THE BASIS FOR EGRESS PROVISIONS IN U.S. BUILDING CODES

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ABSTRACT

Some of the earliest public safety-from-fire regulations in the US are requirements for egress stairs adopted by New York City in 1860[1]. One of the first model regulations promulgated by the National Fire Protection Association (NFPA) was the 1927 Building Exits Code, predecessor of the Life Safety Code. Thus the need to move occupants out of harms' way in building fires has long been central to fire safety regulations.

The need to move occupants to a safe place was underscored in numerous historical fire disasters. Locked exits contributed to the high number of fatalities (150) in the 1911 Triangle Shirtwaist Factory fire and exit doors that opened inwards blocked by crowds was cited in the 492 fatalities of the Cocoanut Grove fire (1942)[2]. Incidents like these resulted in public outcry for stronger code provisions but even today egress problems leading to high numbers of deaths persist. The 100 fatalities at the Station Club in Rhode Island in 2003 provide the most recent example. Since the Rhode Island fire, NFPA and other code authorities are reviewing current requirements for level of safety, especially for assembly spaces.

These current prescriptive codes used for building design contain a list of egress specifications depending upon certain aspects of the building, such as the type of occupancy, the configuration of the space, the presence of sprinklers, and the type of construction of the building. These code specifications aid the designer in providing a certain level of life safety for their building, but little effort has been put into quantifying this level of life safety in terms of egress times.

This paper attempts to describe the prescriptive design process for specific types of buildings. Secondly, by applying some assumptions to the egress specifications listed in the codes, an estimate of resulting egress times for maximum occupant loads were performed for specific occupancies. The egress times were obtained using multiple calculation methods and include estimates of pre-movement time, time to exit the occupied room, and time spent to travel one flight of stairs. Lastly, additional egress issues, such as merging flows and the use of elevators for occupant egress, are discussed.

History of Egress Provisions in Regulations

Some of the earliest public safety-from-fire regulations in the US are requirements for egress stairs adopted by New York City in 1860[1]. One of the first model regulations promulgated by the National Fire Protection Association (NFPA) was the 1927 Building Exits Code, predecessor of the Life Safety Code. Thus the need to move occupants out of harms' way in building fires has long been central to fire safety regulations.

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Basic Principles of Egress Safety

The basic concept of occupant egress implemented in building regulations involves the provision of a properly designed *means of egress* that is continuous and unobstructed from any point in the building to the outside. Proper design includes the width of the spaces and doors, direction of door swing, lighting and marking, protection from the fire and its effects, and geometry of stairs or ramps, among others. Limits on travel distances to reach a means of egress and on common paths of travel, dead ends, and the provision of alternate means of egress if the primary path is blocked by fire are also basic concepts of egress design.

The means of egress described in building regulation consists of three parts. The *exit access* is the corridor, aisle, balcony, gallery, room, porch, or portion of a roof over which an occupant must travel to reach the exit. The *exit* is a door leading to the outside or through a protected passageway to the outside, a smokeproof tower, protected stairway, exit passageway, enclosed ramp, escalator, or moving walkway within a building. The *exit discharge* is the door to the outside, although some regulations allow not more than half the exits to discharge onto a floor with an unobstructed path to the outside, and is protected by sprinklers and a 2-hr separation from floors below.

It must further be possible for all the occupants using the exit discharge to reach a safe place away from the building. Thus if exits discharge to a yard or alley these must lead to a safe place and have the capacity to carry all occupants and to protect them from the effects of the fire as they move away from the building. In Japanese building regulations[3] the means of egress includes the entire path to a safe place of sufficient capacity to accommodate the entire population of all buildings intended to evacuate to that place. Thus Japanese cities are dotted with parks that serve as gathering places for occupants of multiple buildings. Those parks utilize perimeter trees intended to protect people in the park from thermal radiation from fires in surrounding buildings from which they evacuated.

Designing an Egress System

The objective of the egress system design is to allow the unimpeded evacuation of the building population without exposure to fire or smoke. Prescriptive building regulations address this by specifying a population density (people per unit floor area) for each building use group, called the occupant load factor. When multiplied by the floor area, the *occupant load* is obtained on which the egress system design is based (unless there is reason to believe that the actual load will be greater or the owner desires a greater allowance).

The means of egress is then designed to accommodate that occupant load by specifying an egress width per occupant served. Values are specified for stairs and for other egress components, sprinklered and unsprinklered, and with special values for type-H (high hazard) and type-I (institutional) building uses to allow for higher egress speeds (high hazard) and greater number of wheelchairs or evacuation in patient beds (institutional), respectively.

The width of the egress system at each floor is sized to accommodate the number of occupants on that floor only. There is an additional requirement that the egress system width cannot become narrower in the direction of egress travel and beyond any convergence of two or more egress systems from different directions, the capacity cannot be less than the sum of the capacities. These requirements are intended to account for the accumulation of flows from multiple floors.

For very tall buildings, it was recognized that the accumulating flow from a large number of floors would result in congestion in the stairways and a reduction of flow speeds. Widening the stairway to increase the capacity has a serious economic impact that could make tall buildings impractical. Thus the concept of phased evacuation was developed where occupants are evacuated from the (3) floors closest to the fire first, while others wait their turn. Such systems require a voice communication system to manage the process by voice messages from a fire command center staffed by the fire service, and (e.g., in New York City) fire wardens on each floor directing the flow.

Egress System Performance

Egress systems designed in accordance with these rules are considered to allow all building occupants to get to a safe place, "in time." Unfortunately, "in time" is not quantified. In the last 20 years, the engineering concept of *Available Safe Egress Time* (or ASET) vs. Required Safe Egress Time (RSET) has become popular. ASET is defined as the time available for safe egress before conditions within a space or building become untenable[4]. RSET is defined as the time required for the occupants in a structure to evacuate without harm. Time available is normally estimated by fire modeling and the application of tenability limits for human tolerance to fire effects. Time required is estimated by traffic flow calculations for speed of people movement through the egress system.

With use, the ASET/RSET methodologies became more refined. The time required calculations began to include other, significant components such as pre-movement times and behavioral rules to account for many situations where people do not immediately evacuate. Human factors research documented large variability in movement speeds[4] and toxicology research showed large differences in individual tolerance to smoke depending on age and pre-existing physiological conditions. Recently questions have been raised about sub-lethal effects[5] that are difficult to estimate and unethical to measure, further clouding the picture.

Because of the large variability in movement speeds, it is possible for individual designs to pass or fail by selection of a characteristic speed or by the application of an appropriately large factor of safety. A safety factor of 2[4] is generally recommended in the fire protection engineering literature[6]. Thus it would be of value to establish a benchmark for what might be considered adequate escape time. The prescriptive regulatory system for egress system design implies such a benchmark value as follows.

Prescriptive Egress Specifications

Traditional building codes specify the design of egress systems by first estimating the number of occupants in an area to be evacuated, second determining the (combined) width of the exit system needed for that number of occupants, and third dividing that width among the number of exits needed to achieve the travel distance limits.

In current building codes, design occupant densities (called loads) range from 46.5 m^2 (500 ft^2) (gross[13] – the area within the confining perimeter walls of the building) per occupant (aircraft hangers, warehouses) to 0.46 m^2 (5 ft^2) (net[13] – the actual occupied space only) per occupant (assembly, standing space). Common values are 9.3 m^2 (100 ft^2) (gross) per occupant (business, industrial) or 18.6 m^2 (200 ft^2) (gross) per occupant (residential). By multiplying these loads by the floor area, the number of people to be evacuated is obtained.

With the exception of hazardous and health care occupancies, both the IBC[7] (without sprinkler protection) and NFPA 5000[8] (sprinklered or not) specify the same egress system width of 7.6 mm (0.3 in) per occupant in exit stairways and 5 mm (0.2 in) per occupant elsewhere. The IBC reduces egress capacity where sprinklered to 5 mm (0.2 in) per occupant in stairs and 3.8 mm (0.15 in) elsewhere. The egress capacity of the exit system is the smallest capacity of any component. For example, a 0.86 m (34 in) (clear width) door leading into a 1.1 m (44 in) (clear) stair have capacities of 170 (0.86 m/5 mm) and 147 (1.1 m/7.6 mm) respectively. Thus the exit capacity is the smaller of the two, or 147. The minimum number of exits specified in both model codes is two for populations up to 500, three from 501 to 1000, and four if over 1000.

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Finally, building codes specify maximum travel distances to an exit by occupancy. The IBC specifies 61 m (200 ft) (unsprinklered) and 76 m (250 ft) (sprinklered) for most occupancies, except for business which is allowed 91.4 m (300 ft) if sprinklered. NFPA 5000 specifies travel distances without sprinklers of 30.5 m (100 ft) (hotels, apartments, mercantile), 45.7 m (150 ft) (health care, educational) or 61 m (200 ft) (business, industrial, assembly). When fully sprinklered, these increase to 61 m (200 ft) (hotel, apartments, educational), 76 m (250 ft) (mercantile, industrial, assembly) and 91.4 m (300 ft) (business). While most buildings will require two or more exits, the travel distance requirement only applies to the distance from any point to the closest (single) exit. The distance to any other exit(s) is unregulated.

An unforeseen problem may exist involving travel distances of the occupants to the "main entrance" of assembly occupancies. For assembly occupancies, there exists a requirement that the "main entrance" of the building must be designed for half of the egress capacity. The travel distance requirement, however, applies only to the closest (single) exit from any point of occupancy in the building. The question that arises is whether or not a specific travel distance should be required for the "main entrance" of the building, especially since the exit is designed for use by half of the building population.

For example, an assembly space with 650 m^2 (7,000 ft^2) (net) will contain a design occupant load of 1000 people. The code requires 3 exits and sprinklers, which results in a travel distance limit of 76 m (250 ft). The "main entrance" is designed for half of the population (500 occupants), and the two other exits of the building include a larger exit designed for 400 occupants and a smaller exit designed for 100 occupants. If the smallest exit is 76 m (250 ft) away from the furthest occupied space in the building, the travel distance requirement for the building is met. The other two exits, the larger exit and the "main entrance" are not required to meet any travel distance requirements. In this example, 90% of the required egress capacity can be in exits that require excessively long travel distances to reach.

Benchmarking the Intent of the Codes

By applying some assumptions to the specifications previously listed, it is possible to estimate the resulting egress times for maximum occupant loads by occupancy. In each case the occupant load can be estimated by assuming a square compartment with exits in opposite corners so that the diagonal dimension is the maximum travel distance. This establishes an area that, when multiplied by the occupant load, gives the number of occupants to be evacuated.

Egress times are generally taken to be the time between notification of the occupants of the need to evacuate (initiation of the fire alarm system) and the time the occupants get into the stairway or a protected stairway access (this is not the normal exit access corridor but rather an extension of the stairway meeting the same fire and smoke protection requirements).

The time required to evacuate these occupants is the pre-movement time plus the time required to move the (maximum) travel distance plus the time required to pass through the door. Table A[9] presents estimates of pre-movement times for various occupancies and type of warning system. Also, other references provide alternatives for pre-movement times, which were obtained from fire drills, experiments, and post-fire analysis[10,11,12].

Walking speeds on horizontal surfaces vary with density and fall within the range of 1.19 m/s (235 ft/min) at 0.54 people/m^2 (0.05 people/ft^2) to 0.63 m/s (125 ft/min) at 2.17 people/m^2 (0.2 people/ft^2)[4]. While walking speeds vary with exposure to smoke, it is reasonable to assume that codes would be based on no smoke exposure due to the limited data on this interaction. Travel speeds and flow rates are typically restricted by flow through doorways. The maximum rate of flow through doors is given in the literature as 1.3 persons/s-m of effective width (24 people/min-ft)[4].

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Table A – Estimated Delay Time to Start Evacuation

Occupancy Type	W1 (min)	W2 (min)	W3 (min)
Offices, commercial and industrial buildings, schools, colleges, and universities (Occupants awake and familiar with the building, the alarm system, and evacuation procedure)	<1	3	>4
Shops, museums, leisure-sport centers, and other assembly buildings (Occupants awake but may be unfamiliar with building, alarm system, evacuation procedure)	<2	3	>6
Dormitories, residential mid- and high-rise (Occupants may be asleep but are predominantly familiar with the building, alarm system, evacuation procedure)	<2	4	>5
Hotels and boarding houses (Occupants may be asleep and unfamiliar with building, alarm system, evacuation procedure)	<2	4	>6
Hospitals, nursing homes, and other institutional (A significant number of occupants may require assistance)	<3	5	>8

W1: live directives using voice communication system from a control room with closed-circuit television facility or live directives in conjunction with well-trained, uniformed staff that can be seen and heard by all occupants in the space.
W2: nondirective voice messages (pre-recorded) and/or informative warning visual display with trained staff.
W3: warning system using fire alarm signal and staff with no relevant training

The building codes specify that egress doors cannot be less than 0.8 m (32 in) (clear) nor more than 1.2 m (48 in) (clear) in width (per leaf). Door capacities range from 160 persons for a 0.8 m door to 240 persons for a 1.2 m door with a differential of 10 people per 51 mm (2 in) of width.

Egress stairs cannot be less than 1.1 m (44 in) in width with no maximum. Design capacities for stairs range from 147 people for a 1.1 m (44 in) stair to 220 people for a 1.67 m (66 in) stair with a differential of 13 people per 102 mm (4 in) of width.

Horizontal Movement

Tables B1 and B2 show estimates of the worst-case egress times for each occupancy type; assembly without fixed seating, business, and residential (open space). Each egress time is the combination of the travel time to the stairwell door and the time for all of the occupants to go through the door into the stairwell. Prescriptive codes consider the occupant to reach safety as soon as they enter the stairwell. In the tables, egress times are separated first into occupancy type, and then second into whether or not the occupancy is sprinklered (S refers to sprinklered spaces and N refers to nonsprinklered (or unsprinklered) spaces in each table). Both designations ultimately affect the travel distances and number of occupants in a space, as shown in the table.

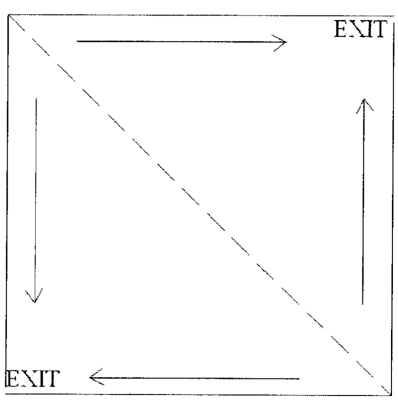

Figure 1: Square compartment

For each occupancy type, a square room is configured so that the diagonal dimension is equivalent to the travel distance. Then, the dimensions of the compartment are used to calculate the number of occupants in the space according to the Life Safety Code[13] (Table 7.3.1.2). The "travel time" is used to represent the longest possible distance traveled by an occupant to reach the stairway door. As shown in Figure 1, this longest distance with all exits available is the distance along the side of the compartment (shown by the arrows in the figure). This provides a conservative estimate of travel time for that space. The speeds used to calculate travel time for each occupancy reflect the actual density of the space and were obtained from Pauls' density correlations in the SFPE handbook[14].

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The next calculation in Table B1, specifically, shows the time for all of the distributed occupants to travel through their designated door. Each occupancy has a different number of exit doors depending upon the

number of occupants in the space. The "through door" time is calculated by dividing the number of occupants through the door by the calculated flow (maximum specific flow x effective door width) in persons/minute. The door calculation takes into account that occupants will maintain a boundary layer of 150 mm (6 in) from each side of the doorway.

Table B1 – Estimates of worst-case egress times using SFPE Handbook values

	Assembly		Business		Residential	
	S[b]	NS[c]	S	NS	S	NS
Travel distance (diagonal dimension–Fig. 1) in meters (ft)	76 (250)	61 (200)	91.4 (300)	61 (200)	61[a] (200)	30.5[a] (100)
Compartment side dimensions in m (ft)	54.3 (178)	43.6 (143)	65.2 (214)	43.6 (143)	43.6 (143)	21.6 (71)
Occupant # (load x area)	6336	4090	458	205	102	25
Travel time (s)	85	69	55	37	37	18
Exit doors, # x width in m (people per set of doors)	14x2.4 (452)	9x2.4 (455)	2x1.17 (229)	2x0.8 (103)	2x0.8 (51)	2x0.8 (13)
Through door (s)	162	163	202	155	77	20

[a]Travel distance shown is from the door to any individual living unit to the exit. Additional travel time would be required for travel within the living unit.
[b]Refers to a Sprinklered space; [c]Refers to a Nonsprinklered space

For Table B2, as a variation to the calculations made in Table B1, it is assumed that the doors act as turnstiles. From video tapes of egress through doors taken by Fruin[15], it can be seen that each exiting person places his/her hand on the door before leaving the building. Nelson[16] speculates that this behavior limits the flow through each door to about 50 to 60 persons per minute. This applies to the full range of door widths from 0.8 m (32 in) to 1.2 m (48 in). For the assembly space, a 2.4 m (96 in) door represents a two-leaf set of 1.2 m (48 in) wide doors, which would indicate a flow of 100 to 120 persons per minute. For all calculations in Table B2, a midrange value of 55 persons per minute per door was used to achieve times through the door. For example, in the assembly space, 452 people will pass through a two-leaf set of 1.2 m (48 in) doors, which corresponds to a flow of 110 people per minute. For sprinklered assembly spaces, the result is 247 seconds to flow 452 people through the 2-1.2 m (48 in) doors.

Table B2 – Estimates of worst-case egress times using Nelson and Fruin turnstile values (each door allows 55 persons/minute)

	Assembly		Business		Residential	
	S[b]	NS[c]	S	NS	S	NS
Travel distance in meters (ft)	76 (250)	61 (200)	91.4 (300)	61 (200)	61[a] (200)	30.5[a] (100)
Compartment side dimensions in m (ft)	54.3 (178)	43.6 (143)	65.2 (214)	43.6 (143)	43.6 (143)	21.6 (71)
Occupant # (load x area)	6336	4090	458	205	102	25
Travel time (s)	85	69	55	37	37	18
Exit doors, # x width	14x2.4	9x2.4	2x1.17	2x0.8	2x0.8	2x0.8

[redacted]

in m (people per set of doors)	(452)	(455)	(229)	(103)	(51)	(13)
Through door (s)	247	248	250	112	56	14
[a]Travel distance shown is from the door to any individual living unit to the exit. Additional travel time would be required for travel within the living unit. [b]Refers to a Sprinklered space; [c]Refers to a Nonsprinklered space						

By using the turnstile approach in Table B2, it can be seen that the flows become restricted in the larger density spaces. This causes a longer time through the door. Again, as with the calculations made in Table B1, these can be considered as conservative estimates of egress times for movement without the presence of fire effects.

Assumptions lead to alternative approach to calculate egress times

There are three assumptions made to calculate the horizontal travel time and time through the door shown in Tables B1 and B2. It should be understood that these calculations are approximations of general situations and certain assumptions needed to be made to complete the calculations for each case. The first assumption involves an even distribution of occupants to the doors leading to the stairwells.

The second and third assumptions correspond to the addition of the "travel time" and the "through door" time to achieve the evacuation time for each room. There is an assumption made that "travel time" and "through door" time do not overlap. In the case where a queue forms after some period of time during the evacuation, the addition of these two values (travel and through door time) produces an evacuation time that is overly conservative. While the most remote occupant travels to the doorway, other occupants closer to the door leave the room. At some point, the remote occupant reaches a queue, meaning that they have not walked the entire travel distance. Once they reach the queue, the "through door" calculation dominates the evacuation time. Also, not all occupants are part of the queue, as was assumed in the "through door" calculation, since some leave while others join the queue.

The third assumption made is that "travel" and "through door" times both have values that are nonzero. This is not always the case. For lower density spaces, such as the residential unsprinklered, if a queue never forms, the evacuation time should equal the "travel" time of the most remote occupant in the space. For the very high density spaces, such as the assembly spaces, a queue forms immediately. In the case of assembly spaces, the evacuation time is equivalent to the "through door" time only.

Because of the previous assumptions made about the addition of travel time and time through the door, several evacuation simulations were run using the Simulex[*] model[17] to correct these assumptions. The purpose of these evacuation simulations was to note how long occupants travel to the door unimpeded before a queue would form at the door, at which time the "through door" egress time dominates the total egress time from the room.

Each occupancy (sprinklered and unsprinklered) was drawn using TurboCAD and imported into Simulex. The room for each occupancy was equipped with exits at opposing corners (except for the Assembly spaces which had doors all around the space) separated by the maximum travel distance along the diagonal. Simulex allows the user to input a travel speed and body size for each occupant in the simulation. For each run, all occupants moved at 1.2 m/s (235 ft/min) unimpeded and contained

[*] Certain commercial entities, equipment, or materials may be identified in this document in order to describe an experimental procedure or concept adequately. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the entities, materials, or equipment are necessarily the best available for the purpose.

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the "median" adult body size (average of men and women). The occupants were spaced evenly throughout the room and moved immediately with the start of the simulation. The model, Simulex, was used only to track the unimpeded movement of the occupants from their starting position to the doorway. Overall, these Simulex runs were used to obtain the amount of time that occupants walked through the door before a queue formed. The results were as follows:

Table C - Simulated time before a queue developed at the doors

	Assembly		Business		Residential	
	S	NS	S	NS	S	NS
Time (s) before queue at door	≈0	≈0	12	12	16	∞

A time of 0 seconds corresponds to a queue developing almost instantaneously in the assembly spaces. This was expected due to the fact that the assembly spaces were packed at an allowable density of 0.46 m^2/person (5 ft^2/person). On the other hand, the unsprinklered residential space never formed a queue at the door, which is described as an infinite time in Table C. This was also expected due to the size of the space and the low number of occupants that needed to evacuate. For the business (sprinklered and unsprinklered) spaces and the sprinklered residential space, there was a recognized time before queuing began, and for the rest of the evacuation, the time through the door dominated. This shows that for these occupancies in this example, the evacuation time is a mix of the travel time and the time through the door. The appropriate evacuation time can be calculated, given the information in Table C.

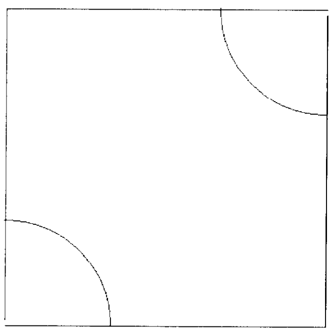

Figure 2: Arc display of occupants who leave the room before queuing occurs

Since Table C displays the time before queuing begins for the three occupancies (Business Sprinklered, Business Unsprinklered, and Residential Sprinklered), the number of people that pass through the door in that amount of time can be calculated. The time before the queue forms and the speed of the occupants at the specific density is known, and from this information, the distance that the occupants traveled to evacuate before a queue formed can be calculated. As shown in Figure 2, an arc is drawn in front of each doorway, with the radius consisting of the distance traveled by the occupants before queuing. Essentially, this arc is drawn to show the position of the occupants that left before queuing began. By solving for the area of the arc, the number of occupants residing in this arc space (using the density of the space) can be found and used as the number of occupants evacuating during the pre-queuing time. These occupants are then subtracted out from the population. Lastly, the time for the rest of the occupants to move through the door is calculated using two different methods; the effective width method and the turnstile method. These values are shown in Table B3.

Table B3 – Estimates of egress times without overlapping travel time and time through the doorway.

	Assembly		Business		Residential	
	S	NS	S	NS	S	NS
Travel distance in meters (ft)	76 (250)	61 (200)	91.4 (300)	61 (200)	61 (200)	30.5 (100)
Compartment side dimensions in m (ft)	54.3 (178)	43.6 (143)	65.2 (214)	43.6 (143)	43.6 (143)	21.6 (71)
Occupant # (load x area)	6336	4090	458	205	102	25
Time (s) before queue at door	0	0	12	12	16	∞ (18)

[redacted]

# of occupants evacuating during pre-queue per door (# of occupants left at time of queue)	0 (452)	0 (455)	17 (212)	17 (86)	15 (36)	13 (0)
Through door (s) for queuing occupants – effective width method	**162**	**163**	**188**	**129**	**54**	**18**[a]
Through door (s) for queuing occupants – turnstile method	**247**	**248**	**231**	**94**	**39**	**18**[a]
[a]These values are equivalent to the travel time assuming that occupants are traveling at the unimpeded speed of 1.2 m/s (235 ft/min) (at least one traveling the entire "travel time" distance).						

For all occupancies, except for the residential unsprinklered, horizontal travel time was not explicitly included in the egress times from each space. This is because the egress times are dominated by the time through the door, as shown in the Simulex runs of each occupancy (except for residential unsprinklered). Because of this, the total egress time for the space is calculated by adding the "time before queue at door" and the "through door" time (depending upon the calculation method preferred).

Overall

If a more conservative evacuation time is preferred, it is recommended to add the travel time to the door and the time through the door for the business occupancy (sprinklered and unsprinklered) and the sprinklered residential occupancy.

<u>Stairs</u>
While prescriptive codes generally designate occupants as safe when they enter the protected egress stair, evacuation often requires that the occupants travel down stairs to the level of exit discharge. From the literature, the maximum flow rate in a (7/11) egress stair is estimated to be 1 person/s-m (18.5 people/min-ft) of effective width. Thus typical/**maximum** flow rates for 1.1 m (44 in) to 1.67 m (66 in) egress stairs range from 49 to 83 people per min. This does not include the effect of congestion in the stairs that results from accumulating flows from several floors accessing the stairs.

Table D shows the time for travel on the stairs from one floor to another (including one landing in between flights). The times were obtained by assuming that the calculated flow (people/min) from one section of the building is equal to the calculated flow on the next section, except for the unsprinklered residential. For the unsprinklered residential occupancy, since no queue has formed at the door, unimpeded speed was used to calculate movement on the staircase. For all other occupancies, the occupants travel from the doorway into the stairwell with the same calculated flow, but different widths, and therefore, different specific flows. It is assumed that they travel from the room at a specific flow of 1.3 people/m-s (24 people/ft-min). The Life Safety code specifies 7.6 mm/person (0.3 in/person) of stair width, which was used to calculate the appropriate stair width for each occupancy, sprinklered or unsprinklered. By solving for the specific flow for the staircase, the appropriate travel speed can be obtained from the SFPE handbook[4] in order to calculate the travel times for the section of stair. Stair travel distance was estimated by first, multiplying the vertical distance of the floor by the diagonal travel distance conversion factor found in Nelson's chapter of the SFPE Handbook, Table 3-14.3[4], and second, adding travel distance of the 2 landings. The calculated range of times for stair travel from one floor to another (assuming a 3.7 m (12 ft) ceiling height – slab to slab and (7/11) stairs) was 12-25 seconds, depending upon the occupancy and method of calculation.

[redacted]

Table D – Travel times on Stairs

	Assembly		Business		Residential	
	S	NS	S	NS	S	NS
Travel distance in room (m)	76	61	91.4	61	61	30.5
People per door/stair	452	455	229	103	51	13
Stair width (m)	3.4	3.47	1.7	1.1	1.1	1.1
Travel dist on Stairs (m)	20.5	20.5	13.7	11.2	11.2	11.2
Time on each flight (s) – effective width method	25	25	16	13	13	12
Time on each flight (s) – turnstile method	22	22	15	18	18	12

Due to the number of occupants evacuating the three occupancies, especially in the case of the assembly space, the stairwells used in Table D are quite wide. The Life Safety Code[13] specifies that handrails need to be placed 1.5 m (60 in) apart in order to provide support for occupants descending wider staircases. This handrail specification affects both the sprinklered and unsprinklered assembly spaces and the sprinklered business space. The calculations provided in Table D account for boundary layers (150 mm (6 in)) around the walls of the staircase, but not the handrails placed in the middle of the stair. Boundary layers from walls are used in evacuation calculations to account for lateral body sway in the stair[9]. For this estimation of stair time, it is assumed that the occupants will allow their bodies to get within millimeters of the handrail, negating the need for additional boundary layers around handrails. It is possible that the presence of handrails in the center of a staircase can negatively affect the flow of occupants during egress, but there lacks a sufficient amount of data on this topic to include such in the estimation.

Thus the benchmark egress times on the initial floor implied in current building codes range from approximately 5.5 minutes (sprinklered assembly) to 0.3 min (unsprinklered residential), depending upon the method of calculation used and the type of occupancy. When added to the alarm time for the initial notification of the occupants (generally on the order of one minute from sustained ignition of the first item), estimated pre-movement times (Table A) and descent times (per floor times number of floors, Table D) as appropriate, these can be used to benchmark egress system performance for systems designed by calculation.

Congestion and Merging Flows on Stairs

Merging flows occur when occupants from a floor and the stairwell above enter the stairwell section simultaneously during downward flow. This can also occur during upward flow if occupants are traveling from basement levels of the building. In a high-rise building, congestion points occur at each entrance into the stairway from all floors of the building.

During merging flows, it is likely for researchers to witness the phenomenon of deference behavior. Deference behavior describes how occupants from the floors above yield to the occupants entering the stairwell from their floor. This behavior is often seen on airplanes where the rows leave before the passengers already waiting in the plane aisle.

Merging flows and congestion frequently occur in high-rise buildings during full or total evacuation of the structure. Currently all US model building codes (International Building Code and NFPA5000) design tall buildings, particularly door and stair widths, based on a partial or phased evacuation plan for the building. The code specifies that the width of the stairs depends on the number of occupants on a particular floor, irrespective of building zones or the entire building population. This would result in congestion in high-rise buildings if the entire population evacuates simultaneously. Since 9/11, New York City has imposed a requirement for an evacuation drill (the entire population evacuating to the street) annually. It is reported that occupants of surrounding buildings seeing the

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evacuation themselves, then evacuate their buildings. Situations like this result in the opinion that the process for evacuation of tall buildings needs to be rethought.

Elevators

Currently there are no building codes that permit elevators to be used as a means of occupant egress, and ASME A17.1[18] requires signs at all elevators warning that they shall not be used in fires. NFPA 5000 permits protected elevators as a secondary means of egress for air traffic control towers and the City of Las Vegas accepted elevators as a primary means of occupant egress from Stratosphere Tower based on a performance-based design[19].

US codes require *accessible elevators* as part of a means of egress that may be used by the fire service to evacuate people with disabilities. These elevators must comply with the emergency operation requirements of ASME A17.1 (Phase II emergency operation by the fire service), be provided with emergency power, be accessible from an area of refuge or a horizontal exit (unless the building is fully sprinklered), and operate in a smoke protected hoistway. Phase II operation involves the use of an elevator by a firefighter for fire service access or for rescue of people with disabilities performed under manual control (with the use of a special key).

According to a survey[20] by the International Organization for Standardization technical committee on elevators (ISO TC178), there are twelve countries that require firefighter lifts, generally in buildings that exceed 30 m (98 ft) in height. Standards for firefighter lifts generally describe a firefighting shaft consisting of protected elevators, enclosed lobbies on each floor and an associated stairway, all of which have at least 1-hr fire resistance and smoke protection. Firefighters use the elevator to move their people and equipment to two floors below the fire, from which point they advance up the stairs, which contain a standpipe and provide a protected path for retreat. These firefighter lifts can be used to provide evacuation assistance for occupants with disabilities after suppression activities are underway.

NIST studies have shown that the use of protected elevators to supplement stairs for occupant egress (not just for people with disabilities) can result in a significant reduction in total egress times, especially for taller buildings[21]. Given the observation that occupants may resist certain evacuation approaches, such as phased evacuation, protected elevators is clearly the most promising to address the problem without incurring huge penalties in decreased leasable space.

Conclusions

Based on the preceding analysis, the longest egress times expected in buildings designed in accordance with current (prescriptive) U.S. codes would occur in larger, assembly occupancies without fixed seating (the so-called festival seating) having the maximum occupant densities. Benchmark egress times would be approximately 4 minutes pre-movement, 5 minutes to get into the stairs, and 0.5 (25/60 s) minutes per floor to get to the level of exit discharge.

In an office (business occupancy) egress times might be 3 minutes pre-movement, 5 minutes to get into the stairs, and 0.3 minutes per floor to get to the level of exit discharge. In residential occupancies egress times might be 4 minutes pre-movement (but with much higher variability since there is likely additional delays to assist family members, obtain pets and valuables, etc.), 2 minutes to get into the stairs, and 0.3 minutes per floor to get to the level of exit discharge. These times attempt to account for queuing entering the stairs but do not include delays due to congestion within stairs that would be expected to increase with building height.

These times represent estimates of the egress performance implied by egress system designs prescribed in current U.S. model building codes. These should not be taken as requirements nor even as the performance intended by the code developers, since this is the first attempt to quantify what might be expected from means of egress complying with the minimum requirements of the codes.

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The intent of this paper is simply to provide benchmarks that can be compared against performance-based egress analyses.

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