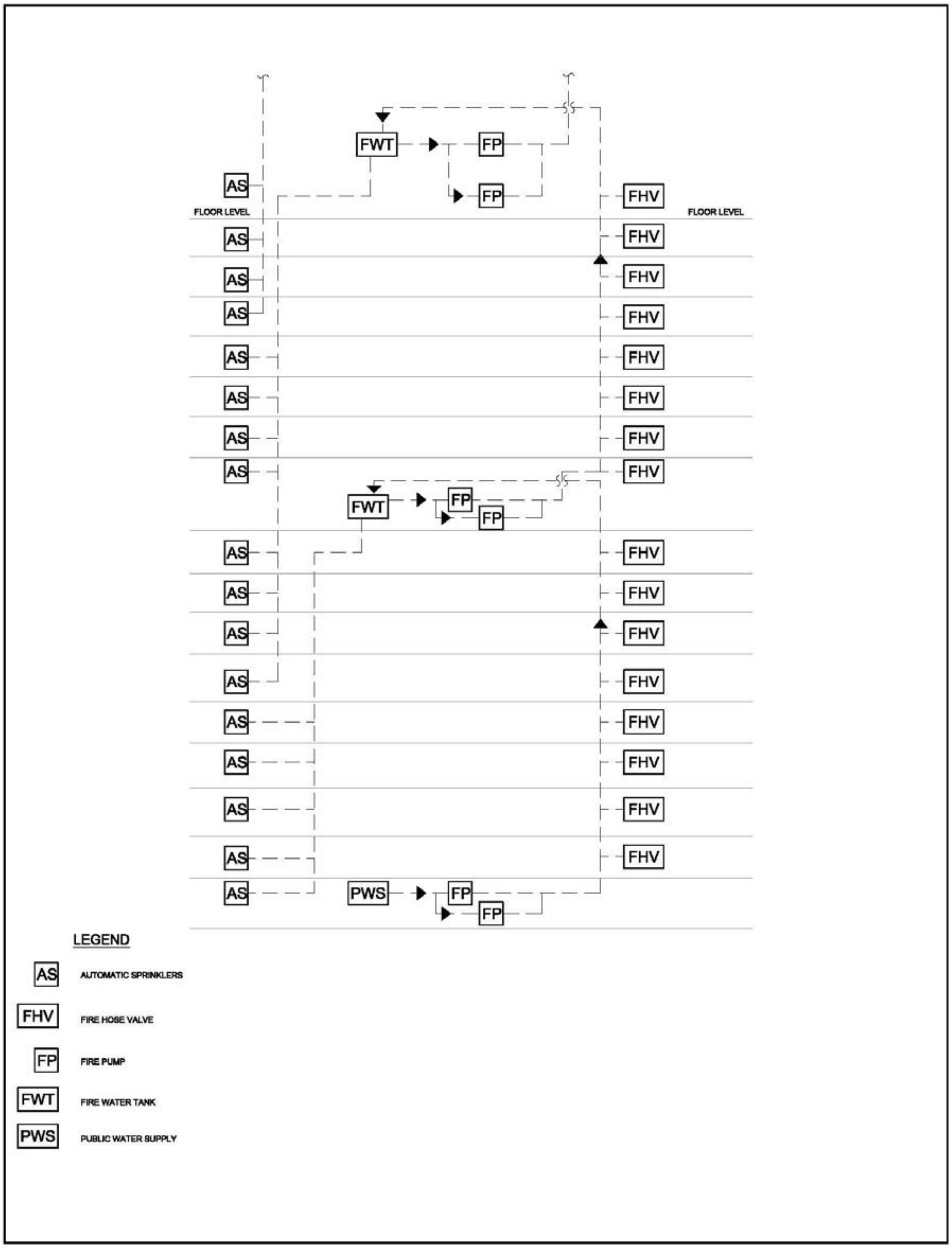


FIGURE 13.1 - Gravity based water storage system for sprinklers

Durations to be used to determine water storage capacities will vary depending upon the Fire Strategy and will need to be discussed and agreed upon with the local fire department. One approach is to provide a water supply sufficient to maintain sprinkler water flow for a duration equivalent to a full building evacuation. This approach could result in a need to storage large quantities of water, which will impact structural design and architectural planning. This concept needs to be resolved and agreed upon early in the design of the building since finding locations within the building for water storage tanks late in design will be troublesome.

Normally, in seismically active areas of the world, a secondary water supply within the building is required by local codes in anticipation of a potential disruption to the municipal water supply to the fire protection systems. If the water supplies of the building are generally self sufficient (i.e. not reliant upon a constant connection to a municipal water supply), there is little need to consider additional storage in case of severe seismic events since the planned water supply likely meets or exceeds those requirements. Nevertheless, it is important to keep seismic design considerations in mind with the development of the water supply system design.

PRESSURE CONTROL

Sprinkler and standpipe system components are typically limited to maximum working pressures of approximately 1,200 kPa. Components with higher working pressures are available, but are non-standard. Combined with city water pressures and booster pump pressures, system components in very tall buildings can be readily exposed to pressures exceeding their maximum typical working pressures. Designers need to consider this issue as they develop their designs of the standpipe/sprinkler riser systems. Establishing the heights associated with vertical zoning is a critical consideration directly related to controlling pressures within the zone.

There are several means to conceptually design the pressure zones in a sprinkler and standpipe piping system. Vertical zones of piping can be designed so that the entire zone of piping maintains pressures less than the 1,200 kPa working pressure. However, this approach is not very efficient relative to pipe zoning. Another alternative is to permit the risers to maintain higher pressures than the normal 1,200 kPa maximum working pressure, but then design the floor sprinkler piping and equipment to realize the normal maximum working pressures of 1,200 kPa. In this case, equipment is needed to modify or reduce the pressure so that the floor piping and equipment realizes maximum working pressures not exceeding their designed maximums. The final approach is to design all system components for the maximum anticipated system working pressures, making sure to not exceed the maximum working pressure of the designed equipment.

Using devices designed to modify (or reduce) pressures on parts of the system is common in very tall buildings. These devices generally fall into two categories, ones that operate in both static and dynamic (or flow) modes and those that operate only in dynamic mode. Those that operate only in dynamic mode, such as flow restricting orifices or pressure restricting valves, will permit a static pressure that may exceed the maximum working pressures of typical system components. Pressure regulating (or reducing) valves (PRVs) are often used because they can regulate pressures in both a static and dynamic mode.

PRVs function based on the use of a heavy duty spring. Being a mechanical device, they require periodic maintenance and testing to be sure they continue to operate as intended. Without proper maintenance and testing, they have been known to be prone to failure.

Another means to control pressures within sprinkler and standpipe systems is based upon the use of variable speed driven fire pumps. Normally, fire pumps run at a relatively constant, rated speed, at which point, they deliver a given flow rate at a given pressure. In a variable speed driven pump, the speed of the pump motor is varied based upon the demands of the system. Such systems use controllers and pump motors specially designed for variable speed arrangements.

FIRE PUMPS

Pumps and other piping system components have practical limits on their maximum working pressures of approximately 4,150 kPa. For the very tall building, fire pumps will inevitably need to be located on several floors periodically as the tower rises to be able to keep moving water up the building. Precisely which floors will be based on the overall building design.

Reliability of pump power supply will also dictate the need for back-up power supplies. It is important to maintain a reasonable separation from the main power supply and that proper protection for pump emergency power supplies is provided. The intent is to reduce the potential that a single reasonably anticipated event is unlikely to disable both of the power supply pathways.

Back-up pumps may need to be provided for each pump used in the system to get the water to the top of the building. The rationale is that if any one pump in the system design were to fail, most of the building above the failed pump will be left without water, especially where local fire department apparatus is incapable of pushing water up to the highest parts of the building. To enhance the reliability of the water supply system, the back-up pump is typically located in a separate room enclosure from that of the primary pump. Both pumps and their respective controllers and power transfer switches should be located within rooms whose walls are designed to be fire rated assemblies.

FACILITIES FOR TESTING

Adequate facilities to be able to test and maintain the equipment used in pressurizing or controlling sprinkler and standpipe systempressures need to be provided as a part of the entire building system. Every fire pump and pressure control device used in the building needs to be able to be operated at capacity on a periodic basis to maximize the potential it will work when needed. This means that water needs to flow, which means appropriate systems and facilities need to be put in place to accommodate the necessary testing and maintenance. One Meridian Plaza, an infamous fire described in Chapter 2 of this Guide, is a primary example of the failures that may occur when mechanical systems are not periodically operated as designed.

Buildings that use PRVs as a regular part of the design for controlling pressures in the floor systems or fire hose valves must provide a drain riser that is sized to accommodate a full flow through the PRV to permit proper maintenance and testing. Demands for floor sprinklers and hose streams will vary from one location to another, but it is highly likely that the drain riser will need to be at least 100 mm. Likewise, provisions need to be made for handling the draining water. Discharging the drain into a tank sized to accommodate 30 minutes of water flow will likely not be adequate for testing hundreds of PRVs.

Designing drain systems for the full flow of fire pumps likewise requires careful consideration. Running fire pumps in churn once a week for 15 minutes may not sufficiently test the pump. Fire pumps need to be operated at full flow to properly evaluate whether they are operating as intended.

Water conservation should be a consideration in the development of designs of drain systems. Being able to recycle fire protection water is critical in many areas of the world. Creating the piping and storage tank arrangements necessary for water conservation will need careful consideration.

14 Detection and Alarm

GENERAL

Fire detection and alarm systems are intended to provide notification of fire events within the buildings in which the systems are installed. They provide early warning notification to building occupants and notification of fire events for both on- and off-site emergency response personnel. They also provide control of fire safety functions for fans and dampers to reduce smoke spread , recall and shutdown elevators and control fire doors.

Fire detection is provided through initiating devices such as heat detectors, smoke detectors, flame detectors and other fire-related detection devices. Fire alarm systems also monitor extinguishing systems such as automatic sprinklers, gaseous agents and other extinguishing agents. Recognition of a fire event can also be provided by building occupants via manual fire alarm stations. All of these input devices provide an indication that a fire event may be present within a facility. These input functions also serve to initiate specific output functions. See figure 14.1.

Output functions include occupant notification, emergency response notification, fire safety functions and annunciation of input device type and location. Occupant notification can occur throughout the building or within selected zones as required for building evacuation concepts. Emergency response notification can be transmitted directly to the Fire Department, but typically occurs through a third party or by onsite personnel responsible for monitoring the fire detection and alarm system.

Fire/smoke damper and fire door closure is often used to compartmentalize buildings areas to limit the spread of smoke and fire. Fire safety functions also include elevator recall for fire safety service use and building occupant safety, along with shutdown in the event of a hoistway or machine room fire.

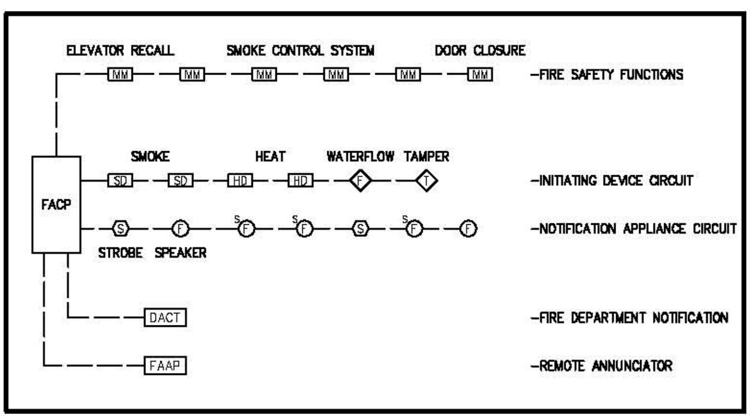


Figure 14.1 Typical Fire Alarm System Configuration (Courtesy JBA Consulting Engineers)

There are many brands and models of fire detection and alarm systems available. For very tall buildings, addressable systems using networked panels are a common practice. Addressable systems allow for a variety of initiating devices to be placed on a common circuit and allow for individual annunciation of the device. This reduces the number of circuits needed relative to a conventional zoned system. Initiating devices can be combined on one circuit on an addressable system while still providing discrete information on the device type and location. This aids response time in that the exact alarming device location is displayed at the panel rather than having to survey the incident area. For very tall buildings, this can reduce response time.

Networked systems use multiple panels to distribute circuits and power supplies throughout the building while still allowing for common control and annunciation areas. They can also be configured to allow for control of specific areas if part of the network is disconnected or malfunctions. For very tall buildings, this can be beneficial since panels can provide localized controls if connection to the overall system is lost due to a fire or other event.

RELIABILITY/ROBUSTNESS

Because the primary function of a fire detection and alarm system is to provide early warning of fire events, its role in a very tall building is crucial. System reliability is important to the building fire strategy. Because many tall building evacuation strategies incorporate partial evacuation, the ability to communicate to building occupants is important. The fire detection and alarm system must remain operational during events in order to facilitate this communication.

In the design of fire detection and alarm systems for tall buildings, the designer should take into account the potential for loss of service to certain building areas. How that impacts the overall fire strategy will dictate the amount of redundancy or robustness to be included in the system design. Items to consider are:

- The number of floors being served by an individual panel.
- Whether a networked or master/slave system should be used.
- A reconfigurable network design versus a standalone degraded mode.
- Quantity of primary control panels and their locations.

For very tall buildings, panels are typically distributed throughout the building with a certain number of floors served by each panel. That number varies depending upon design criteria and system limitations. Most systems can easily serve five to seven floors, but even three floors pose a challenge for certain panels. An odd number of floors is generally used ,since that allows the floor the panel is located on to be served by the panel, while allowing for a certain number of floors directly above and below the panel.

By limiting the number of floors served by a panel, should that panel be damaged, only those floors served by the panel will be impacted. Consideration should be given to limiting the floors served by an individual panel based upon building height. If the building is very tall, it might be beneficial to reduce the number of floors to no more than three per panel. While this will increase the cost of the system, it will also increase the overall system reliability.

Most multiple panel systems are wired with redundant circuitry to increase system reliability. Redundant circuitry will allow the system to operate should there be a fault on a circuit, such as an open, short or ground.

Consideration should also be given to system configuration. Networked systems allow for each panel to be standalone and serve as a local control panel while sending required signals to other networked panels. Should the network be impacted, a typical system will allow for only that portion of the compromised system to be affected, keeping the remainder of the network operational. This can allow for those areas to be covered by a system capable of basic operation, even though the overall system is not operable. See figure 14.2.

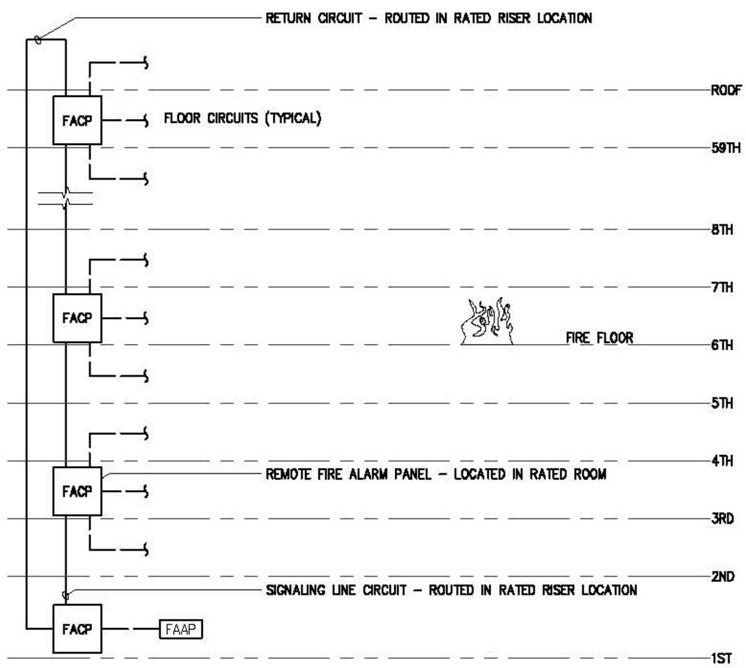


Figure 14.2 - Distributed Fire Alarm Panels with Redundant Signaling Line Circuit (Courtesy JBA Consulting Engineers)

Some systems are designed using a master control panel that is connected to slave panels in the field. These systems rely on the main control panel to perform all output functions while the local panels are used to provide local circuits and power supplies. These systems do not allow for the local panels to continue operating should communication to the master panel be lost. For very tall buildings, this approach may not be consistent with the overall fire strategy developed.

Most networked systems will reconfigure under fault conditions. Depending upon the fault, they may automatically reconfigure to continue operating. This fault can vary from a partial loss of network signal to a complete loss of signal between panels.

When a complete loss of signal occurs, most systems can reconfigure to allow communication between the panels that are still interconnected. This can be useful for very tall buildings since portions of the building will not be completely lost if a break occurs in the network circuit. In addition, most systems are capable of defaulting to a degraded mode that sounds evacuation signals to the floors served by the panel if all communication is lost to the remainder of the system. This would allow for at least an evacuation of the floors covered by the panel should an event occur within the building with loss of communication.

Often very tall buildings can have large footprints and/or multiple towers. Most building and fire codes require some type of fire command center for first responder personnel to access the building life safety systems.

When a building encompasses a large footprint, it should be determined in the fire strategy and system design whether multiple command center locations should be incorporated. This would provide additional levels of redundancy should the primary command center be blocked or impacted by an event. If this condition occurs, responders and on-site personnel can assemble at an alternate location to monitor and control the life safety systems.

SURVIVABILITY

For very tall buildings a large portion of the fire alarm and emergency evacuation system will likely be in non-fire areas. Therefore, it is important to consider system operability during fire and emergency events. For very tall buildings, it is important to have a system operate in non-fire areas even though a fire may impact a portion of the system. Designs can include measures to improve the survivability of the fire alarm system panels and circuits within the building. Some of the design considerations include:

- Protection of panels from fire.
- Protection of fire alarm circuits from fire.
- Configuration of fire alarm circuits.
- Shielding of panels.

Consideration should be given so that an attack by a fire within an evacuation zone does not impair the evacuation system operation outside the zone. This will allow system operation and communication to occupants even though a fire may impair other portions of the system.

Some of the design considerations to improve the system to survive a fire event may include panel and circuit protection. It might be desired to locate remote network panels in fire-resistance rated rooms so that a fire event on a floor that contains a remote panel does not impact on the system elsewhere. It may be practical to consider locating the panels in rooms having a fire-resistance rating similar to that of the floor assembly. This would provide the same level of protection afforded by the floor assembly to the fire alarm control panel.

Circuit protection, especially for vertical circuits (risers), should also be considered. Since remote panels in very tall buildings will be located on various floors, the circuits that interconnect these panels will run vertically within the building. As with the protection of panels, consideration should be given to the riser protection. This can easily be accomplished by routing them in the same rated enclosures as with the panels and by rating rooms or enclosures that contain just the riser circuits. This will provide protection of the circuits that connect remote panels, as well as devices and appliances on floors, from a fire event.

Selection of circuit styles for fire alarm systems should be evaluated for very tall buildings. Fire alarm circuits are categorized in classes which provide requirements for operation under certain fault conditions. Basic circuit configurations include those that operate up to the fault condition, such as an open circuit, whereas enhanced circuits operate under single fault conditions. In very tall buildings, consideration should be given to enhanced circuit design for risers and laterals.

Enhanced circuit design will allow portions of the system to continue to operate even though other portions may be impaired. By using enhanced circuit design the system survivability is increased. Many of the systems allow enhanced circuits to be routed in the same raceways, which allows for increased reliability without significantly impacting overall costs.

Risers interconnecting panels should be designed to incorporate enhanced levels of protection, whereas horizontal circuits to initiating devices and notification appliances could be either basic or enhanced depending upon the implemented fire strategy concepts. Enhanced circuit methodology involves the interweaving of basic circuits such that alternating devices are on a separate circuit. This can be done for notification appliances so that if one circuit is impacted, some coverage is still provided by the alternate circuit. See figure 14.3.

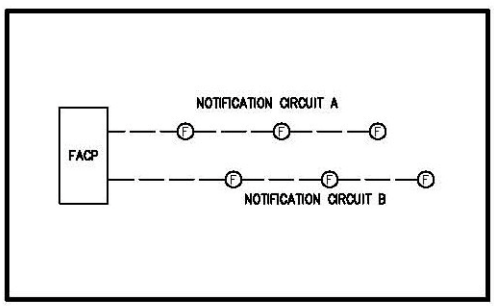


Figure 14.3 - Alternating Notification Circuits (Courtesy JBA Consulting Engineers)

Another consideration for protection of fire alarm equipment is to protect the panels located within the room. Shielding of the panels can be done to prevent water damage, as well as locating conduit entries only in the sides and bottom of the panel enclosure and not on the top. This will reduce the potential impact to the electronic equipment inside the panel from water that may seep into the enclosure from penetrations on the top.

NUISANCE ALARMS

The primary benefit of a fire alarm and detection system is to provide early warning of a fire event. This allows for evacuation to occur before conditions escalate while summoning emergency response personnel to the building within an appropriate timeframe. When alarm systems experience nuisance alarms, building occupants can start to ignore evacuation signals thinking that it is just another false alarm. For a very tall building, nuisance alarms can have a detrimental impact to the fire strategy and evacuation schemes.

Maintenance of devices is critical to limit and/or avoid nuisance alarms. A regular maintenance and inspection program that includes the cleaning and/or replacement of detectors should be implemented, especially in very tall buildings. This will limit the number of alarms within a building while improving system integrity. Because a very tall building often relies on defend-in-place or partial evacuation strategies, occupants cannot afford to ignore alarm signals thinking they are false alarms.

VOICE COMMUNICATION

Very tall buildings employ voice communication systems to alert building occupants of fire or other emergency events. They can provide evacuation signals through tones, pre-recorded messages, and/or live voice messages from monitoring and response personnel. With partial evacuation systems, they are helpful in providing evacuation messages to the fire areas and instructions to other areas about the fire event.

One of the drawbacks of pre-recorded and live voice messages is the language to be used. Many tall buildings are developed in multi-cultural populations where there is not just one language spoken. Consideration should be given to the use of multiple language pre-recorded messages that account for the primary languages spoken in the region.

While it is difficult to address all languages, the primary ones should be used. This can be done by having pre-recorded messages sequence through the various languages repeating the same message.

This also applies to those who may be providing live messages. They should be trained in multiple languages, or else adequate staff should be on hand to address to address the multiple languages required for voice evacuation. This should be considered when developing the overall fire strategy.

Voice communication systems are often integrated into the fire detection and alarm systems, sharing the control panels used for the detection system. For very tall buildings, amplifiers are distributed in the building inside of remote panels. Audio circuits are driven from these amplifiers to the building speakers.

Pre-recorded and live messages typically come from the primary monitoring and control locations. These signals are routed through the audio circuits that interconnect the remote panels. When an alarm is received, one of the output functions is to turn on fire area speaker circuits. This allows for the tones, pre-recorded and live messages to be routed to the speakers.

The audio circuits interconnecting panels can be either single or multiple channels. A single channel system will allow all messages or tones to be routed to active circuits . Essentially, only one message or signal can be broadcast on the system at a time. Multi-channel systems allow for different messages to be sent to different areas as part of the overall building fire strategy.

Because of the size of very tall buildings, it is often desired to send evacuation messages to the fire area while also sending informational messages to areas adjacent to the fire area. This could serve to alert occupants that a fire may exist in the building, that occupants from the fire floor will be relocating to their area, and to be prepared to receive these people. However, this may cause individuals on the non-fire floors to evacuate so care must be given to message content.

Pre-recorded or live messages can be sent to multiple areas of the building depending on how many channels the system has. Multiple channel design in very tall buildings can be beneficial for defend in place or partial evacuation strategies. See figure 14.4.

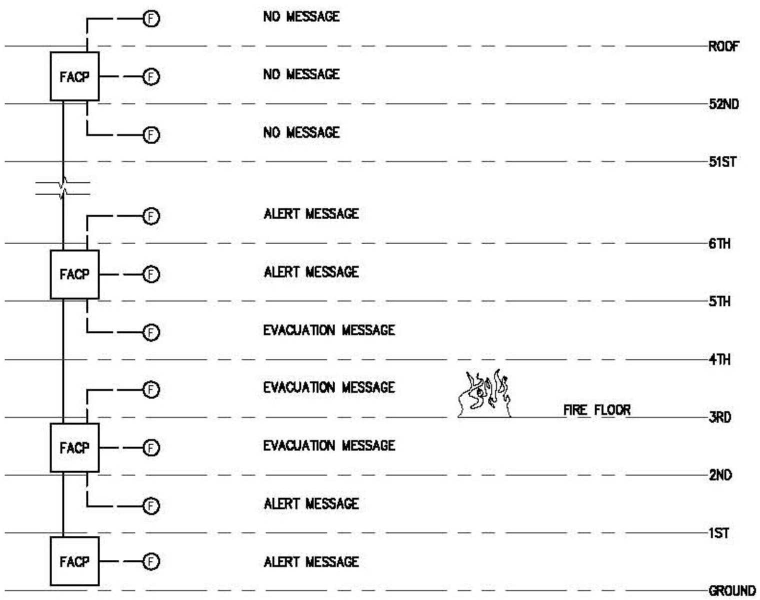


Figure 14.4 - Partial Evacuation Concept (Courtesy JBA Consulting Engineers)

VISUAL NOTIFICATION

In certain portions of the world, fire event audible annunciation is accompanied by visual notification from devices such as strobes. These provide event notification through flashing lights - often imprinted with the word “FIRE”. They are used to inform the hearing impaired of an event so they can take necessary action. Unfortunately, they do not provide specific information on events as with live audible messages.

For fire alarm systems, strobes are used primarily to alert occupants of fire conditions. While the devices cannot provide specific instructions, they are useful in alerting occupants of an event so they can seek assistance from other occupants who are not hearing impaired.

In addition to strobes, textual visible appliances can be used in fire alarm systems. These appliances can be connected to the fire alarm system to provide specific generic instructions to building occupants, similar to pre-recorded messages. They can be beneficial in very tall buildings where additional information is needed for those who may be hearing impaired.

Textual displays are also common in mass notification systems. Mass notification systems are used to alert building occupants of any event, not just a fire alarm. Strobes and textual displays can be combined with the fire alarm and mass notification systems to provide an integrated notification system.

For very tall buildings, event notification to building occupants is critical in the overall fire strategy. Since an event may be isolated to a small building area, occupants in other areas remote from the event and may not be aware of the ongoing situation. By providing notification to all building areas on a selective basis, occupants can be made aware of the incident while not impeding actions in the incident area.

MASS NOTIFICATION

Mass notification systems are used in large complexes to alert occupants of any event that warrants instructions. In-building notification systems are used to provide information and instructions to people in a building using audible and visual signals, text, graphics and other communication methods. These can include textual display boards as noted above, fire alarm or other speaker systems, paging devices, cell phones, and personal digital assistants (PDAs).

In-building mass notification systems provide benefit to the overall fire strategy for very tall buildings. They can be used to alert occupants of certain building areas of the building that an event is occurring remote from their location. They can provide specific instructions through a variety of methods that may not be readily available or employed by the fire detection and alarm system.

As many very tall buildings use partial evacuation or defend in-place evacuation strategies, mass notification systems can be a benefit in providing building occupants incident information. It can use a variety of technologies to provide specific instructions to all building occupants to instruct them on potential relocation requirements. They are useful in the variety of evacuation schemes as they can be designed to integrate with any concept. Mass notification systems should be considered in very tall buildings as part of the overall egress plan.

15 Smoke Control

INTRODUCTION

Smoke control is incorporated in the overall fire strategy in many different building types, independent of size. However, the matter of smoke spread and smoke control is a little more complicated in tall buildings. Their inherent geometry, occupant distribution, the physics of smoke flow and the characteristic design features such as extensive networks of shafts, complex ventilation systems and spatial interconnections makes for a structure potentially more vulnerable to smoke spread and its negative consequences. Refer to the *SFPE Handbook of Fire Protection Engineering*,[103] the *Principles of Smoke Management*,[104] the *Fire Protection Handbook*[105] or the ASHRAE Handbook for specific details.

Careful consideration should be given to the desired performance goals for the structure. Once the goals are developed and criteria are set, an appropriate smoke control strategy can be implemented. A number of different smoke control strategies are possible incorporating one or more of a variety of design features. Features that might achieve the goals vary from the simple, passive reliance on smoke barrier walls and floors to utilization of air handling systems that develop pressure differentials to restrict smoke spread from a fire zone. A sprinkler system can similarly be thought as an effective smoke control feature because it restricts fire development, limiting smoke production and reducing buoyancy.

Even sprinkler controlled fires can continue producing smoke, albeit at a reduced rate, until final extinguishment is accomplished by the fire brigade or fire department. Without any floor by floor smoke barriers, smoke from sprinkler controlled fires can spread to adjacent floors. Such smoke could also damage property in other areas of a building. Although a tall building equipped with a sprinkler system might meet the local life safety code requirements for minimizing smoke spread, the owner’s performance goals may require a higher level of performance.

The smoke control strategy for a given building will therefore be determined based on the performance goals established among the stakeholders. Occupant life safety, as the most common goal will influence the design. Consequently, the type of egress plan – phased, staged defend in place etc, will influence the smoke control design. Additional performance goals may also need to be considered, including fire fighter safety and the aforementioned property protection. These goals need to be reviewed and established before developing the smoke control strategy. The design solution needs to address the nature of the building, its relevant occupant characteristics, the stakeholders’ performance objectives and, lastly reliability.

FACTORS THAT INFLUENCE SMOKE CONTROL IN VERY TALL BUILDINGS

“Smoke control” is not a special system meant only for unusual structures (underground buildings, theaters, sporting arenas) or unique geometries (atria or shopping malls). Smoke control is more a part of the holistic approach to fire safety in a building, established by the integration of one or more building characteristics, features, or systems.

For example, the provision of automatic fire sprinklers can be considered a fire safety feature or system which provides a form of smoke control. Other forms of smoke control abound. Throughout a variety of buildings, one finds a number of features that could be deemed “smoke control”: smoke detectors installed in air handling systems to provide shutdown to prevent smoke recirculation, smoke resistive floor construction to minimize the smoke spread between stories, the provision of smoke alarms in residential units to provide occupants time to escape, and/or the provision of self or automatic closing cross corridor doors which close building sections from impending smoke intrusion down a corridor.

Smoke control concepts can provide a means to address different egress strategies. A defend in place concept, or similarly phased evacuation, would likely necessitate one or more forms of passive or active smoke control, whereas the evacuation times of tall buildings may necessitate an active type of system to protect the vertical egress pathways. See Chapter 10.

Because of their nature, very tall buildings complicate smoke spread and therefore make smoke control more difficult to achieve. The inherent geometry, multi-use and multi-tenant space programming, and characteristic design features such as extensive network of shafts and services in very tall buildings creates greater vulnerabilities to smoke spread and its negative consequences. Its height, the higher overall occupant load with limited means of egress access, evacuation times, complex ventilation systems and the network of ducts and shafts altogether pose smoke spread challenges not normally seen in other types of buildings.

These challenges require a thoughtful, strategic approach. Consideration needs to be given to a broader pallet of concerns from occupancy considerations to construction details. The possible solutions are also numerous: from passive to active smoke control including features such as, but not limited to: smoke barrier walls and floors, stairway pressurization systems, pressurized zoned smoke control provided by the air handling equipment, addressable smoke dampers, fire alarm activated doors and more. The solution or solutions chosen need to address the nature of the building, its uses, its occupancy, relevant occupant characteristics and, above all, reliability.

Stack Effect

A tall building’s height makes it inherently more vulnerable to smoke spread than shorter buildings. This vulnerability, referred to as stack effect can be thought of the natural flow of air within the building due to temperature differences between the inside and outside. The effect is correlated positively with height and is of greater concern in tall buildings.

This flow of air can spread smoke via unprotected floor openings, unsealed penetrations in floors or shaft walls, and other gaps in construction. The taller the building, the greater the stack effect. Also, the greater the temperature variation between the interior and the exterior of the building, the greater the stack effect. When the exterior temperatures are low, the heating of a building causes a natural flow up and throughout the building. See figure 15.1. The cooling of a building in an otherwise hot climate, can cause a reverse stack effect, causing smoke, once cool having drifted far afield from the point of fire origin, loses its buoyancy, and is further drawn down through building by the reverse stack effect. See figure 15.2. The stack force is present in building whether there is a fire or not.

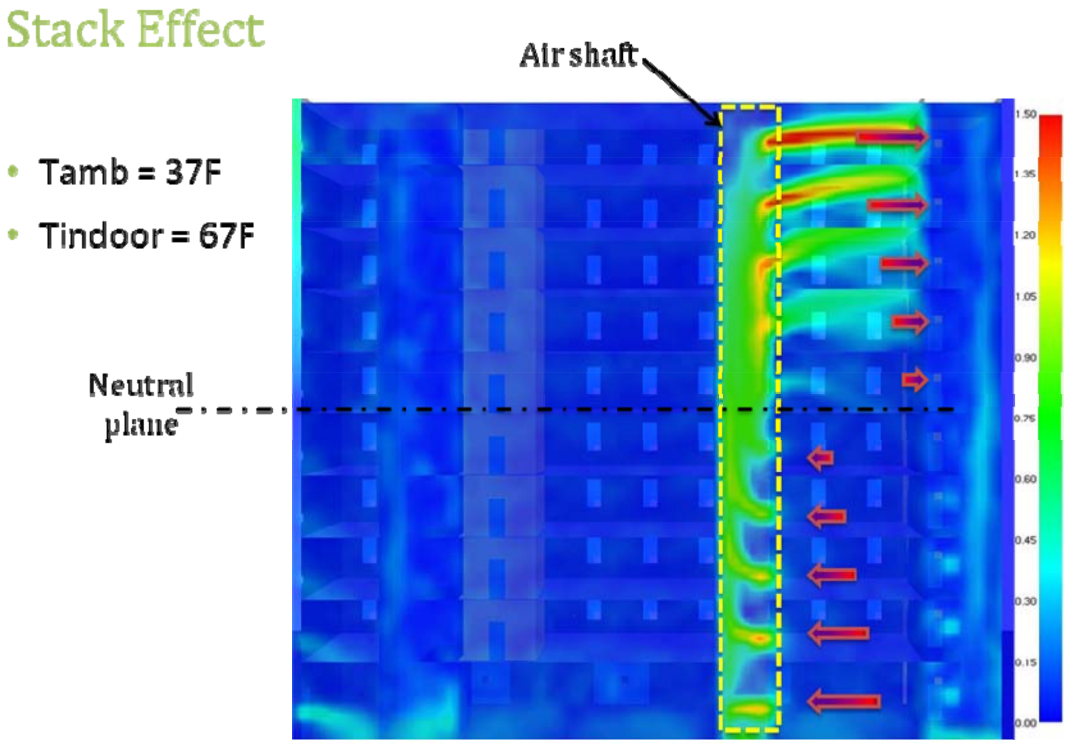


Figure 15.1 - Stack Effect

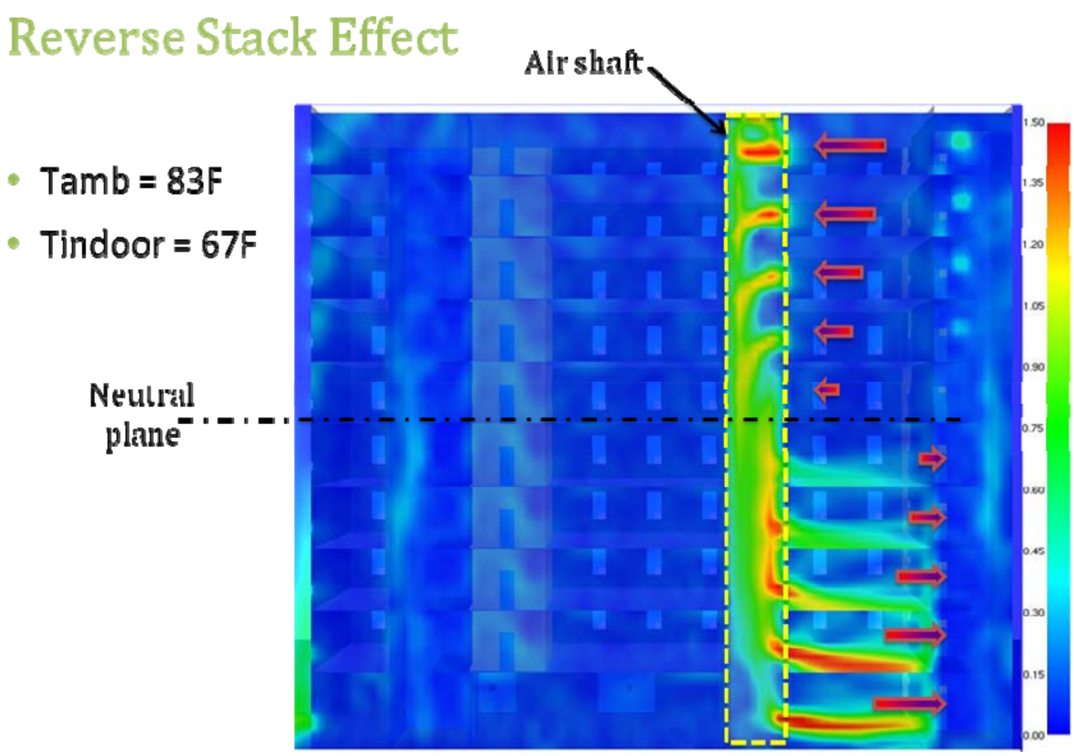


Figure 15.2 - Figure Reverse Stack Effect

Analytical equations have been developed to describe the stack effect for simple uniform buildings.[104] The equations can be extended to buildings with multiple shafts, provided the shafts are similar to each other. The analytical method is not suitable for buildings which have shafts of varying heights and varying geometry.

Computer network models have been developed to address the design of pressurization systems in complex buildings.[106] An advantage of the network model such as CONTAM is they can address wind and HVAC influences. An example of a CONTAM model is provided in figure 15.3.

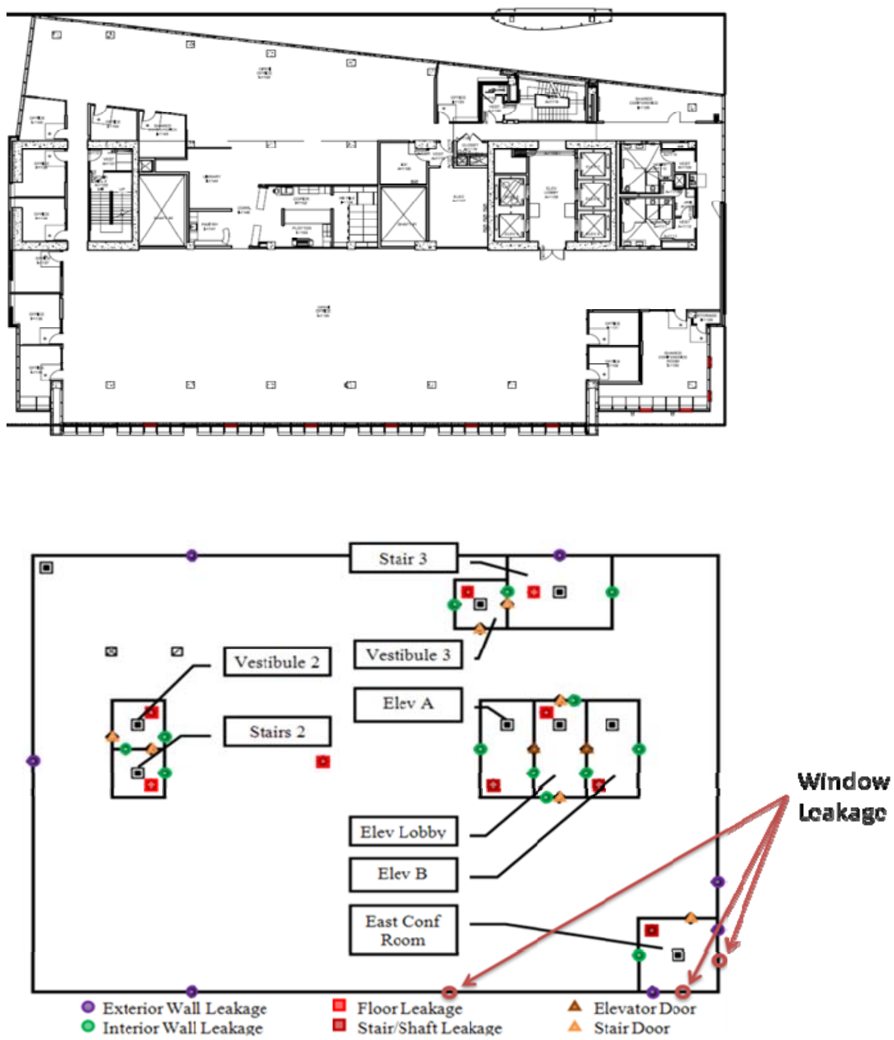


Figure 15.3 - CONTAM Model

Table 15.1 illustrates the forces generated by the stack effect for various building heights, leakage areas and space linkage. Leakage area is a key consideration as this varies with floor layout, internal partition construction and façade construction *etc.*

Table 15.1 Stack Forces

Height (m)	**Shaft to outside(Pa)**	**Shaft to interior - (Pa) A_{si}/A_{io} = 1.7**	**Shaft to interior – (Pa) A_{si}/A_{io} = 7**
9.25	17	5	0.2
92.5	160	42	2
305	550	140	10

These forces are not large, but are significant enough to push smoke through cracks, openings and penetrations in large enough quantities to put the tenability of adjacent spaces at risk.

Piston Effect

Another concern, found in high rise buildings is the air movement created by the piston effect of elevators. The air movement caused by the elevator cars ascending or descending within the shafts can force air through the elevator shaft doors into the floor space. Alternatively, the same effect can create a suction effect and draw smoke into the shaft. This can create a path and pumping system for smoke to move between floors. This effect is pronounced taller buildings when higher speed elevators are employed.

Building Mechanical

HVAC systems can play a role in smoke spread. Normal use of the tall buildings can cause conditions that transport smoke due to mechanical forces generated by building services. Heating, ventilation and air conditioning systems (HVAC) can spread smoke by extracting smoke from the fire compartment and re-circulating in adjacent compartments, and by over pressurising the fire compartment pushing the smoke through gaps and openings.

Elevator shafts can be efficient smoke conduits, which act like chimneys spreading smoke to other floors, especially in the proximity of the entrances to the stairways. If the systems are not properly designed or equipped with proper safety devices such as integrated smoke detection shut down, the systems could enhance smoke spread from a compromised space to other spaces, endangering life and property in remote areas of the building, far from the fire. Even for naturally ventilated tall buildings, openings to the exterior can be result in either increased stack effects or wind induced smoke spread concerns. In naturally ventilated buildings in temperate climates where the inside temperature is similar to the exterior temperature, stack effect is less pronounced.

Double skin curtain wall facades are occasionally employed as part of a building's ventilation system. Often, such facades are of glass or similar material. The "double skin" creates an unprotected shaft which can allow smoke to spread unmitigated between and across floors. Sprinkler protection may not suffice as a growing fire adjacent to such a shaft has the potential to breach the shaft before sprinkler operation. Once breached, the double skin creates a smoke spread hazard. See the chapter on facades for more information.

Wind

As buildings increase in height, the effects of wind are more pronounced. Wind can play a role in causing smoke spread, or a role in affecting smoke control features. In general, the taller the building, the greater the expected wind speeds and resulting wind pressures at the upper levels. In some high density urban corridors with multiple tall buildings, high winds can present themselves at 10 meters above ground just as commonly as at 50 meters above ground.

In general, wind pressure on the face of a building out in an open space increases with the height of the building.[104]

With an emphasis being placed on sustainable building methods, modern façades are being constructed to form tighter barriers between internal and external environments, thus the influence on internal pressures due to wind has reduced. However, facades can be fitted with openable window,s which can result in substantive internal wind pressures. Likewis,e the failure of external façade can result in the increase pressures. See Chapter 12.

PERFORMANCE GOALS

With a comprehensive understanding of the potential issues, the design professional, with input from the stakeholders, is prepared to develop smoke control performance goals for the building. In some cases, fire safety codes might prescribe certain goals. In other cases, the owner, insurer, engineer or authorities could have interests and goals that are not reflected in the codes. These other interests may affect the performance goals, the criteria and the resulting design.

The development of performance goals can be affected by such factors including, but not limited to, building geometry, expected occupant groups, expected contents, desired levels of risk to life and property, and even long term life cycle issues. For example, a tall office building structure with expected high turnover of tenancy may have different performance goals than a tall mixed use structure with health care occupancies and laboratories.

Examples of performance goals for the smoke control system might include:

1. Minimizing the potential for smoke spread in order to protect occupants who are expected to remain in place for a given time before evacuation.

2. Minimizing the potential for smoke spread between floors in order to protect occupants while evacuating.

3. Minimizing smoke spread between floors for the purposes of protecting contents from smoke damage.

4. Minimizing the exposure of occupants to hazardous levels of smoke such that they can reach a place of safety that is designed to be free of smoke.

5. Providing means for fire fighters to access all areas of the building, such as a stairway or elevator system, that is the guarded from becoming untenable or unusable for fire fighting operations.

6. Minimize the spread of hazardous smoke to occupants on remote floors given a fire following earthquake.

Once the goal or goals are clarified, a set of practical performance criteria are established. The performance criteria are generally the set of requirements or limits agreed upon that are used during the design and analysis. Optimally, such performance criteria are established with the stakeholders before any design or analysis takes place.

Depending on the goal or goals, the criteria might be quite simple. For example, criteria necessary to meet performance goal #1 may include a set of tenability limits established in the literature, maintained for a given amount of time, under loss of normal building power. Advanced analyses with computer fire modeling may be necessary to prove that the tenability limits have not been exceeded.

The goals described in this section are not meant to be an exhaustive list, nor are they necessarily mutually exclusive. One may have both a goal of protecting vertical pathways for the use of the occupants and of protecting the fire fighters while maintaining another goal of minimizing smoke spread to remote areas of the building. Since the design process, and the possible solutions, will be dictated in large part by the established performance goals, the stakeholders should be consulted during goal development such that the design professional has the appropriate direction before starting any analysis or design.

DESIGN CONCEPTS

Smoke control design concepts are described in the aforementioned handbooks. Those concepts include active and passive methods.

Active Smoke Control

Active smoke control system features include dedicated fans to pressurize exit stairways, elevator shafts, or both. Other active features may include either dedicated or non-dedicated fan systems to provide means to counter the buoyant flows of smoke and stack effects. In the active use of fans to prevent smoke flow between building areas or "smoke zones", a given zone in alarm (fire location) is identified by the fire alarm system, which commands the building management system to exhaust the zone to create a negative pressure zone relative to adjacent zones. Or alternatively, the zones which surround the zone in alarm can be supplied by the air handling systems in order to cause pressurization, while the air handling system to the zone in alarm is either shut down or is set to exhaust. This provides a similar benefit – reducing the possible smoke spread from the zone in alarm.

Zones could be an entire story, multiple stories or a portion of a story. The concept is to reduce or overcome the stack effect and reduce the potential for smoke spread to remote portions of the building. Implementation of active systems, beyond that of stairway pressurization systems, should be approached with caution. Such systems should remain as simple as possible. Zoned smoke control systems, in very tall, mixed use structures, when properly programmed and maintained, are very effective in managing the hazards due to stack effect, but can be complicated to install, program, test and maintain over the lifetime of a building. Any unnecessary design complexities can have severe impacts in these later phases of a building's life.

Passive Smoke Control

A passive approach to smoke control includes those elements that need no action on the part of a HVAC system or fire sprinkler system to achieve the intended objective of controlling smoke. Passive features include floors, walls, shafts and the associated opening protection provided for the barriers, doors, shutters, dampers and windows.

Passive approaches to smoke control are often the common approach for controlling smoke in apartment, condominium or hotel type buildings. These types of occupancies offer a high degree of smoke control because these tend to be well compartmentalized. Walls between residential units are typically fire and/or smoke resistive, lending each story to a number of compartments with a series of multiple barriers which guard against smoke spread. This minimizes the likelihood of smoke transmission to remote areas.

For tall buildings which rely mostly on such passive smoke control concepts, a potential weakness lies at the edge of slab. Many tall buildings are designed with curtain wall systems. In the event that passive smoke control is the primary means to control smoke transmission, the intersection of the curtain wall with the perimeter edge of the floor slab can be a weak link. It is an area that requires attention during design, construction and inspection. The appropriate installation of smoke sealant and fire safing at this junction determines whether the passive approach has been successfully implemented and the floors are truly smoke resistive. A number of products and assemblies have been tested by laboratories; however, since an almost infinite number of combinations of wall systems and slab systems could be designed, if testing data is not available, careful evaluation of this assembly is warranted to ensure proper performance.

In determining the necessary systems for the control of smoke in a building design (passive, active, passive and active), consideration should be given to the building occupancy and population profile. Different occupancy types may require different levels of protection. A very tall office building, where people are expected to be alert, aware of their surroundings, able bodied and familiar with the building may require different considerations than a very tall hotel or hospital, where occupants are expected to be asleep, incapacitated or unable for self-preservation.

Since occupants of an office building can be expected to be familiar with their environment, have less delay in starting their evacuation, and are generally more mobile and able bodied, they will likely take less time to reach protected exits. Therefore, an office building smoke control system might be limited to active systems to protect its stairways and passive means to protect floor-to-floor smoke spread. If, however, the same office building has high occupant loads per floor or the building includes assembly or dining at the top floor(s), or there is a simultaneous evacuation of numerous floors resulting in longer evacuation times due to queuing, additional analysis may be necessary to determine whether additional active or passive smoke control measures are necessary.

In comparison, additional means of smoke control may be necessary for very tall hotel buildings whose occupants are expected to be delayed during their pre-movement time during the initial stages of the alarm (waking, dressing, investigating), and may be disoriented as they find their way to unfamiliar exit stairway locations. The “additional” smoke control may be additional passive features such as fire and smoke resistive corridors, or active features such as elevator pressurization systems.

DESIGN CONSIDERATIONS

Designing for Wind

In some cases, wind effects can affect on smoke spread or the smoke control system itself. This effect is pronounced for buildings with operable windows or buildings where the exit stairways or exterior walls are along the perimeter. For tall buildings with operable windows, any active smoke control system, if deemed appropriate, must be designed to account not only for stack effect but also the effects of wind on the façade. See figures 15.4 and 15.5. A stairway along the windward side of a façade may experience significant increased pressures during the 1% wind conditions, resulting in over pressurizing the stairway.

This can result in an increase in door opening forces for those occupants attempting to enter the protected stairway. Similarly, a stairway along the leeward side of the building may be subject to negative wind pressures, accommodating a greater stairway pressurization flow to account for the lesser due to wind. In either case, the stairway pressurization system may be over pressurized in either the wind condition for the windward stairway, or in no wind condition for the leeward stairway. Such effects are generally pronounced in very tall buildings or buildings in particularly windy urban building corridors. In some urban environments, the wind conditions are difficult to predict. In cases where data is available, the smoke control system designer should include it in the analysis.

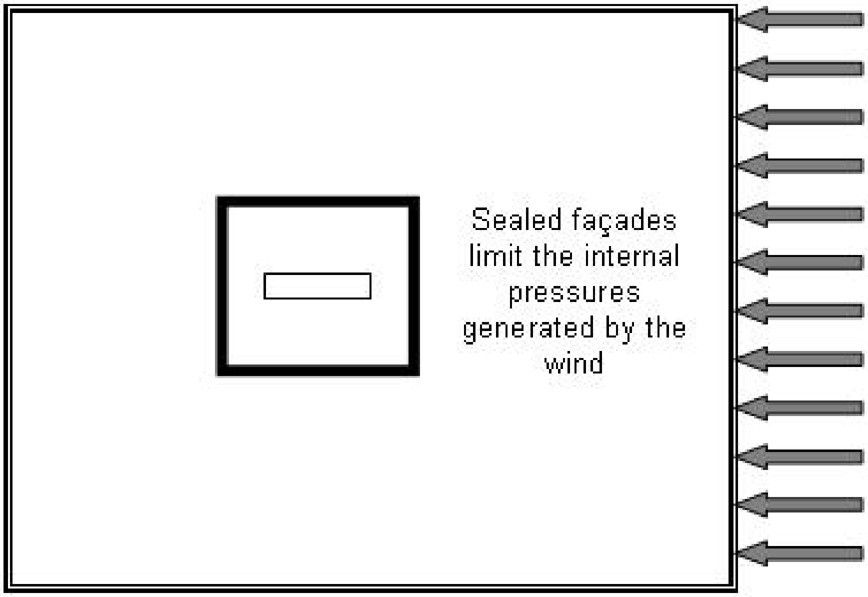


Figure 15.4 – wind pressure on façade

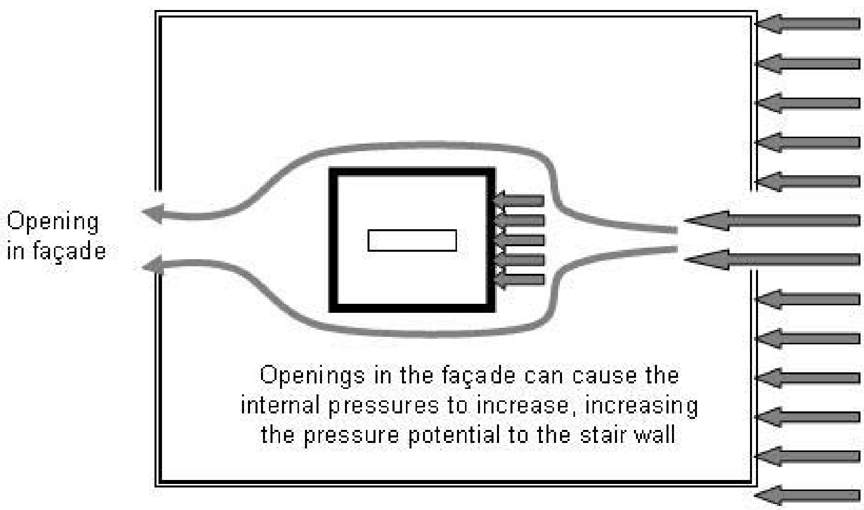


Figure 15.5 – wind pressure on open façade
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Operable Windows

For very tall buildings with manually operable windows, where windows are expected to be open on the windward side of the fire floor, wind effects can pressurize a "fire floor" resulting in increased smoke production and increased smoke spread concern. Conversely, if a zoned smoke control system is designed and implemented to offset such conditions (i.e., offset the positive force of the wind by exhausting the fire floor zone in alarm), the floors with operable windows above and below the fire floor can cause additional challenges. If the floors above and below have operable windows open on the leeward sides of the building, the floors may become "negative" relative to the fire floor between them, and may draw smoke into their spaces. However it is unlikely that a fire will occur during a windy day on the floor with operable windows open only on the windward side, and operable window on adjacent floors only open on the leeward side.

For this reason, wind tunnel testing should be performed to better understand the influences of wind on the building, in the particular environment. Figures 15.6 and 15.6 indicate a wind tunnel test on a tall building in San Francisco.

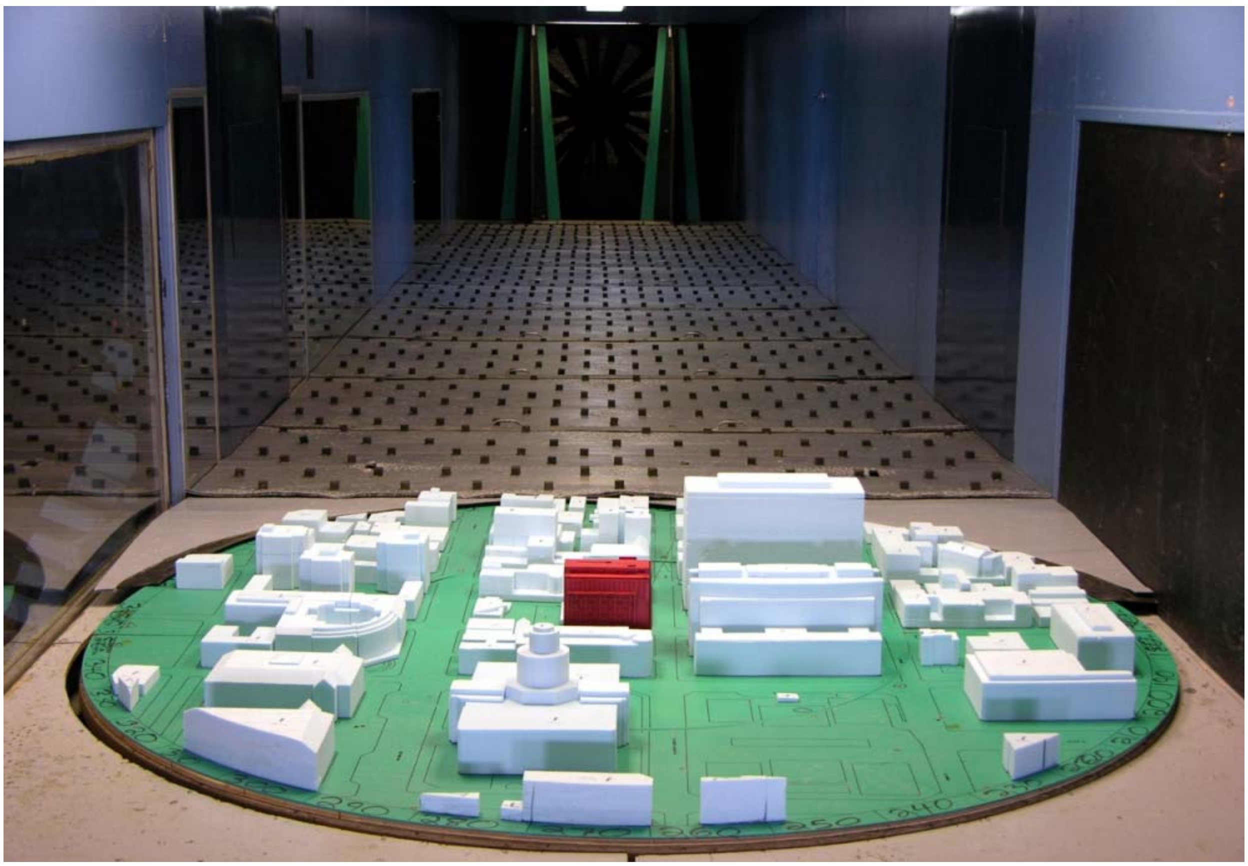

Figure 15.6: Wind Tunnel Testing of a Tall Building in San Francisco, California

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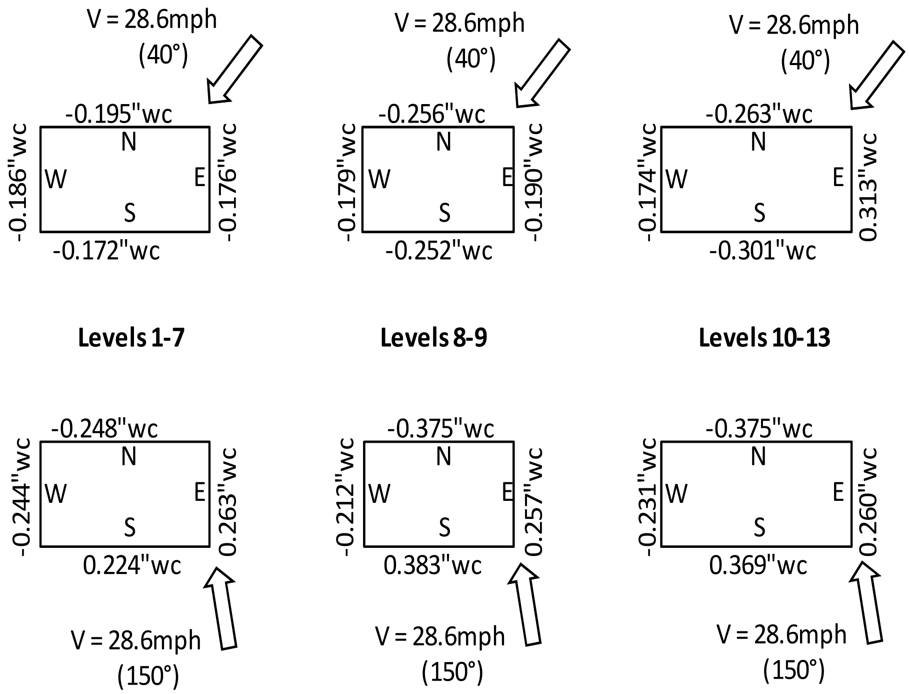

Figure 15.7: Results of Wind Tunnel Testing of a Tall Building in San Francisco, California

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Reliability

The level of reliability of any smoke control system should be established early, during the development of performance objectives. A risk analysis such as described in Chapter Six is important to establishing those objectives. Expectations of reliability will inform the design and analysis process.

One way to characterize a system's reliability is by categorizing its controllable or uncontrollable factors. Controllable factors include hardware or building design features. Uncontrollable factors include weather, such as wind and climate.

Where multiple fans and dampers are required to modulate, there is a greater potential for failure of the system. As one means to address reliability of system hardware, fire alarm monitoring and automatic system testing may provide the acceptable level of reliability. Or, where the normal building power supply is inadequate to meet reliability goals, stand-by power may be necessary.

The level of reliability may be dependent on the assumptions, or boundary conditions, made during the analysis. As stack effect, which could be considered a “boundary condition”, is strongly influenced by temperature differences, what temperature differences are to be assumed? What is the reliability of the system under wind conditions? If a building includes operable windows, is it intended to have a zoned smoke control system that works 100% under extreme wind conditions? Is it likely that the windows would be closed by the occupants during such wind conditions? Should the smoke control system need to function under extreme wind, during extreme stack effect? Is it reasonable to design the event of a fire occurring, with an ineffective sprinkler operation, during such conditions? Such questions should be considered and discussed among the stakeholders during the early stages of design.

Designers should also recognize not only the immediate needs of the system reliability relative to its occupancy characteristics, hazards, population and uses, but also the potential flexibility and reliability of the smoke control system in the event the occupancy characteristics or building geometry change. An active floor-to-floor zoned system appropriate for a single tenant per story open office lease plan may be jeopardized if the leasing arrangements and resulting geometries change years later to accommodate multiple enclosed offices. Similarly, an active zoned system may be jeopardized if the same tenant expanded to multiple floors and created open stairways to interconnect the stories. Improvements which occur during the lifetime of a building can create hazardous situations if not carefully monitored and addressed.

For these reasons, it is prudent to consider the least complicated, most flexible and transparent system whenever possible. See Chapter 8 for more information about reliability.

Stairway Pressurization

As stairways will generally be used as part of the egress plan for the majority of tall buildings, it is imperative to maintain tenability within the stairway. Pressurisation systems are a popular approach to protect stairways in tall buildings from smoke infiltration.

Stairway wall construction

The ability of the stairway walls to resist fire and smoke which must be preserved over the duration of a fire. During a fire, it’s possible for the core to be displaced and/or cracking to occur. Considerations should be given to what type of fire sealant/filler is used for joints, as it may have to be flexible to cope with displacements. When designing stairway pressurization, it is necessary to estimate the leakage that will be present. Some codes contain impact resistance requirements in an effort to harden the stairways; this could affect the leakage of the stairway.

Vestibule – natural ventilation

Natural vestibule ventilation (venting directly to outside) is generally not used in tall buildings as these systems are particularly sensitive to pressures generated by wind.

Vestibule – Mechanical Ventilation

It is common in some parts of the world to provide a vestibule between the stairway and the floor as a buffer against smoke spread and to minimize the pressure differential across a single door. The vestibule may either be pressurized or ventilated with a mechanical system. Under the latter approach, extraction is provided at the top of the vestibule while inlet is provided at the bottom. The designer has to be careful that the pressure differences stay within tolerance to allow effective opening of the doors. These systems are sensitive to internal building pressures generated by stack and wind which increase with building height.

Two examples of stairway pressurization systems are given in the figures 15.8 and 15.9. The first offers an approach that is a simple system whereby only the shaft is pressurized to protect from inflow of smoke and hot gasses into the stairway. The second is a diagrammatic representation of a pressurized vestibule inserted between the floor and the stairway, which may or may not include an elevator. The vestibule provides a buffer from the floor, reducing the chance of smoke entering the stairway and can provide a staging area for fire fighters.

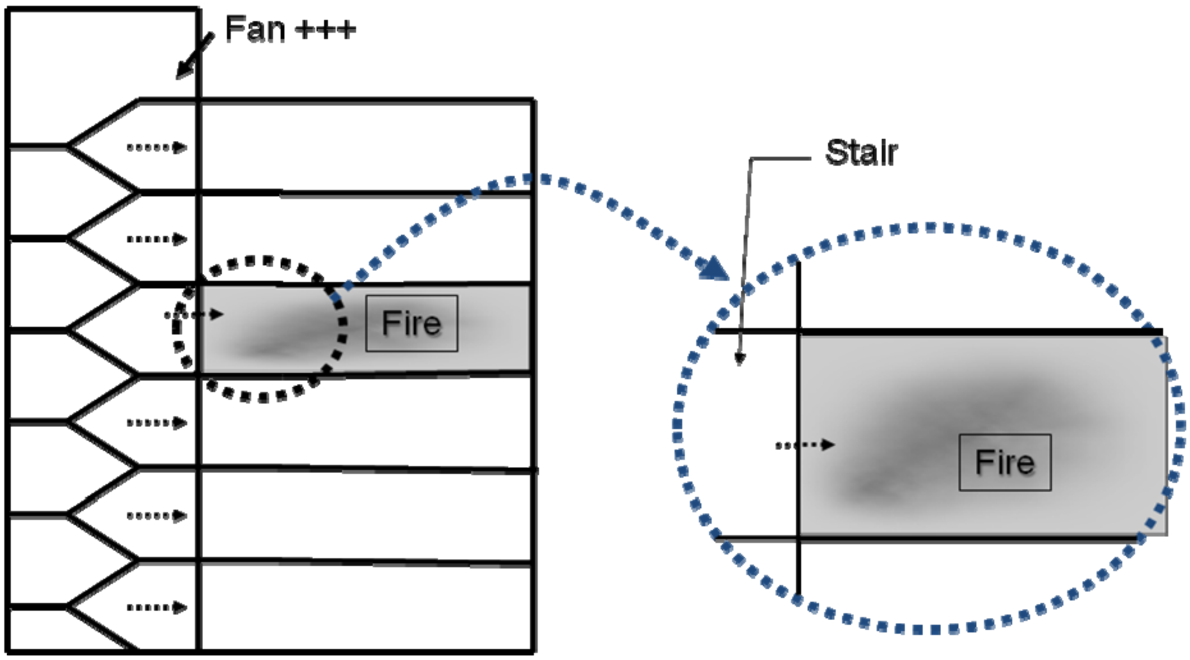

Figure 15.8 Stairway Pressurization System: No Vestibule Between Stairway and Floor

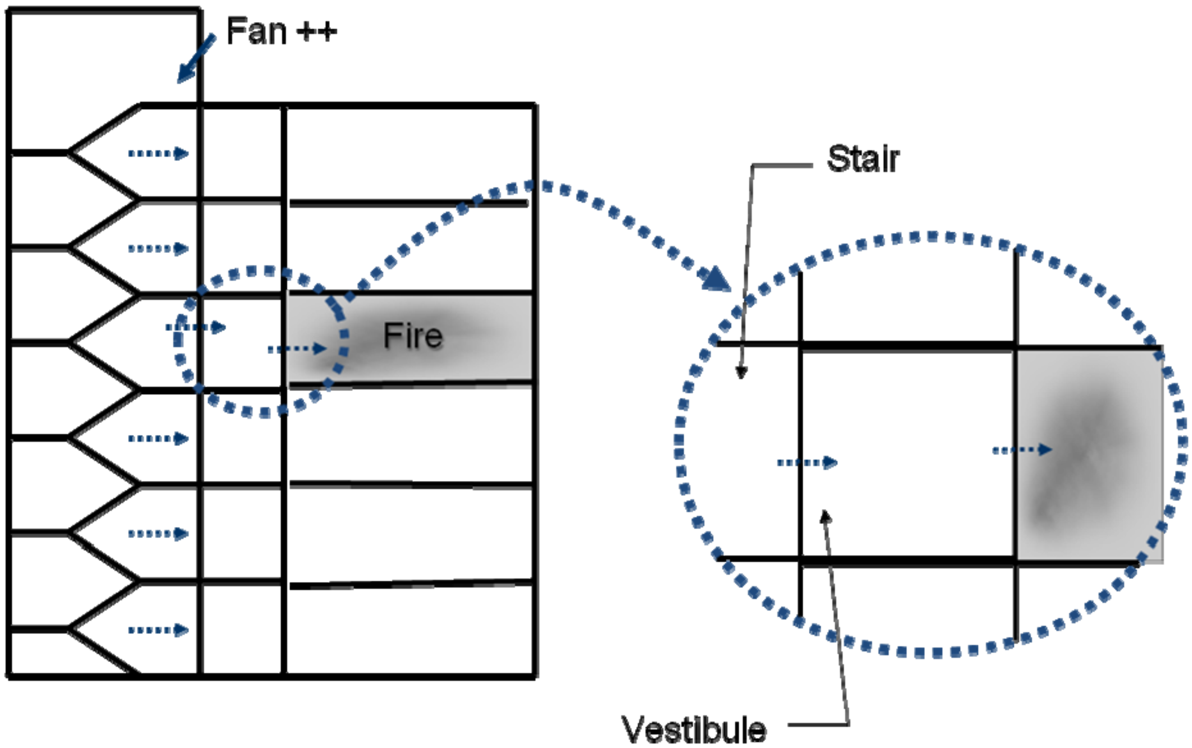

Figure15.9 Stairway Pressurization System: Vestibule Between Stairway and Floor, Vestibule is Mechanically Pressurized

The above mentioned design standards provide guidance on minimum and maximum pressures, calculation methods, types of systems, number of injection points, and venting. Because standards vary considerably, agreement from the Authority having Jurisdiction should be sought on the use of appropriate standard.

Height limit

Designers must ascertaini the maximum effective height that pressurisation systems can operate. The maximum height depends on several factors, such as minimum and maximum working pressures, leakage areas, and climatic conditions.

In order to provide pressurisation levels within the boundaries of the minimum and maximum pressures, stairways may have to be sub-divided (known as compartmentation). When doors between stairways are open, the effect of compartmentation is reduced. Compartmentation does have a disadvantage from an economical and architectural view in that it it's likely that it cannot be achieved without increased stairway landing area space, thus losing usable floor space.

A key component of the design evaluation is the assumption on how many open doors are used to calculate the fan design load. The designer should evaluate the implications of the evacuation methods, building configuration and local fire fighting operations on the quantity, frequency and length of time doors are open.

Stacked Atria

It is becoming more common in modern tall buildings to use stacked atria, where the building is vertically divided into multiple open sections. See figure 15.10. These atriums can expected to be evacuated as a single zone, therefore potentially multiple doors can be open simultaneously for significant period of time. As such, the designer may have to consider this when calculating the fan design load. In general the designer should consider the effects of unusual building configuration on the operability of pressurization systems.

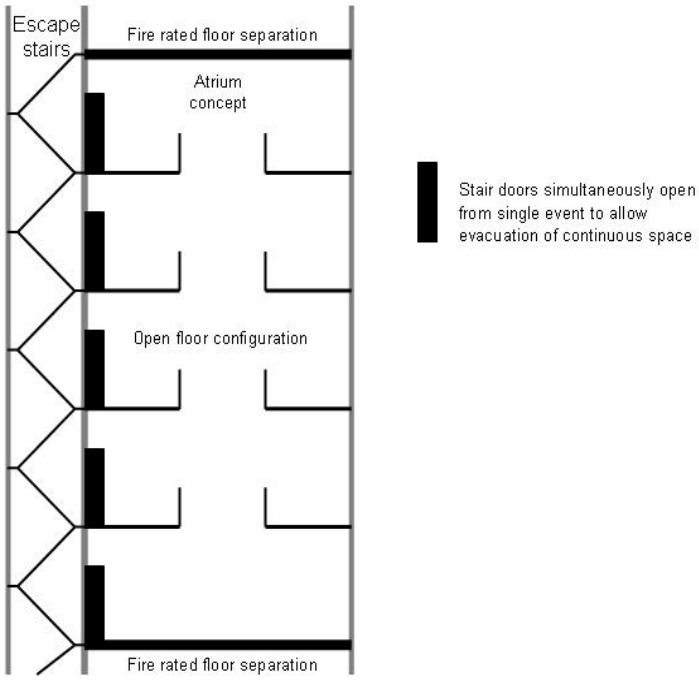

Figure 15.10 – Village type configuration

Stacked atria have implications for the calculation of buoyancy forces, as buoyancy forces are a function of height. Furthermore, sprinkler operation may be delayed in such mini atria (due to the ceiling heights), allowing for larger fires and greater smoke production rates than in standard ceiling height buildings. A significant exhaust system may be necessary to address the atrium hazard, whereas a stairway pressurization system, with multiple doors open could be necessary for the stairway. This combination of features and factors need to be considered during the analysis.

Fire fighting Operations

The effectiveness of stairway smoke control systems are sensitive to fire fighting operations, as the operations involve the opening of stairway doors for long periods. The placement of standpipe riser outlets in the stairway vestibules reduces the frequency and period of door openings. This does not eliminate the problem, because fire fighters may run hose from the floors below up the stairway onto the fire floor. The designer should be aware of how fire fighting operations integrate with fire safety, and particularly the operation of the smoke control system. See chapter 13 for more information about standpipe placement.

Duration of Operations

The time a smoke control system operates for will be driven by the hazard and risk assessment conducted for the building. The designer should be aware that in taller buildings the evacuation time can be considerable, therefore as matter of course, the minimum operation time should be at least equal to the total evacuation time. It is prudent engineering practice to use a safety factor to build a degree of robustness into the design. See chapter 10.

Protection of Elevators

Similar to the need for pressurization or enclosure of stairways, smoke movement through elevator shafts should be addressed for very tall buildings. While elevator shafts have historically been addressed with passive smoke containment, such as elevator lobbies, an alternate or supplemental approach might involve elevator pressurization. Elevator pressurization systems can be intended to prevent floor-to-floor smoke migration, to aid in emergency evacuation or relocation of occupants, or to allow fire fighter access to upper floors. While the focus of this section is on systems intended to prevent smoke migration, some of the information also applies to pressurization systems intended to aid in elevator evacuation and fire fighter elevators.

Pressurization systems need to be designed to maintain adequate pressurization across the elevator hoistway opening, which means pressurization within minimum and maximum values of pressure differences. For example, the minimum and maximum pressure differential values specified in the International Building Code[107] are 0.10 and 0.25 inches of water (25 and 60 Pa) relative to the adjacent building areas.

The minimum pressure difference needs to be sufficient to prevent smoke from entering the elevator shaft, and the maximum pressure difference should minimize the potential for door jamming and adverse impacts on the elevator equipment.

Sometimes, pressurization can cause elevator doors to get jammed in the closed or open position. Network airflow models can be used to evaluate stack effect and floor-by-floor air movement to determine the air flows and vents necessary to maintain these pressures.

There are potential issues with the velocity of air moving past cables and other elevator equipment, which could adversely impact the performance of these systems. Elevators in tall buildings usually have high operating velocities, and pressurization systems must address the piston effect resulting from these velocities.

The piston effect is reduced in shafts with two or more cabs. There is no piston effect once the cabs are parked at the recall floor. However, if an elevator is designated for firefighter use, it may run continually throughout a fire incident. For buildings not relying on the continued use of the elevators, the designer can evaluate if the piston effect is of significant consequence for the relatively short time until the cabs are parked. These potential impacts should be accounted for in the design, and reviewed as part of the testing of the system.

Elevator pressurization requires roughly more supply air than stairway pressurization, resulting in unique design challenges. Except for very loose (leaky) construction, the large amounts of air flowing from the elevator shaft and through the building envelope make it difficult or impossible to maintain adequate pressurization with a system that simply supplies pressurization air to the elevator shaft. This is particularly true on floors where the cabs are recalled with the doors open.

As part of LEED requirements and current design standards, corridors are often relatively small and tightly constructed. Elevator pressurization can result in the corridors becoming pressurized due to leakage from the pressurized shafts. Depending on the design of these systems and the tightness of the shafts, this can lead to issues achieving the required pressurization at the stairways and elevators and preventing excessive door opening forces across the doors of other rooms and spaces opening to these corridors.

Two approaches for dealing with this challenge are floor venting and focused pressurization. Floor venting consists of putting vents in exterior walls that open in a fire situation such that the building envelope becomes similar to that of a leaky building. This may be necessary on the recall floor or on multiple floors in the building. Focused pressurization consists of using a relatively small amount of supply air and exhausting the fire floor and an agreed upon number of floors above and below the fire floor to achieve the required pressure differentials. With focused pressurization, the system is only balanced to maintain adequate pressurization on the few floors that are exhausted.

In buildings with elevator and stairway pressurization and floor by floor active smoke control, design analysis of these systems needs to be done with all systems operating. When used for emergency evacuation or fire fighter access, the analysis should also include situations where the floor by floor supply and exhaust is not operational or is only partially operating. Coordination of pressurization and elevator recall systems is necessary.

When the elevators recall and the doors open, these systems may not maintain pressure differentials across the elevator hoistways doors located below the recall floor. This will require elevator lobbies on these lower levels, or a means to supply air below the recall level. Attention should also be given to protecting the shaft, cabs and control systems from water.

Extreme Climates

As with any smoke control system which requires HVAC/mechanical intervention, care should be taken in extreme climates. In general, when air is necessary to either pressurize stairways, elevator shafts, or provide zoned smoke control systems, the rule is to use 100% outside air. Under extreme climates such as summer in the Middle East, or winter in Scandinavia, 100% outside air, injected into a stairway for example, in a very tall building, may create environmental conditions inside the stairway that are not tenable for egress of more than a few stories. Under such situations, it may be necessary to have dedicated systems intended to heat or cool the injected air.

16 First Responder Issues

Tall buildings can be challenging to first responders, not only due to the height of the structure, but also due to the complexity of the structure and the mixed uses found inside these structures. First responders who may respond to an incident in a tall building could include fire, police, emergency medical units and utility companies. These incidents can be divided into two categories: Acts of God and human-caused. However, these two categories can be broken down even further.

- Natural events
    - Weather
        - Snow/Ice
        - Rain
        - Hurricane
        - Tornado
        - High Winds
        - Extreme temperatures
    - Earthquake
    - Tsunami
    - Drought
    - Flooding
    - Volcano

- Human event - Accidental
    - Fire
    - Loss of power
    - Water leak
    - Natural gas leak
    - Medical emergency
    - Structural failure
    - Loss of vertical transportation system
    - Loss of building climate control system

- Human event - Intentional
    - Fire
    - Loss of power
    - Water leak
    - Loss of vertical transportation system
    - Loss of building climate control system
    - Active shooter
    - Work place violence
    - Bomb threat / suspicious package
    - Criminal activity
    - Terrorism
    - Toxic/biological threats

- Technologically
  - Communication loss
    - Radio
    - TV
    - Telephone
    - Cell phone
    - Voice Communications
  - Computer problems
    - Server crash
    - Software / program failure
    - Virus / cyber attack

These incidents can create hazards to the structure, occupants and the first responders. The design team and the ownership should review these possible incidents and determine what type of safeguards will be installed to reduce the risk associated with these types of incidents. The first responder should also provide to the design team and ownership information on what type of resources the first responders can bring to an incident and the action that they can take to mitigate and bring the incident under control.

The ability to move first responders and equipment to the incident location may be one of the challenges a first responder may face. This challenge is due to the multiple numbers of elevator and shaft systems. Hence, the design team should take into account how the first responder can be transported with their equipment from the response level to the highest level in a safe manner.

COMMAND AND CONTROL

The design team should meet with the local first responders to determine what type of management / command and control system will be used if an incident does occur within the structure and how first responders will interface with the building staff and what built in fire protection / life safety systems are available. For example, a management system called "Incident Command System" (ICS) is used in North America by many fire departments, law enforcement, medical services, federal agencies and even private companies as a tool to organize, control, command, and share information about the incident with the first responder and public.

Communication

The ability to communicate during an incident between first responders, building occupants, owners, and facility employees is critical to understand the impact the incident is having on the building and occupants. Without communication, these groups will not be able to understand if the building’s built–in systems are working properly, determine how first responders and occupants should respond, and determine if additional resources or actions are required to control the incident and bring the structure back to a normal state.

Many first responders use some type of radio communication system. The ability to communicate with other first responders and other groups, such as building security, may not be possible due to different radio frequencies or interoperability between the radio systems. Pre-programming the frequencies of first responders and other responding agencies into the communication system can prevent this problem.

Fire alarm systems that are installed within these tall buildings may have a fire fighter phone system that will allow first responders to communicate from elevators, elevators lobbies, and stairways to the fire control/command room. This system will include a combination of phone station and/or phone jacks. The fire control/command room will have additional phone handset for the first responders use.

Another issue that most first responders find with radio communication systems within buildings is that the building components can affect the ability to transmit radio signals to the other units outside. Equipment can be installed to support this communication; however, this problem is not typically realized until after the building is completed. The ability to add additional radio equipment to facilitate first responder radio communication is very expensive after the building is built due to the time factor of installation and finding space for the additional radio equipment. The reliability of the radio communication system must be reviewed to ensure that there is no one point of potential failure.

The key to any type of communication system that the first responder may use is to ensure that the system is user friendly for the types of incidents that may occur. The reliability and robustness of these systems should be considered as described in chapter 8.

BUILDING ACCESS

The ability of the first responder to gain access to the site and within the building will be critical in order to provide services. A fire apparatus access road that meets the needs of the first responders needs to be provided. Several access points may be needed depending on the configuration of the building. It would include sufficient width for local apparatus, turning radius, clearance height, passing lanes and be structurally sufficient to support the loads of the equipment and any outrigger supports. The hazard of falling glass should be evaluated with respect to the location of the fire lanes, fire hydrant placement and entrance/exit points

The fire apparatus access roads, fire hydrant and water supply should be designed to meet the needs of the first responders’ equipment. Hence, the design team may need to conduct an inventory of current equipment and future planned purchases by the first responders.

Security devices that may be installed along the fire apparatus access road, such as bollards or gates, can be equipped with devices that allow first responder to have access without the need of on-site security force or special key/knowledge to unlock or lock down the area. Very tall buildings that are iconic in nature may have security features that are intended to restrict access to the building, and first responders will need to have means to access the building when necessary.

First responders will need access to all parts inside the building(s). This can be achieved via a lock box with access keys for the first responders. The use of electric locks, keys, and card access may be used as part of security for a building of this type; however, the first responders must be able to unlock and maintain security as warranted. The design team should coordinate the design security locking systems with the needs of the fire responders and other fire/life safety systems.

Vertical transportation will be necessary in any incident to transport first responders to the immediate vicinity of the incident. The vertical transportation will typically be via elevator. The elevator must be able to function in a harsh environment, which may include water and smoke inside the shaft or on the equipment. The elevators should be sized to transport a large number of responders and their equipment. This is most often accommodated in the form of a service elevator that is not normally used for passenger use. North America only recently had adopted code language for fire service elevators where European Countries had code language for fire service elevators since the early 1990's.

Fire service elevators are designed to move personal and equipment from the ground level to few floors below the floor of incident, then the first responders will transfer into a stairway to travel the remaining levels to the fire floor .

Elevators designed for use by first responders will need some special features. Some of the safety features that may be used in a fire service elevator may include structural integrity of the hoistway enclosures, elevator lobbies sized for the first responders, water protection to limit water entering the hoistway shafts, no shunt trip protection, additional lighting of the hoistway shaft and standby power for elevator equipment. The reliability and robustness of these systems should be considered as described in chapter 8.

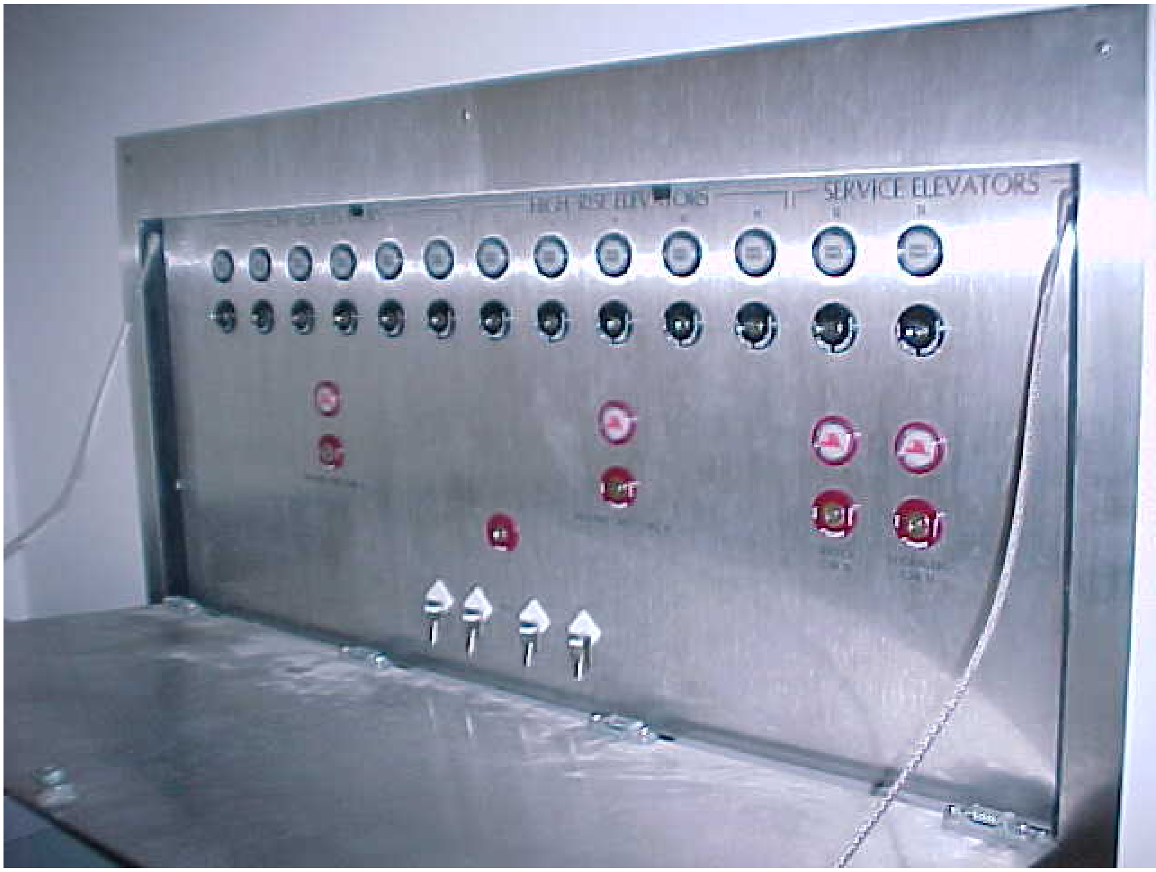

Figure 16.1 Elevator control panel located inside Fire control room
Photo by Joe McElvaney

ROOFTOP HELIPADS

Helicopters have been used to rescue occupants from the roof and to place first responders above the floor of event /emergency. Some of these past fires include the 1980 MGM in Las Vegas, 1972 and 1974 in Sao Paulo, Brazil, and the 1986 DuPont Plaza hotel in Condado, Puerto Rico.

The use of helicopters in fire emergencies is a controversial issue that seems to divide many fire safety professionals and first responders around the world. The use of helicopters in building evacuation is discussed in Section 10 (Emergency Egress). The use of helicopters for first responders is discussed herein.

Advocates of helicopter use by first responders point to a number of instances whereby their use has been effective. Opponents are concerned for the safety of first responders trying to utilize landing pads on top of a burning building. Nevertheless, the use of helicopters should be carefully evaluated as part of the overall fire strategy if being considered for first responders.

Many tall buildings are provided with helipads as part of the building's functional use, such as hospitals or a high end residential/hotel development. In such instances, the use of this helipad may seem a good additional safety feature; however, whether to provide helipads for fire fighter access requires careful consideration.

The Los Angeles building code is one of the codes that requires helicopter landing pads on 'high rise' buildings. This requirement, in place for over 30 years, has had an effect on the cities architecture and has defined its skyline with numerous tall buildings with flat roofs. Required by Los Angeles Fire Department as a means to deliver fire-fighters and equipment above the fire in tall buildings, the provision has the benefit of aiding in the emergency response if appropriate.

The benefit of using helicopters for first response is the ability to deliver personnel and equipment to the upper portions of a building, avoiding delays caused by climbing stairwells or impairments with elevators or lifts. For very tall buildings, this approach could reduce response time. However, landing of a helicopter on the roof of a burning building is, in itself, a dangerous operation. Lack of visibility due to smoke and high winds could cause the helicopter to crash which would exacerbate an already dangerous situation.

The design team will need to coordinate with the first responders to determine if helicopters will be used and the type of crafts that may be used to determine proper design loads and the location of the helicopter pad.

INITIAL RESPONSE

Once the call for help is received by the first responders, units begin collecting information on the nature of the incident. This information will be used to develop an action plan for the incident.

The first responders will depend on the fire/life safety systems working correctly and the staff from the building being available to assist during the incident. This may include controlling the use of elevators, stairways, entrance/exit points and the fire control room

The design team should assist the first responders in developing pre-plans or action plans based on some of the common types of incidents. These plans should consider if there is a failure in a system, what the first responders can expect to happen and actions that may be needed to overcome failures of the systems.

The location of standpipe outlets, hose stations and the type of threads on these devices will require coordination with the first responders. Additionally, they will need to understand the suppression systems, including design pressures that supply water to the site and fire protection systems.

The fire department should consider how they will replenish Self Contained Breathing Apparatus (SCBA). Building designers should coordinate their design with the approach that will be used by the fire service.

On concept of replenishing SCBA is a refill system that allows first responder that ability to refill SCBA via a piping system of breathing air suitable for the SCBA. See figure 16.2. This system may include an air compressor, air cylinders or other means for supplying air. Refill stations can be located throughout the building in locations that are acceptable to first responders.

Typical locations may include stairways and/or elevator lobbies. The design team needs to verify that the system that is implemented will be used by the first responders. Additionally, inspection and testing of the system will increase reliability of the system.

Figure 16.2 - Fire fighter air refilling station located inside a stairway
Photo by Joe McElvaney

Another concept that first responders have required is installing equipment stations on per determined floors to store equipment that can be used by the first responders. The type of equipment and the location of these equipment stations is usually determined by the first responders. The equipment rooms should be designed to meet the needs of the first responders. Additionally, the building owner may be required to supply the necessary equipment that the first responders will use.

When equipment that will be used by the fire department is designed into the building, the continued operation and maintenance of these systems should be addressed. The reliability and robustness of these systems should be considered as described in chapter 8.

COORDINATION WITH EGRESS OF THE STRUCTURE

The first responders with need to establish entrance and exit control points that can be used by the first responders and the evacuees. See chapter 10 of more information emergency egress.

Fire control/command center

The fire control/command center is the nerve area that will provide information about the incident and how the building systems are operating / responding during the event/emergency. In many jurisdictions, a dedicated room will be used for this area. The fire control/command area is sometimes co-located within a room that is staffed around the clock with personnel that has a working knowledge of all building systems and can control these systems, such as in a security room. See figure 16.1.

Fire control/command centers need to accessible to the first responders in order to facilitate a rapid response time. Located within the fire control /command center should be the controls for all building systems, contact information for key building management and operations personnel, current plans of the structure, emergency action plans, egress plans, preplans, and business continuity plans.

System controls located within these areas may include:

- Fire alarm panel
- Security cameras
- Security alarms
- HVAC fan control systems
- Normal / emergency power supply status indicators and remote start
- Smoke management / control panels
- Vertical transportation status panel and remote recall and stop functions
- Access control systems / keys with remote control to unlock doors
- Mass Notification / Paging System panels
- Fire pump status panels and remote start
- Other features unique to the building

Very tall buildings can have large footprints and multiple towers. When buildings contain large footprint,s it should be determined in the fire strategy and design of the system whether multiple command center locations should be included. This would provide additional levels of redundancy should the primary command center be blocked or impacted by an event. If this condition occurs, responders and on-site personnel can assemble at an alternate location to monitor and control the life safety systems.

SAFETY PLANS

The first responders should have input into and use the building safety plans. These plans may includes hazardous materials communication plans, shelter in place plans, emergency evacuation plans, lock-down plans, and business/operation continuity plans.

Training and drills of these safety plans should be developed in cooperation with the first responders

17 Electrical

GENERAL

Electrical systems for very tall buildings are crucial for normal operation and life safety. Their reliability can be evaluated as described in Chapter 8. Some places will have normal power available at all times, except for unique circumstances, whereas other places may have power only certain times of the day or for only days at a time. As part of the design of the electrical systems, the reliability of utility power should be investigated.

The reliability of utility power can be evaluated through historical data available from the power company. When this data is not available, it is more difficult to estimate, and allowances should be taken into account. Furthermore, evaluating the reliability of the utility power needs to consider both total power outages and the quality of power being delivered, as this may impact the equipment as well. In areas where utility power is considered unreliable, enhancements to on-site electrical supply systems should be considered.

Using the same equipment for both the augmentation of normal power and emergency power needs to be considered. It may be practical to increase the level of power generation to take into account the dual use of such equipment. For example, if on-site generators are used to provide normal power and emergency power, these systems may need to be enhanced to increase their reliability during emergency conditions.

The quality of on-site generated power affects the reliability of the power. Often, power coming from generators is sufficient to run critical systems for limited periods of time, but these generators may not be designed to run equipment continuously. If on-site power generation is required on a continuous basis, the system needs to be designed as a primary power system rather than standby. One of the things to consider about on-site generated power is the impact that quality of power will have on equipment that is used during both normal and emergency situations.

EMERGENCY AND STANDBY POWER

Many life safety systems require power to operate. The integrity of the power supply needs to be evaluated for very tall buildings. Many building and electrical codes govern which systems require secondary power and what type of power they need. Loads are subdivided, so that those most directly impact preservation of life and safety are given the highest priority. Typically these include:

- Emergency power.
- Standby power.
- Optional standby power.

The time required to initiate emergency power after loss of loss normal power affects the performance of the life safety systems and therefore needs to be determined. During loss of normal power, batteries can be used on some equipment to maintain operation during switchover. Other systems will have a temporary loss of power until emergency or standby power can be provided.

Some systems will tolerate a very short switchover to emergency power, while other systems can have a longer duration of power loss. Generally, emergency power is provided within 10 to 15 seconds, whereas standby power is provided within 60 seconds, based on many of the standards and codes used around the world. Emergency systems for high-rise and very tall buildings include the following:

- Exit signs and means of egress illumination.
- Elevator car lighting.
- Fire detection and alarm systems.
- Emergency voice alarm and communication systems.
- Electrical fire pumps.

Standby power is typically required to be available after power is provided to emergency equipment. For very tall buildings, the items that might need standby power include:

- Elevators.
- Smoke control systems.
- Power and lighting for Fire Command Rooms.

Optional standby power systems can also be connected to on-site emergency generators. It might be prudent to separate optional equipment from code required standby systems.

When designing systems for very tall buildings, emergency and standby power is necessary for the continued operation of essential life safety systems. The integrity of the emergency and standby power systems will need to be evaluated as part of the overall building fire strategy. Maintaining power to critical equipment is essential to the preservation of life during emergency events and building evacuation.

Consideration should be given to the level of protection provided for emergency and standby power circuits and equipment. If a defend in place strategy is implemented, protection of rooms containing emergency and standby power switchgear and transformers may need to be considered. Providing fire-resistance for these rooms consistent with the rating of floor assemblies may be appropriate because this will provide a level of protection consistent for the overall compartment. Fire resistance of vertical risers consistent with this level of protection may also be desirable to protect feeders and circuits supplying systems outside the fire area.

On-site electrical generators are normally used to provide emergency and standby power. Survivability of systems is a fundamental principle for the design. Separation of the generation system and engines from the normal/utility power service to the building should be considered to avoid common mode failure of sources. The reliability and integrity of the generator system should be evaluated as part of the design process. For very tall buildings, it may be appropriate to provide multiple parallel backup generators so that power is available should one generator be down or taken off line.

The type of fuel that supplies generators should also be evaluated. Most generators use diesel fuel, but some use natural gas. If natural gas is considered, the fuel source needs to be evaluated. If diesel fuel is being used, the storage and delivery methods need to be evaluated. If transfer of fuel between the main storage tank and secondary day tank is provided, then the integrity of that fuel transfer system needs to be evaluated, and protection of the fuel transfer systems should be considered.

The location of the generators should be determined. Generators located within the building should be located in rooms provided with fire-resistance to the level of protection afforded by the surrounding building elements, such as floor assemblies. They should be located where access is reasonably provided and away from other potential hazards. If located outside the building, protection of the generators as well as the fuel supply from vehicular or other damage needs to be provided. Survivability and separation of power sources should be a fundamental design philosophy.

For very tall buildings, the integrity of the emergency and standby power systems is an important part of the overall fire strategy. The life safety systems used to protect building occupants and responding personnel rely on emergency and standby power systems to function under emergency and fire conditions. Separation and segregation for system survival in the event of an incident should be given due consideration as the consequences for common mode failures can be extreme for very tall buildings. This starts with separation of sources and segregation of feeders and distribution infrastructure.

EMERGENCY LIGHTING

One of the systems requiring emergency power is emergency lighting. This includes power to operate exit signs and means of egress illumination. If normal power is interrupted, minimum lighting levels are needed for safe egress as well as for emergency response personnel.
Power for emergency lighting, as well as exit signage, can come from on-site generators or from batteries. The time to establish egress illumination should be included in the fire strategy. For a very tall building, this power normally comes from on-site generators, as they are already provided. For buildings without generators, backup power comes from battery packs integral to the sign or light. As noted above, the integrity of the emergency power system is a factor in the operation of emergency lighting and signage under loss of normal power conditions.

Battery power can be used for providing emergency power to lights and exit signs. The battery power can be from centralized (UPS type) systems or batteries integral to the device. Both approaches require periodic testing and maintenance. For a very tall building, the sheer quantity of devices may make an integral battery approach impractical. Centralized battery based systems reduce maintenance requirements and the number of locations the maintenance has to be performed.

It may be beneficial to consider certain key areas of the building to provide battery backup units in addition to generator supplied power. These could include Fire Command Rooms, emergency generator and power rooms, refuge areas on individual floors if refuge areas are part of the egress plan, and other strategic locations.

ELEVATORS

Elevators may be used by emergency response personnel to access areas in the building during fire events. They recall to the primary response floor and wait for use by emergency personnel. In some buildings, especially very tall buildings, they are also used for occupant egress because they can reduce time needed for evacuation.

If elevators are being used for occupant evacuation, power supplies and circuits need to be coordinated with the elevator machinery and cars. Most likely, these cars and their control equipment would be provided with standby power, but standby power related critical features should also be considered. This includes power supply circuits for ventilation and cooling equipment as well as other circuits necessary for the operation of these cars.

Protection of the power supplies should also be considered. The level of protection necessary should be consistent with the evacuation scheme and time to evacuate using the elevators. Even if the elevators are not used for evacuation, consideration of power supply protection should be given to emergency operation elevators.

If elevators are used for occupant evacuation, the egress time should be evaluated to determine if the prescribed fuel supply duration is sufficient to meet this timeframe. If not, the fuel supply should be increased to provide sufficient run time for generators to provide for the time necessary for occupant evacuation using elevators.

DEFEND IN-PLACE COORDINATION

Many high-rise and very tall buildings employ partial evacuation, where only a portion of the building is evacuated and the remainder of the building is not evacuated. Power supplies to life safety systems need to include an evaluation of protection and duration to match this concept. Survivability and avoidance of common-mode failure risks due to co-located infrastructure should be a consideration for defend in place strategies due to the consequences of system failures.

The overall fire strategy will need to account for defend in place durations needed, and emergency and standby power systems will need to be designed towards this. This may also apply to systems that are not considered required emergency or standby systems, but which are needed in order to provide for occupants that remain in the building. This can include electrical power for HVAC equipment, pumping systems for domestic and plumbing services, as well as other non-emergency needs.

Another consideration for emergency and standby power supplies is the load and duration needed for emergency response personnel operations. The required systems are generally those needed by response personnel to work in the building under an emergency event. However, for very tall buildings, additional time and loads may be required to serve response personnel needs. This could include increased run time for emergency elevators, smoke control systems, smoke removal systems, breathing apparatus systems, *etc*.

The optional standby loads will impact the sizing and selection of the generators. If not taken into account during the design of the power supply systems, the generators may not be adequate to sustain personnel in the building in defend in place strategies, both occupants not being evacuated and emergency response personnel working within the building.

18 Buildings Under Construction

INTRODUCTION

Fires can occur in a very tall building during construction. Buildings under construction present fire protection risks that are often overlooked. These risks are magnified in very tall buildings, suggesting that a risk analysis is recommended for each project. The risk analysis may drive the need to plan for activating fire protection systems as the building is constructed.

Awareness of emergency conditions is critical to the successful evacuation of persons from a very tall building. However, some parts of the designed building's egress systems, as well as other passive and most of the active systems, are likely not operational at points during construction of a building. Construction phasing plans need to be coordinated with the life safety systems because of the number of workers that can be present within the building as it nears completion.

FIRE HAZARDS

There are a number of fire hazards present within a building under construction. Those hazards will vary with the construction techniques employed. Since construction techniques can be almost as varied as the designs of a new building, a detailed assessment of those potential hazards should be conducted for each project.

Those hazards can be roughly grouped into: 1) conditions increasing the potential for fire development, which includes unusual ignition sources, increased fuel loads, and fuel loads that may not normally be encountered in the typical tall building such as flammable solvent vapors; 2) lack of permanent fire protection systems and 3) conditions that can hamper firefighting operations. The latter will be addressed later in this Chapter.

The ignition hazards in a very tall building under construction differ little from those observed in other buildings under construction. As such, the ignition hazards are not considered herein. What is different is the fact that there is a great potential for many more occurrences of ignition hazards to exist, and they will be spread over a much greater area.

In a very tall building, firefighters must be inside the building to attack the fire. Firefighters may need to travel great vertical distances within the building to bring fire protection equipment and water to the fire. The vertical transportation systems may not be developed sufficiently to assist in those firefighting operations. These are the extra challenges firefighters must face in very tall buildings.

Given the large amount of stored construction and packaging materials as a normal circumstance of construction, one ignition hazard that occurs on construction sites is careless discarding of smoking materials. Smoking is prevalent on construction sites, which creates an environment having a higher likelihood for ignition and growth of a fire in a building that has little or no fire detection or suppression systems. Regular disposal of packaging materials becomes critical in the construction planning considerations.

BUILDINGS UNDER CONSTRUCTION

Construction of very tall buildings can take a number of years to complete. There can be a large number of workers in these buildings, and in some instances, workers have been domiciled within the building. With fire alarm signaling systems not yet complete, informing the construction workers within the building of emergency events is difficult. Occupant awareness of potential fire situation is likely by word of mouth or through direct-connect phones.

Planning for worker safety is usually left up to the general contractor. However, in very tall buildings, the design team will likely have to be involved in planning for and designing for fire protection systems to come on line during the course of construction, if for no other reason than to support firefighting operations that are significantly impacted during the construction of a very tall building. Providing for a protected means of egress is a significant consideration during construction, especially since other fire protection systems are not likely to be active throughout the building. Maintaining a fire rated means of egress starting two or three floors below the main line of construction provides a degree of protection to the workers.

A number of conditions will hamper firefighting operations when a fire occurs in very tall buildings under construction, and some of them can be particularly challenging. Site access is usually restricted to keep the general public from being hurt on the construction site. However, restricting site access also limits the ability of the fire department to maneuver apparatus necessary to carry equipment or pump water into the building. Proximity to the building's vertical transportation system is critical.

The availability of vertical transportation becomes even more important in very tall buildings because firefighters rely upon elevators for transportation of personnel and equipment to just below the fire floor. Overhead crane operations must also be taken into consideration when planning fire department access. It is critical to consider firefighter operational needs as the general contractor plans the projects' vertical transportation during construction.

One of the biggest challenges in fighting fires in very tall buildings is having sufficient water supply. Most fire department vehicles are capable of supplying standpipes and providing adequate pressure up to about 130 m of building height. Taller buildings must rely upon internal water storage and fire pumping systems to provide water for firefighting at higher elevations. Some fire departments in developed countries with experience with high-rise buildings have special apparatus designed specifically for very tall buildings, capable of pumping to heights higher than 130 m. That apparatus is likely to have multi-stage pumps that are capable of achieving pressures of 4,100 to 4,800 kPa. These pumpers can achieve a 700 kPa residual pressure at the top of a 365 m building for firefighting purposes. More commonly, no such apparatus is available. When such systems are employed, the pressure ratings of piping and equipment must be designed to accommodate these higher pressures.

Providing standpipes with automatic water supplies is even more complicated while the building is under construction, since some of the planned final standpipe piping and fire pumps will not yet be installed. Temporary standpipes may be employed early in the construction of a very tall building, but close coordination with local fire departments will be necessary to determine their fire pumping capability. Specific plans need to be made when buildings are to be constructed to heights exceeding the capability of the responding fire department's water pumping ability to have the fire pump systems operational. That should include having the properly protected power supply in place.

PHASED OCCUPANCY

For purposes of this Guide, phased occupancy is defined as permanently occupying part of the building prior to completing the construction of the building structure or exterior envelope. Generally, vertical construction continue when phased occupancy is used. There are higher risks associated with this type of occupancy.

More and more owners of tall buildings are realizing the economic need to phase occupancy in order to begin generating revenue to meet financial obligations. Phased occupancy has become so common that many jurisdictions have devised their own policies on what has to occur to allow phased occupancy for a project.

Phased occupancy presents higher risks for both the building occupants and the firefighters. A detailed hazard and risk analysis of the proposed phased occupancy is encouraged to address the unusual conditions that will be specific to a given project. If there is to be phased occupancy, it should be planned during the design phase. The risk analysis should be conducted as part of the overall design for phased occupancy.

One or more cranes may be attached to the building, and overhead operations are likely to continue on a daily basis. However, building occupants and firefighters need safe access for ingress and egress. Therefore, overhead protection of ingress and egress paths is necessary. Although construction operations may occur on opposite sides of the building from normal occupant access routes, overhead protection nonetheless must be provided because the need to conduct overhead operations over the access routes cannot be foreseen.

Protection from overhead is also needed for building service equipment, especially that which the fire department needs to use in fighting a fire in the building. This will include fire department connections, including paths leading thereto, and the path leading to the fire command center door. Consideration should also be given to provide protection from overhead at points and paths where the water supply pipes, power supply and communications lines enter the building. Depending on the overall height of the building and the depth of cover over these utilities, buried utilities could be damaged from construction materials inadvertently falling from the crane that can penetrate into the ground.

The part of the building that is to be permanently occupied must be essentially complete and functional. Fire protection systems, including sprinkler, standpipe, fire pumps, fire detection and alarm, smoke control, stairway pressurization, emergency power and elevator emergency operation systems within the area to be occupied must be fully functional and connected with intended integrated systems as part of the permitted phased occupancy. Therefore, the design of the fire protection systems must provide for zoning of those systems to coordinate with that part of the building which will be permanently occupied. These systems should be tested and commissioned as if there were to be no further construction. It is also advisable to perform spot checks of previously-approved systems which are subject to possible compromise during the remainder of the construction, e.g., the programming of a fire control panel can be altered after an acceptance test has been conducted in the previously-approved portion of the building.

Beyond the area to be occupied, standpipes must be available within the construction areas. Careful planning will be necessary in phasing the extension of the construction area standpipe system from permanent systems serving the occupied part of the building, especially in climates where standpipes within construction areas may be subject to freezing temperatures. Manual fire stations can be connected to the building fire alarm system, even if only temporarily so, be provided within the construction area.

A less formal variation of phased occupancy may occur during the construction of very tall buildings in that work forces may actually reside within the building while not working. Transportation vertically in the building is severely limited and can be a significant barrier to efficiently moving construction workers up and down the building. This practice is not likely to be known during design phases, but must be addressed once identified. Providing properly protected means of egress and means of communicating with the building workers is paramount, even if only temporary.

PARTIAL OCCUPANCY

For purposes of this Guide, partial occupancy will mean the incomplete occupancy of a structure wherein the only significant ongoing construction is that of tenant build-outs. This situation will occur most often in the construction of a new very tall building. It is inevitable that there will be some shell space not yet leased and therefore unoccupied.

There are no significant differences in the occurrences of shell space in very tall buildings over those that may occur in other high rise buildings. The key difference is the potential impact of a fire in one of these spaces can be greatly magnified if proper precautions are not in place. Therefore, access to these areas needs to be controlled.

Electrically supervised sprinklers should be provided for empty shell space, as they often turn into storage rooms. Any fire detection required should also be provided and functional. Risk assessments may suggest these spaces should be isolated from remaining areas on the floor by fire-resistant assemblies in an attempt to contain the fire. Finally, smoke removal systems that may be required within the building should also be functional within these spaces as well.

TENANT CHANGES

Tenancy in very tall buildings is a dynamic condition. As a result, there is a constant evolution of changes to the design, fit-out and use of stories or parts of stories within the overall building. Each and every tenant change that includes renovation of the space will impact a number of life and fire safety attributes designed for the building.

In the design phase, it is important to consider how the progression of tenant changes will affect the overall safety of the building. For instance, changes in occupancy can affect fire protection system capabilities (i.e., automatic sprinklers, smoke control, *etc.*), egress capacities (*i.e*., doors, stairways, corridors, *etc.*), and differences in fuel loading that may impact the design fires used as the basis for a performance-based fire protection design or the hazard classification basis for design of a sprinkler system.

Fire protection system impairments and increased fire hazards (*i.e*. rubbish/waste fuel loads, presence of flammable/combustible liquids, hot work, *etc.*) could increase the risk to building occupants. Depending upon the scope of the tenant renovation, it may be prudent to conduct a risk analysis to identify unusual risks to building occupants so that specific provisions to address those risks can be developed.

CHANGE OF USE/OCCUPANCY

Changes of occupancy can present a major impact to the use of an existing very tall building. The means to deal with the issue is the same as for any building, varying only in degree.

For instance, sprinkler system design densities appropriate for a previous tenant may not be sufficient when a transition occurs. Design assumptions, especially those in a performance based design, may be invalidated when fire loads or occupant loads are changed in a building. Specific types of detection and suppression may no longer be applicable when tenant changes occur. As such, tenant changes should be reviewed within the context of the building fire/life safety program as a whole.

19 Building Life Cycle Management

BUILDING OPERATIONS

Unique assembly events may incorporate the use of either flame effects or pyrotechnics. Flame effects can be used in conjunction with performers or simply to add effect to a room, while pyrotechnics may also be used on building rooftops due to the vantage points provided from very tall buildings. Both represent ignition sources that would not normally be encountered in very tall buildings and may often be coupled with ornate interior finishes. As the combination increases risks to building occupants, careful consideration should be given when pyrotechnics or exposed flames will be used.

Operations in very tall buildings need to consider any special provisions that may be associated with the facility. It is important that change control be implemented for very tall buildings where unique design features have been implemented to allow for design flexibility that may not be anticipated.

For instance, an elevator taken out of service in a very tall building may need to be addressed in a manner similar to the closing of a stair or blocking of an exit door in a normal building. Provisions may need to be implemented to limit occupant loads or instruct building occupants to potential exiting configuration changes, particularly in a situation where a majority of building floors could be impacted.

The integrity of horizontal exits and other fire-resistant separations also needs to be maintained. The simple act of routing telephone cable across these barriers may impact their integrity, yet this occurs commonly in current construction. Without proper knowledge and demarcation of these barriers, contractors or even building occupants themselves may violate the integrity of these barriers without knowledge.

If the unique safety provisions incorporated into the building's design are not documented for future building users, the very existence of these safety provisions may be lost. As renovations occur and design professionals previously associated with the building pass on, documentation should be made available to future designers.

Building personnel should be charged with a method to document potential building changes that could impact any of the various unique design provisions. These provisions are probably best communicated through a single document which summarizes fire/life safety provisions. Fire Protection Reports should include the pertinent fire protection/life safety features incorporated into the building design. These can include, but are not limited to, the following:

- Any alternate methods of construction or performance-based design provisions used in the building design, including documentation of all modeling performed.
- Passive fire-resistant provisions, including structural fire-resistance, fire-resistive separations and interior finish requirements.
- Egress system provisions, including the use of horizontal exits, phased evacuation zones, egress and exit travel distance calculations, and unique exiting configurations.

- Fire suppression system provisions, including sprinkler design densities, unusual fuel loads, special suppression systems and fire pump arrangements.
- Fire alarm system provisions, including zoning, special detection provisions, and emergency communication system configurations.
- Smoke management system provisions, including design approaches, pertinent design calculations and integration with fire suppression and detection systems.
- Emergency and standby power provisions.
- Hazardous materials.

FIRE WARDENS AND EVACUATION MANAGEMENT

Fire wardens can be both beneficial to evacuation strategies in very tall buildings. Since very tall buildings may not lend themselves to standard evacuation methods, fire wardens can provide information to building occupants during emergency scenarios as outlined in Chapter 10.

Emergency operations plans should be established for very tall buildings. Building personnel of all types have roles during emergency operations, and these roles must be outlined and practiced prior to an emergency occurrence. These personnel include, but are not limited to, the following:

- Building engineers
- Building security
- Fire wardens
- Facility first responders

Emergency operations plans can include all necessary actions required to interface with first responders. This can include shutdown of building utilities, coordination with fire wardens for evacuation, and coordination with building security for access to normally inaccessible portions of the building. Specific roles and responsibilities should be outlined, documented and imparted through regular training activities.

When implementing the assistance of fire wardens in building evacuations, it is important to consider the “human element.” Fire wardens can be sick, affected by the event itself or absent from a building during a fire event. Periodic training on the facility fire/life safety provisions and applicable evacuation methods needs to be implemented and regularly rehearsed. Additional staff should be trained in the event primary fire wardens are unable to assist during the event. Methods of communication need to be devised to allow for the implementation of such a program in the early stages of a fire evacuation.

20 Commissioning

Proper commissioning of building systems, and as related to this document, fire protection systems, is critical in very tall buildings. In general terms, commissioning is intended to verify that:

- the owner's requirements have been met
- the building has been constructed as designed
- all systems and features are functioning as intended
- the owner has been provided with the required documentation regarding the operation, inspection, testing, and maintenance of the building
- building personnel have been properly trained to operate and maintain the building.

Due to the complexity of the systems associated with very tall buildings as outlined throughout this document, the importance of proper commissioning cannot be overstated.

COMMISSIONING STARTS WITH THE DESIGN

Proper commissioning needs to be considered throughout the design process, including the conceptual design phase. One of the reasons commissioning is performed is to determine that the owner's requirements have been met. During the planning phase, the owner's requirements need to be clearly defined. In developing the owner's requirements, consideration should also be given to how the commissioning shall take place. What is the role of the design team during building commissioning? Will the installing contractors be responsible for performing the tests? How are the integrated systems to be tested and by whom? NFPA 3 recommends that there be a Fire Commissioning Agent.[108] ASHRAE Guideline 5[109] describes Commissioning of Smoke Control Systems.

To illustrate the complexity of commissioning just one fire protection feature of a very tall building, one need only consider a zoned smoke control system. The smoke control system is most likely initiated by automatic smoke detection or sprinkler water flow. Activation of the smoke control systems typically requires interface with controls for the building HVAC system. Dedicated fans and dampers specifically designed for the smoke control system may need to be activated. The building evacuation methodology may result in operation of elevators for egress purposes or the opening of doors used for egress purposes. The basis for the design of the smoke control system may assume environmental factors (temperature, wind, *etc.*) that are not the same as may be present the day the system is commissioned. How many members of the design team and how many installing contractors are involved in the above general description of one of the many systems that may be present in a very tall building? If the responsibilities for commissioning, along with the procedures to be used, are not considered early in the project, problems will likely arise as the owner tries to get the building opened and the authority having jurisdiction attempts to approve the building for occupancy.

It is common for contractors to assume some responsibility for testing the systems, features, and components that they install. However, proper commissioning of the overall system, such as the smoke control system, requires coordination and cooperation between multiple designers and contractors. There are also scheduling considerations to make sure the necessary members of the team are present when such integrated systems are commissioned. Without proper planning, the owner can anticipate additional costs and scheduling delays as the project proceeds towards completion.

During the design phase, the design teams needs to identify what features of the building or system need to be evaluated and how they are to be evaluated. In many instances, the procedures and documentation for verifying compliance with individual components and systems are covered by a code or reference standard. However, the reference standards are often limited in scope to the respective system addressed by the standard and lack proper guidance on how to perform proper commissioning of an integrated system. Therefore, the design team should also consider how each system in the building is integrated with others and determine what aspects of the integration must also be tested or evaluated. Lastly, the design team needs to develop athe commissioning process that provides the necessary information for the ongoing periodic inspection, testing, and maintenance of the building.

The assumptions made during the performance based design, or as part of an equivalency, need to be properly documented by the design team so they can be evaluated during useful life of the building. These assumptions and the resulting inspection, testing, and maintenance requirements need to be properly documented as part of the operations and maintenance manual for the building.

The information necessary for proper commissioning, as well as the information needed by the owner for the life of the building, will often be included in a "Basis of Design" document. This should be included in the documentation provided to the owner at the completion of the project.

COMMISSIONING AND THE CONSTRUCTION PHASE

Although it is often misunderstood that the commissioning happens at the end of the construction phase, there are aspects of commissioning that need to occur throughout the construction process. Certain aspects of both active and passive fire protection features can only be confirmed during the construction phase, without resulting in additional costs, destructive testing/investigation, or project delays.

Access to evaluate through-penetration fire-stop systems, the construction of a fire resistant assembly, and to confirm the type of sprinkler pipe that is installed may not be available after construction is complete.

The design documents, particularly the commissioning documents, should clearly identify what aspects of the commissioning process needs to occur at various phases of construction. Some party, possibly the general contractor or the Fire Commissioning Agent, should monitor the progress of construction and determine that all commissioning activities occur according the schedule. In addition, all changes made to the original design documents or to the construction schedule need to be evaluated to determine if they affect the commissioning plan.

Another aspect of commissioning during the construction phase is the development of the documentation for the owner, specifically record ("as-built") drawings. If an owner is to be provided with accurate record drawings, contractors need to constantly update the drawings with the information, changes, and modifications that occur. Failing to do so, and waiting until construction is complete typically results in poorly prepared and inaccurate drawings, and subsequent delays in the commissioning of the building and systems therein.

In very tall buildings, this activity can be compounded by the fact that construction and occupancy of the building may take place in phases. The commissioning plan needs to take this into account, not only to provide proper protection of the occupants who may be located in the areas of the building in which construction is complete, but to also allow for the ongoing commissioning of building features and systems as the construction progresses in other areas of the building.

COMMISSIONING PRIOR TO OCCUPANCY

While commissioning starts in the planning phase and continues throughout design and construction, a major part of commissioning will occur just prior to occupancy. This includes testing and evaluation of the installed systems and building features. Documentation should be submitted that will allow the owner to proper occupy, inspect, test, and maintain the building systems and features throughout the life of the building.

In buildings using risk assessments and performance-based design approaches, the documentation associated with those methodologies must be part of the material provided to the owner. The bounding conditions and assumptions must be understood and documented so that they continue to be met throughout the life of the building.

21 Inspection, Testing and Maintenance

INTRODUCTION

The performance of a tall building as a system will depend on the reliability and performance of the systems components. In this regard, a program of routine system inspections, testing and maintenance (ITM) will be directly correlated to its reliability.

Chapter 6 of this Guide addresses how fire protection system reliability becomes part of the overall reduction in risk to an acceptable threshold. ITM programs can discover problems in a system that could result in a failure. By correcting such problems, system failure rates will decrease, thereby increasing the overall reliability of a fire protection system.

In addition to fire protection systems, other components of fire safety design should be inspected and maintained to achieve the goals and objectives of the fire protection engineer. These components include fire resistant construction, egress and exiting systems, changes in occupancy or fuel load, and additional electrical loads. The occupants of very tall buildings would be vulnerable to hazards from fire, earthquake or other man-made and natural disasters if critical life safety components are not maintained and kept in service.

For a system to be deemed reliable, it must function as originally designed. This is based on the design goals and objectives of the stakeholders but, for very tall buildings, would generally be based on the following objectives: (1) provide life safety, (2) conserve property/limit property damage, and (3) provide continuity of the critical mission functions of a facility. The reliability of a system is the combination of the reliability of multiple components including system design, installation, equipment and operational maintenance. Reliability is a function of statistical probability and can be calculated following the Lusser Product Law, which is calculated through the product of individual component's reliability.[39, 110, 111] This becomes a very important design parameter to consider in performance based fire safety design, where a particular reliability is assumed in the fire risk assessment.

Life cycle costs should be considered when determining the appropriate measures to be implemented into an ITM program. Life cycle costs are generally incurred through the inspection, testing and maintenance (ITM) process for fire protection systems, particularly in large structures like tall buildings. These life cycle costs are typically offset by the increased reliability of fire protection systems. This is especially critical in very tall buildings where interdependence on these systems is necessary for life safety.

Consideration should be given to performing a life-cycle cost analysis to determine total costs associated with building operation during the life of the building.[112] The rate of return for these savings can be calculated to determine the total cost savings provided through an ITM program.[36]

OPERATIONS & MAINTENANCE MANUAL

An Operations and Maintenance (O&M) manual is a tool for the building owner, the construction installers, and to the facility staff to operate and maintain the systems present in a tall building. While an O&M manual is necessary for buildings designed with a performance-based approach to properly document the design basis, it will also become invaluable through the life cycle of the building.

It will serve as the basis for the ITM program in tall buildings, as well as prescribing boundary conditions and restrictions related to occupancy, fire protection system design and fuel loading. [17] While traditional construction procedures often leave much of the O&M manual production to the system installers, it is important in tall building design for the fire protection engineer to be involved in the process of documenting the parameters related to fire protection systems. The engineer's insight into the design basis and boundary limitations may not be readily apparent to the installing contractors, which could in turn inadvertently leave important facets and operation and maintenance missing from this document.

Because most tall-building designs will employ at least some approaches in performance-based design, it is useful to have an O&M manual available to the owner/tenant, building maintenance engineers, AHJs and other stakeholders. Templates are available for writing O&M manuals for fire protection systems. It is also important for the O&M manual to cover changes that would affect the design basis parameters. It is difficult to maintain the design criteria for tall buildings unless the O&M manual is available and kept current. .

CODES AND STANDARDS

Requirements for Inspection, Testing and Maintenance that will provide overall fire safety in very tall building design begins with an examination of building codes and standards, as well as insurance considerations applicable to maintaining fire protection system reliability. The use of a particular code or standard is often determined by the requirements of the sovereign nation or entity where the building is to be constructed. However, in some developing nations, there may not be standards regulated by law, but there will most likely be a requirement from the building owner or insurer to comply with certain codes and standards.

The fire protection engineer for tall building design should also be familiar with performance-based test and inspection methods that will help to achieve the design goals and objectives. .

In many performance-based design approaches, fire protection systems are pushed more to their operational limits. As a result, reliability becomes even more critical function for the fire protection engineer to consider. In tall building design, the engineer may determine that ITM schedules in excess of what would be required by the applicable local codes and standards may be necessary to better address the overall building system reliability.

Impairments to fire protection systems will likely occur during the life cycle of the building. So, it is important to consider a program for impairments – both for those planned impairments during building alterations and modernizations, as well as the unplanned or emergency impairments that are likely to occur. The Operations and Maintenance Manual (O&M manual) should include impairment procedures to verify system performance and reliability during building construction changes and emergency situations.

The qualifications for ITM program personnel/contractors are important to consider in implementing a proper maintenance program. While codes and standards typically indicate the need for such persons to be qualified, standards do not typically specify the training programs, education, certification or licensure to qualify a particular person to perform inspection, testing and maintenance. In development of the O&M manual, the user should refer to particular certification and licensure programs relevant to the system demands.

AHJ INSPECTIONS

The Authority Having Jurisdiction (AHJ) may play a role in ITM programs. A regular inspection program has been documented to reduce property damage and casualties in buildings where regular inspections were performed.[113] Thus, very tall buildings will benefit from regular inspections to verify ITM programs, abate noted hazards to fire and life safety, and maintain fire and life safety system reliability.

The AHJ can take many roles, but is generally part of a municipality or insurance interest. AHJ inspections typically take on the role of fire prevention inspections, property maintenance inspections, or risk evaluations in the case of insurance interests. The user of this document is advised to refer to the local codes and standards in effect for the jurisdiction in question. These various codes and standards are typically used in conjunction with other local building codes to address risks from inadequate maintenance.

The aspects of performance-based design implemented into tall building designs must be maintained, so it becomes critical for the engineer to consider maintenance inspections throughout the life of the building. In development of the Operations and Maintenance (O&M) manual, the fire protection engineer must consider the role of municipal or other insurance inspections, as well as the frequency, qualifications, fee structure and even methods for employing third-parties independent of the AHJ for inspection purposes. The O&M manual will also prove to be invaluable insight to the AHJ in understanding the boundary limitations of the tall building design so that appropriate requirements will be applied.

Appendix - Recommended Readings

History

World Trade Center Building Performance Study, FEMA 403
NIST NCSTAR 1: Federal Building and Fire Safety Investigation of the World Trade Center Disaster: Final Report of the National Construction Safety Team on the Collapses of the World Trade Center Tower
NFPA *Life Safety Code,* NFPA 101
International Performance Code
SFPE *Guide to Performance-Based Fire Protection.*

Hazard, Risk and Decision Analysis in Very Tall Building Design

SFPE Engineering Guide to Performance-Based Fire Protection
SFPE Engineering Guide to Fire Risk Assessment
SFPE Handbook of Fire Protection Engineering
FEMA 426, 2003
Meacham and Johann, 2006
Meacham and Galioto, 2008

Suppression

NFPA 13 – *Standard for the Installation of Sprinkler Systems*
NFPA 14 – *Standard for the Installation of Standpipe and Hose Systems*
NFPA 20 – *Standard for the Installation of Stationary Pumps for Fire Protection*
NFPA 22 – *Standard for Water Tanks for Private Fire Protection*
NFPA 24 – *Standard for the Installation of Private Fire Service Mains and Their Appurtenances*
NFPA 70 – *National Electrical Code*
NFPA 72 – *National Fire Alarm and Signaling Code*

BS EN 12845, Fixed firefighting systems
BS 5839, Fire Detection & Alarm systems

Designer's Guide to Automatic Sprinkler Systems, *Robert M. Gagnon*
Design of Special Hazards and Fire Alarm Systems, *Robert M. Gagnon*
National Fire Alarm and Signaling Code Handbook
Automatic Sprinkler Systems Handbook
Handbook for Stationary Fire Pumps

Emergency & Standby Power, IEEE Orange Book – Standard 446-1998
Power Systems Reliability, IEEE Gold Book – Standard 493-1997

Buildings Under Construction

NFPA 241

Building Life Cycle Management

NFPA 160 – *Standard for the Use of Flame Effects before an Audience*
NFPA 1126 – *Standard for the Use of Pyrotechnics before a Proximate Audience*

Commissioning

NFPA 3
ASHRAE Guideline 1.5
ULC-S1001, Standard for Integrated Systems Testing of Fire Protection and Life Safety Systems

Inspection, Testing and Maintenance
International Fire Code
International Property Maintenance Code
NFPA 1, Fire Code
NFPA 25, Standard for Inspection, Testing and Maintenance of Water Based Fire Protection Systems
NFPA 72, National Fire Alarm Code
AS1851, Maintenance of Fire Protection Systems and Equipment
CEN/TC 191 – Fixed firefighting systems
Fire Prevention Law of the People's Republic of China
GB 50261, Automatic Sprinkler and Standpipe System Installation and Commissioning
GB50166, Automatic Fire Alarm and Detection System Installation and Commissioning
The Fire Service Law
National Fire Code of Canada
England/Wales Building Regulations, Part B (Fire Safety Regulations)
BS EN 12845, Fixed firefighting systems
BS 5839, Fire Detection & Alarm systems
Code of Practice for Inspection, Testing and Maintenance of Installations and Equipment, Fire Services Department

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