Design of Occupant Egress Systems for Tall Buildings

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ABSTRACT

This paper presents a discussion of the features of protected elevator systems that can provide safe and reliable operation both for fire service access and for occupant egress during fires. These features include water tolerant components, fail-safe power, lobbies on each floor designed as areas of refuge, smoke protection, occupant communications, and real time monitoring of the elevator position and operating conditions from the fire command center. Egress simulations are used to quantify the improvements in efficiency that can be realized by incorporating elevators into the access and egress procedures for tall buildings. Finally, operational procedures will be discussed for the most appropriate use of vertically zoned elevator systems that are found in most tall buildings. These procedures would form the basis for the elevator control software that needs to be developed for such systems.

INTRODUCTION

The unexpected collapse of the World Trade Center buildings has prompted a re-examination of the way egress systems are designed for tall buildings. Current designs specify a certain number, width, and spacing of stairs that depend upon the assumed occupant load and building use. The egress system at each floor is sized for the number of occupants on that floor, reflecting the assumption that tall buildings will be evacuated by partial or phased evacuation procedures. In the discussion of the need to design for simultaneous evacuation of tall buildings, concerns have been raised about the adequacy of relying solely on stairs to move large numbers of people from significant heights.

These discussions naturally turn to whether the elevators that normally provide vertical transportation can be designed to supplement the stairways and provide a safe exit route during fires. It is speculated that if future buildings were required to be designed for simultaneous evacuation under current egress design practices, there will be a building height beyond which the stairs would occupy such a large portion of the floor area that such buildings would be impractical. Despite a 30-year policy in the U.S. codes against the use of elevators in fires, many experts now feel that elevators can be made safe for occupant egress. Some of the relevant research was done in the 1980s by NIST in support of egress elevators in air traffic control towers[1,2] where the small footprint prohibits the provision of two, remote stairs. NIST is once again working with the U.S. codes and standards organizations and the affected industries to address any remaining technical issues and to develop performance requirements for elevator egress systems. This paper presents a discussion of the features of protected elevator systems that can provide safe and reliable operation both for fire service access and for occupant egress during fires.

CURRENT REQUIREMENTS FOR EMERGENCY USE OF ELEVATORS

All U.S. building codes contain a requirement for accessible elevators as a part of the means of egress in any building with an accessible floor above the third floor. These

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requirements are all identical, being extracted from the ADA Accessibility Guidelines (ADAAG) and mandated under the Americans with Disabilities Act (ADA).

A recent survey[3] by the International Organization for Standardization (ISO) TC178 Committee identified at least twelve countries that require firefighter lifts in tall buildings (generally those exceeding 30 m (98 ft) in height) to provide for fire department access and to support operations as well as to evacuate people with disabilities. England has such a requirement supported by a British Standard (BS 5588 Part 5)[4] requiring firefighter lifts in buildings exceeding 18 m (60 ft) in height. Firefighter lifts are also provided in the Petronas Towers, the world's tallest buildings in Kuala Lumpur, Malaysia.

The NFPA's Life Safety Code (NFPA 101)[5] includes provisions for egress elevators to be provided as a secondary means of egress for air traffic control towers where the small footprint prohibits two, "remote" stairs. However, these are secure facilities not open to the public and with limited numbers of occupants.

While the above requirements exist for elevators for emergency use by firefighters and people with disabilities, there are currently no codes or standards in the world for egress elevators for use by general building occupants. Since 1973, ASME A17.1, the Safety Code for Elevators and Escalators[6], has contained emergency procedures that take the elevators out of service if smoke is detected in any lobby, in the elevator machine room, or hoistway. Under this condition the elevators are directed immediately to the ground floor where the doors open and the elevators are locked out (called Phase I recall). Subsequently, the responding fire department can reactivate individual cars under manual control using a special key (called Phase II operation).

Several issues concerning elevator use in emergencies, such as equipment reliability, communication, control, human behavior, and operational procedures, need to be addressed before this mode of vertical transportation can be implemented.

FEATURES OF PROTECTED ELEVATORS

Safe and Reliable Equipment[7,8]

If used in an emergency, an elevator needs to be able to withstand the problems associated with heat, smoke, and water from a fire. It is important to address issues of water tolerant elevator parts, fail-safe power, enclosed lobbies on all floors, and smoke protection of the equipment, hoistway, and lobby.

Because water can come from many different sources, such as sprinkler systems and fire fighting operations, the elevator must be equipped with water tolerant components. Water can possibly enter in an elevator shaft and short out safety components such as switches that prevent the doors from opening unless there is a car present, and even compromise the safety brake. Elevators can be designed to operate on the outside of buildings, so it is clear that water-tolerant technology is available and used today.

Another reliability issue is emergency power for the elevators if the main power fails. Current codes require at least one elevator that serves every floor to be provided with emergency power. If the power and control wiring is installed within the hoistway the elevator would continue to operate as long as the hoistway was intact.

To protect occupants from the fire while awaiting the elevator and provide an area of refuge for people with disabilities, enclosed lobbies should be provided on each floor of the building. The lobby also protects the hoistway from direct exposure to the fire and smoke that might threaten the elevator car moving past the floor of the fire. These lobbies would require at least 1 hour fire rated, smoke tight enclosures (assuming a fully-sprinklered building).

Elevators would be installed in a smokeproof shaft constructed to a 1 hour fire resistance and pressurized against smoke infiltration. This would prevent smoke and heat from moving through the building via the shafts. The elevator lobby would be pressurized to protect it from smoke and to minimize pressure differences across the hoistway door that can jam the door mechanism.

Emergency communication[7,8]

Occupants and firefighters can communicate with the Fire Command Station via two systems, the emergency phone in the elevator car and a two-way voice communication system provided in the lobby. This allows the occupants in the lobby to remain informed of the status of any impending rescue. Further it allows the fire command personnel to understand the number and situation of the occupants on each floor waiting for the elevators.

Control

The firefighter manually operating the elevator (Phase II operation) knows little about the fire conditions in other parts of the building, especially the conditions in the elevator machine room to which the controller is exposed. Using the newly developed fire service interface[9,10] it is possible to provide real-time monitoring of elevator system status and any conditions that may threaten its continued safe operation. This interface was developed as a tool for incident management that can collect information from its own sensors and other building systems (through a common communication protocol such as BACnet) and display the information in a format common to all manufacturers' systems. The interface further supports specific control functions so that the operator could manually initiate recall if any monitored parameters exceed the allowable operating envelope.

Because continuous monitoring of the system is crucial to safe and reliable operation it would employ a triple redundant communication pathway. The fire alarm system is currently required to incorporate two, redundant communication trunks usually run up the two stairways. Either trunk is sufficient for the full system operation and two-way communication to the entire building. While these trunks are "remote" it is possible that a single event could sever both trunks, rendering the portion of the system above the breaks inoperable. By providing a third wireless link between the bottom (generally the fire command center) and the top of the system, this should maintain full operation of the system if both trunks fail. This would add little cost, high reliability, and can be done with current technology. Emergency power could be supplied by conductors run up the hoistway, so that power is available as long as the hoistway is intact.

EGRESS SIMULATIONS

In order to quantify the increase in efficiency of fire department access and egress via elevators, two studies were performed. The first involves fire department access to a fire floor in a high-rise building. The fire department access times using elevators were compared with access times using stairs. The second case study reviews work done at NIST in the early 90s to show the benefit of elevators for egress in four GSA buildings[11].

Firefighter Lift Case Study

For this case study, the commercial building used was designed by a Dallas architectural firm and stretches 40 stories above ground with 4 parking levels below. A typical floor of the building contains approximately 3000 m^2 (32,292 ft^2) of floor space, with 500 m^2 (5382 ft^2)

occupied by the core space. The core contains elevators, 2 stairwells, bathrooms, and mechanical closets.

The stairs are located diagonally across the core area from each other, each measuring 1.2 m (44 in) wide with 26 7/11 steps per flight. The 7/11 terminology refers the height of the riser followed by the depth of the tread in inches, meaning that for each step, the riser height is 0.18 m (7 in) and the tread width is 0.28 m (11 in). The height of each floor is 4.5 m (15 ft), creating a travel distance of 11 m (36 ft) per flight of stairs, including the landing distance.

The elevators for a commercial building are assumed to have a speed of 5.08 m/s (1000 ft/min), per Table 10.7 of the Vertical Transportation Handbook[12], and average acceleration of 1.5 m/s^2 ($5\ ft/s^2$). For this case study, it is also assumed that a crew of 5 firefighters and their equipment will be traveling in the elevator and stairs together at one time. There are other characteristics that were assumed for the elevators that only affect the outcome of this case study in a trivial manner, such as the full car load, type of door, the door inefficiency, and door closing time.

For this case study, the fire originates on the 35th floor. Two groups of five firefighters are analyzed in their attempts to reach floor 35. Group 1 traverses 34 flights of stairs from street level to floor 35. Group 2 takes the elevators to the 33rd floor and travels the stairs an additional 2 flights. Hand calculations were made for firefighter travel up the stairs, while hand calculations and the ELVAC model were used to calculate the one-way elevator travel time from the lobby to the 33rd floor. ELVAC is a model used to calculate gross elevator evacuation time from buildings, and the hand calculated one-way elevator travel time was used to compare to ELVAC results.

The travel times calculated for both Groups in this case study neglect firefighter response time to the building, travel to the elevator or stairs from the building entrance, and time spent on the floor locating the point of attack, since both need to perform these activities in a fire situation.

To obtain firefighter travel speeds on stairs and horizontal building components, adjustments were made to data already recorded from people movement studies[13,14,15]. Frantzich's data show a range of velocities for upstairs movement from (0.5 to 0.75) m/s, Fruin gives values of (0.5 to 0.65) m/s and Predtechenskii and Milinskii state a range of (0.33 to 0.92) m/s for low density situations. On one hand, these values may be low if studied during nonemergency situations, but alternatively, firefighters are typically equipped with heavy gear and equipment, on the order of 25 to 45 kg per firefighter, which should be accounted for.

The primary walking speed used in this case study for firefighter travel up stairs is 0.35 m/s (adjusted from 0.5 m/s[13,14,15] for heavy gear). Another velocity used came from the New York Fire Department's rule of thumb that states firefighters average 60 seconds per floor (unobstructed flow), which is not sustainable throughout the ascent of high-rise buildings. 60 seconds per floor will be used as the conservative ascent time and 0.35 m/s will be used as the other extreme. For horizontal building component speed, again the standard value of 1.2 m/s[16] was adjusted to a conservative value of 0.8 m/s for gear and heavy equipment.

The breakdown of the elevator calculations are as follows (multiple values indicate a range of travel speeds for that calculation):

Group 1:

- The time to traverse 34 flights of stairs = 17 min at 0.35 m/s; 34 min at 60 seconds per flight (more conservative)

Group 2:

- The one way travel time of the elevator from the lobby to the 33rd floor = 45 s with 5.08 m/s elevator speed

- The horizontal travel time from the elevator to the stairs on the 33rd floor = 30 s at 1.2 m/s; 45 s at 0.8 m/s (more conservative)
- The time to traverse two flights of stairs = 60 s at 0.35 m/s; 120 s at 60 seconds per flight (more conservative)

After performing an additional calculation of adding the elevator travel, horizontal travel, and stair travel times together for Group 2, the results are as follows:

- Group 1: 17 to 34 min
- Group 2: 2.5 to 3.5 min

It may seem obvious that an elevator would give some advantage in speed over stair use. But, when other factors, such as heavy gear and equipment and increased elevator technology play a role, elevators substantially become a more viable and constructive option. The difference between use of stairs (Group 1) and elevators (Group 2) for firefighter ascent ranged between (15 and 30) min. This is a large difference in time lost to travel by stair, especially when a fire can grow significantly in a matter of minutes. By using elevators as the primary means of ascent, Group 2 was able to reach the fire at least 15 min earlier in this case study. In 15 min, the environment can be less toxic for the occupants, the fire smaller, and the property less damaged. Also, Group 2 would have more energy to exert on fire fighting activities on the floor, when compared to Group 1. The limitation associated with the calculations was the estimation made in the firefighter movement speed, as shown by the range of results in both Groups.

Elevator Evacuation Study

In the early 90s, four General Services Administration (GSA) buildings were analyzed as potential applications to incorporate elevator evacuation[11]. The four selected were chosen to gather different building heights, elevator capabilities, and architectural characteristics.

For each building, evacuation times were calculated for the following conditions: 1) Total evacuation of the building by stairs only; 2) Total evacuation of the building by elevators only; and 3) Total evacuation of the building by various distributions of occupants to stairs and elevators (the optimal time value is shown in Table 1).

For the stair calculations, Klote et al.[11] used the people movement methodology laid out by Nelson and MacLennan[17]. For these calculations, people on each floor were assumed to be waiting at the door to the stairs as soon as evacuation begins. For the elevator calculations, the ELVAC model[18] was used which simulates 2-stop elevator trips (movement occurs only between the specific floor and the ground floor) until the entire building has been evacuated. Again, for these calculations, people were assumed to be waiting at the closest elevator lobbies as soon as evacuation began.

Table 1 shows the characteristics of each building, including the number of floors, the number of stairs and elevators used, and the total population of each building. Also, the table shows the total evacuation time of the building (minutes) if only stairs were used, the total evacuation time if only the elevators were used, and the last column shows the optimal (fastest) gross evacuation time when a combination of stairs and elevators are used. Additionally, the Hoffman building and the White Flint North Building's analysis did not use the full capacity of elevators available to the building. The Hoffman building used 5 out of the 6 elevators in each group and the White Flint building used 4 out of the 6. This was due to the fact that the existing elevator lobbies were incapable of holding as many people as would be discharged from all elevators simultaneously, and in that case, the evacuation capacity of the elevators is restricted by the size of the lobby.

Table 1 **Summary of GSA buildings and modeling results**

Building	Floors	Stairs/ Elevators	Total Population	Evac. Time by Stairs	Evac. Time by Elevators	Optimal Time by Both
Hoffman	13	2/ 2 groups of 5	3506	14.9 min	24.3 min	11.2 min
White Flint	18	2/ 1 group of 4	1425	14.3	28.6	12.0
Jackson	36	2/ 3 rises of 6	3021	23.1	16.5	12.8
GSA	7	6/ 6 groups of 2	3621	7	17	6.3

In each of the four buildings analyzed, the optimal time was reached by designing for a combination of floors or percentage of the floor dedicated to elevator usage while the other portion of the building evacuated by stairs. The use of elevators for evacuation made the largest contribution for the tallest building, which was the Jackson Federal building equipped with low, mid, and high rise elevators. The elevator designation that provided the optimal result for this building was the following: 65 % of occupants from the mid and high rise floors, all occupants from floors 11 through 14, and only 3 % on floors 1 through 13. All others in the Jackson building used the stairs. Even though the percentage distributions of occupants to stairs or elevators are quite detailed and complicated in this example, they are presented in order to show the generality that more occupants from the higher floors would use the elevator and more occupants from the lower floors would be distributed to the stairs. In an actual evacuation plan, the distribution of occupants to certain building components (stairs or elevators) should be more straightforward and easy to follow.

For the single rise elevator systems in the Hoffman, White Flint, and GSA buildings, the elevator designation that provided the optimal result was for total elevator evacuation from the upper floors of the building and stairs from the lower floors. Overall, it was shown that by using a combination of evacuation systems, stairs and elevators, the total evacuation time of the building can be reduced by a substantial amount with taller buildings. This study is limited by the averaged movement calculations used, and the assumption that all occupants were waiting at the stair or elevator lobbies as soon as the evacuation began. Also, another limitation is that occupants were not studied using both stairs and elevators during a single evacuation route.

OPERATIONAL PROCEDURES

Prior research and recent advances can address all of the technology issues identified as critical to the safe and reliable operation of elevators during fires. The remaining piece is the development of operating procedures for firefighter access, occupant egress, and rescue of the disabled that are sensitive to human factors issues and the need for these activities to occur simultaneously in tall buildings. Thus, the systems must be designed and used such that they do not interfere with all three uses.

Firefighter Lifts

Many US fire departments, Phoenix Fire Department for example[19], have adopted operating procedures for fires in tall buildings that incorporate elevator access that are similar to those described in a draft CEN/ISO[20] standard for firefighter lifts. The primary differences relate to the fact that most firefighter lifts are dedicated to this use and thus are immediately available to the fire service on their arrival. In the US, firefighters use passenger elevators that are either still operating or are waiting at the ground floor in Phase 1 recall.

The procedure is for the firefighters to use the lift to transport people and equipment to the protected lobby 2-3 floors below the fire floor where they stage for their suppression operations, as discussed earlier in the firefighter lift case study. The firefighters then move up the stairway to the fire floor with a standard length of hose (30 m (98 ft) is common in the US and 60 m (197 ft) in Europe), which is connected to the standpipe located in the stairs. This is important because once charged with water the hose becomes very stiff. The hose is usually looped down the stairs and back up so that it can be advanced onto the fire floor more easily. Working from the stairway also provides a protected area to which the firefighters can retreat in case the fire threatens them. The common hose lengths dictate the distribution of firefighter lifts within a building in the same way as the distribution of standpipes. For example, the New York City building regulations require standpipes located so that one is within 38 m (125 ft) (30.5 m (100 ft) of hose plus 7.6 m (25 ft) of water throw from the nozzle) of any point on a floor.

This operating procedure highlights the importance and interrelationship of the firefighter lift, protected lobbies, associated stairway and standpipe. These components form a system described in BS5588[2] as a *firefighting shaft*. The need for an associated stairway impacts on the arrangement of the components and on the designation of multiple cars of an elevator group as firefighter lifts.

Occupant Egress Elevators

As mentioned earlier, with only rare exceptions for special cases, elevators are taken out of service in fires and people are advised not to use elevators during fires. This policy does not represent a severe hardship for most buildings and occupants, but poses problems for people with (mobility) disabilities and for tall buildings where stairway egress times can be measured in hours. Coupled with the recent loss of public confidence in the structural stability of tall buildings caused by the collapse of the World Trade Center, there are increasing pressures to find ways in which elevator assisted egress can be provided safely.

Operational procedures for occupant egress elevators raise some interesting issues. First, the 30-year campaign cautioning the public against the use of elevators in the event of fire could severely lessen the occupants' confidence in the elevator system. Also, occupants could become impatient and overcrowd the elevator, which can cause the car to stop functioning and remain at the floor indefinitely[21]. Due to a fundamental lack of understanding of human use of elevators in emergencies, the time for which occupants will wait at an elevator is also unknown. Without proper preparation and training, occupants may become fearful of the dangerous conditions and decide to use the stairs. If the building is designed for a certain distribution of occupants between stairs and elevators, this could cause congestion in the stairway. It seems natural to suggest that fire wardens, who understand the capabilities of elevators in such emergencies, will lead the occupants to safety by following the planned evacuation procedure for their floor. The evacuation plan of a single rise elevator system could involve, for example, the use of elevator by the higher floors of the building, stairs by the lower floors, and the fire wardens on each floor directing his/her occupants to the correct evacuation route[11]. However, this implies that the fire wardens are present at the time of the emergency, have the appropriate training, and that the other occupants will follow their directions. Another concern for the evacuation procedures is whether or not the elevators attend to the disabled population first before evacuating other building occupants. This is crucial to understand because if a disabled occupant resides on a floor designated to take the stairs, the building should be aware of the occupant's needs and plan accordingly. Overall, it will be essential to understand the human behavior of the occupants during their interaction with the elevators. Work has been done in the human factors engineering and psychology fields about such a concern[22,23,24], but much more work still needs to be completed to update current elevator use and concerns in light of September 11, 2001. For instance, will social groups within the building stay together throughout the duration of the evacuation, or will they allow group break-up during elevator descent? This is crucial because of the possibility of sending elevators without full capacity to the ground floor.

Egress elevators are most likely to be utilized in tall buildings, some with systems that are vertically zoned in 30- to 40-floor sections. A concern for these tall buildings is how elevator evacuation would be operated with vertically zoned elevators. One example where this is being done is for an 88-story building currently under construction in Melbourne, Australia[25]. In the

Eureka Place Tower, elevators in the vertical third of the building containing the fire are taken out of service and occupants all use the stairways to the next (lower) transfer floor where they board express elevators to grade. People with disabilities are assisted by firefighters in their dedicated lifts within the zone of origin in order to evacuate the building. This strategy is similar to the Petronas Towers where occupants above the sky bridge level use stairs to that level, move across to the other tower, and use the elevators to grade.

Egress Assistance for People with Disabilities[26]

Standards for firefighter lifts all include their use by firefighters to provide evacuation assistance for people with disabilities. Even in the US where there are no firefighter lift standards the building codes require *accessible elevators* (part of an accessible means of egress) that may be used by the fire service to evacuate people with disabilities. These elevators are normally used for travel in nonemergency situations, but may be used by the fire service for disabled occupant egress if an emergency occurs. The procedures generally are that such occupants proceed to the protected lobby (sometimes called an area of refuge) and request evacuation assistance through a two-way communication system (to the fire command center) provided. Exceptions are provided for fully sprinklered buildings.

Not covered is any procedure for coordinating the use of the lift for evacuation assistance with that of firefighting. First priority will be given to moving firefighters and equipment to the staging floor to allow the start of suppression operations. Then a firefighter would presumably be assigned to begin to collect waiting occupants in the lift under manual control. Command staff in the fire command center could inform the operator on which floors there are occupants waiting and these could be gathered in some logical order and taken to the ground floor. If there are more occupants than can be assisted in a single trip, there is a question about the order in which they are removed. Presumably, this would be done for the floors nearest the fire first, then above the fire and finally below the fire. Because these people are required to wait, it is especially important to provide this two-way communication system to the lobby so that they can be reassured that assistance is coming. The real-time monitoring system described earlier would assure that conditions in the occupied lobbies remain tenable.

CONCLUSION

Elevator use in emergency situations can provide safe and reliable operation both for fire service access and for occupant egress. A combination of reliable features, appropriate equipment, and effective operational procedures allows for successful evacuation of buildings via elevators and stairwells.

During a fire situation, the elevator needs to be able to withstand the effects of smoke, heat, and water. The current elevator technology can successfully perform this duty with the inclusion of water tolerant elevator parts, fail-safe power, lobbies of all floors, and smoke protection of the equipment, shaft, and lobby. Also, to aid in the use of elevators for fire department access and occupant egress, the use of emergency communication and remote manual control accompanied by continuous monitoring of the fire situation add another level of safety to elevator use. The Fire Command Station is continuously made aware of the increasing danger to occupants and the firefighters, and can change their evacuation, rescue, and firefighting strategies accordingly.

Elevators can make a significant time saving contribution to travel towards the fire for the fire service and the evacuation of the occupants in the building. The calculations done for the firefighter case study showed that firefighters traveled to the fire floor 15 min to 30 min faster via elevators when compared to stair access. The stair travel calculation, using two different estimates for the firefighter walking speeds, resulted in a range of travel time values differing by a factor of two. Research is needed in the area of firefighter movement to assess which travel times within the calculated range 17 min to 34 min are more accurate. Also, the evacuation time of occupants using a combination of stair calculations and ELVAC calculations for the elevators shows improvement over stair or elevator movement alone for the GSA examples studied. This is especially true for the taller building with multi-rise elevators.

Lastly, operational procedures are crucial in ensuring quick movement to safety for all occupants and emergency responders in the building. It is key for the occupants to recognize their main mode of travel (elevator or stairs) and understand the wait times associated. As part of this, other occupants may have priority, such as the disabled.

With all elements in place, safe and reliable features, operational procedures, and comfort in using elevators by occupants and firefighters, the use of elevators can provide a faster and safer route for evacuating a high-rise building.

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