EDSGN 100H Spring '09

High-Rise Emergency Egress System

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Executive Summary

The focus of this project is to design an emergency escape mechanism for high-rise buildings. The mechanism should safely and cost-effectively facilitate the safe and rapid evacuation of individuals from high rise buildings in times of crisis when all other means of exiting are inaccessible. Our group restricted the design factors to consider the aspect of evacuating large volumes of people in a relatively short period of time.

The customer needs were identified and forty different concepts were generated based on these needs. After narrowing these concepts down to the final five that were thought to be the most implementable, surveys were undertaken in the market in order to determine the one mechanism that was widely preferred over the others. The final concept that was chosen was a system that employed a safety harness that would be operated in elevator shafts using an I-beam track under a computer controlled program to avoid congestion.

Introduction

Owing to increasing population density, to maintain efficient and compact floor space, and for purely aesthetic purposes, the number of skyscrapers in many cities is growing dramatically. The benefits of high-rise buildings are numerous; not only are skyscrapers space-efficient, they also serve as symbols of development in cities around the world. However, along with the benefits come major concerns regarding safety. As buildings increase in height, the ability to evacuate in a fast and safe manner decreases. During crisis situations like fires and electrical breakdowns, elevators become impractical to use because of the dangers of mechanical failure and limited capacity. Stairwells become congested and pose a serious health threat to anyone who is not in good physical condition.

An important concern to be considered was the safety of individuals in a floor of the building that's higher than the floor on which the breakdown or fire has occurred. These individuals are potentially cut off from all routes to safety and proceed to either cause a stampede down the stairwells or resort to jumping out of the windows in order to have an almost infinitesimal chance of saving themselves. Thus, we decided to focus our group's design on evacuating large volumes of people safely, within a considerably small period of time.

Research

Research into current methods of emergency high-rise egress revealed several products based around a parachute concept. The High Office Parachute Escape – Aerial Egress, or H.O.P.E., is one such product. This system costs $1,145 per unit [1]. Being so expensive this product would be impractical to employ on a large scale, which is what the project was intended for. Another negative aspect of a parachute based system is the high variability in wind conditions surrounding skyscrapers.

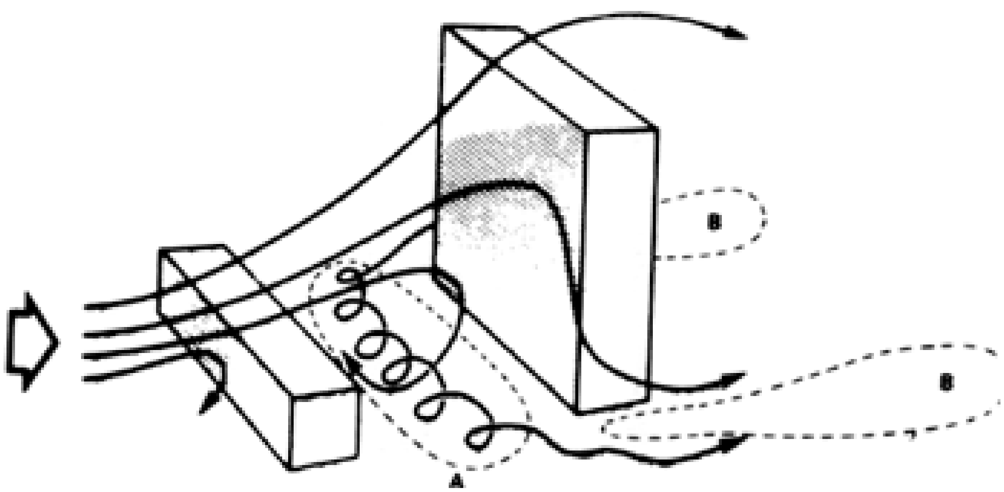


Figure 1 – ***Air flow around a building***

As seen in figure 1, the airflow around buildings can be highly variable. Updrafts, downdrafts and vertical vortices form near tall buildings [2]. These wind conditions make it difficult to control any sort of flying device such a parachute. Also, most existing skyscrapers rely largely on stairwells for emergency evacuation.

However, stairwells could easily get blocked by a fire, or could accumulate smoke making it very difficult for people to move through them. Also, it is very impractical for people to use these stairwells for getting down if they are in a skyscraper like building with a large number of floors since it would cause fatigue and also lead to trampling incidents if some people aren't as fast as the others. For these reasons, it is clear that an ideal solution to evacuating large numbers of people from high-rise buildings currently doesn't exist.

Currently the tallest building in the world is the Burj Dubai building in Dubai, standing at around 2683 ft. The top two hundred tallest buildings average in height at around 930 ft [3]. It is important that the system design works efficiently with all the ranges of tall buildings, including the tallest.

The population of a building is also important when considering an evacuation system. Most U.S. Fire Safety Codes mandate that there be $100ft^2$ per person on a floor [4]. The actual number of people on a given floor of a high-rise building will depend on many factors such as:

- The function of the floor
- The number of tourists or visitors present
- The floor area

Since the number of people on a floor will vary depending on the building, floor, time of the year and day of the week, it is important for the emergency egress system to be able to accommodate a large volume of people and be custom designed to meet each building's needs, while providing a holistic general solution for most buildings.

Target Specifications

The target specifications of the final product were established by considering the needs of the customer, the problem at hand, and using the engineering team's insight into the project. The general purpose of the product and its function imply needs the product must fulfill. Metrics quantify these qualitative needs. Table 1 shows a list of these needs and metrics, and a Needs Metrics Matrix considering which qualities affect the various metrics is in Appendix 1. A Needs Metrics Matrix reveals which needs have an impact on each other. For instance fulfilling the need for a product to be cheap and affordable may make it unsafe.

Needs	Metrics
Robustness	Still usable 95% of the time after being dropped from 4ft 100 times
Cheap	Cost should be less than $750 per person
Safe	Greater than 99% survival rate
Fire resistant	Can withstand 800^{o}F for greater than 5 minutes
Accommodates large volumes of people	Evacuates greater than 50 people per minute
Compact	Total system occupies less than 5% of floor space
Long service life	Has greater than 20 year service life
Easy to use	Requires less than 1 hour of training per person Requires less than 10 minutes to figure out how to use without prior instruction
Accessible	Takes less than one minute to reach
Fast individual escape rate	Single person can escape in less than 5 minutes

Table 1 – *Quantification of needs by using metrics*

Concept Generation

The initial concepts for our high-rise escape mechanism came from a single individual brainstorming session. We followed a basic format where we came up with as many as ideas as possible, no matter how ridiculous or impractical, within a period of 5 minutes. This method alone produced as many as 20 ideas from each member of the group, becoming more unique and innovative as each list went on. While some concepts were preconceived, the majority were spontaneous. After pooling the ideas together, the numbers began to shrink as they were compared, analyzed and criticized. In the end, there were 11 ideas, ranging from an external elevator to a zip line that was to be considered as a potential design our project could be based on. Please refer to Appendix 2 for a sample list of brainstormed concepts.

Concept Screening

The next step in the concept development process was further concept screening, specifically, through the utilization of a 3-point scale version of a concept screening matrix. Initially, there were quite a number of different criteria to which the ideas were compared. However, after removing repetitive measurements and specifications, the matrix became what is displayed in Table 2.

The evaluation criteria were defined as follows:

- Large volume - A measurement of how well the system could handle large quantities of people
- Cost effective – Efficiency with which the product facilitated safe escape for the overall price of the system
- Safe – A measurement of reliability of the escape system and the likelihood of injury during use
- Rapid Escape – The quickness with which the system could move the occupants out of danger zone
- Simple to use – The amount of training that was required before the effective use of the system, and how quickly the system could be utilized
- Practical - The likelihood of the technology for such a system being available.

	Large Volume	Cost Effective	Safe	Rapid Escape	Simple to use	Practical	Total
Safe room	+	-	+	+	+	-	3
Bridge	+	-	0	+	+	-	2
Personal Rail Descent	+	0	-	+	-	+	1
External Elevator	0	0	0	0	0	0	0
Inflatable Slide	+	+	-	+	0	-	0
Abseil	+	+	-	+	-	-	-1
Parachutes	-	-	-	+	-	-	-3
Ride Elevator Cable	-	+	-	-	-	+	-3
Vertical Escalator	0	-	-	0	-	-	-3
Zip line	-	+	-	+	-	-	-3
Ladder	-	+	-	-	0	-	-4

Table 2 – *Concept Screening Matrix*

The External Elevator became the baseline due to its similarity to already existing systems (the internal elevator, and an external elevator currently being developed in Israel) and its seemingly middle-of-the-road performance.

This proved to be a good choice, as the deviation between the best and worst scoring ideas was +3 and -4 (though, it is important to note that only 3 ideas scored above the baseline).

After all of the points were tallied, the five best-scoring ideas were selected for further development:

- The Safe Room
- Bridge
- Personal Rail Descent
- External Elevator
- Inflatable Slide

Pair-wise Comparison

For each of these five concepts, a concept sheet was created. The concept sheet basically consisted of a pictorial depiction of the system along with a short description of how it worked. These concept sheets were used in the survey that was undertaken in order to find out how the market ranked the 5 ideas that we had chosen. The purpose of the concept sheets were to help us further understand the benefits and limitations of each system, as well as to allow others to visualize more effectively how the products would work (these concept sheets are available in Appendix 3). In order to create a Pair-wise Comparison Chart to make more informed judgments about the preferences of potential users, a total of thirty-one people were interviewed, each asked to rank the various ideas from best to worst. The resulting chart is shown in Table 3.

	Elevator	Slide	Personal Rail Descent	Safe room	Bridge	Total wins
Elevator	x	12	13	12	12	50
Slide	19	x	18	18	15	70
Personal Rail Descent	18	13	x	16	16	63
Safe room	18	13	15	x	13	59
Bridge	19	16	16	18	x	69

Table 3 – *Pair-wise comparison chart*

An important characteristic to point out here is how dissimilar the individual surveys were (please refer to Appendix 4 for the individual results). The best scoring idea in one survey is almost guaranteed to be the worst in another. The importance of this cannot be understated. Had such a wide variety of people *not* been interviewed, the results of the chart would have been greatly skewed in one direction or another.

Once all of the surveys' results were combined, however, the best three ideas became clear: the Slide, the Bridge, and the Harness. If evaluated strictly by these results, the slide should have been chosen as the final concept. However, the reason for not simply picking the best of these results as the final product was due to a combination of a number of different factors.

Firstly, to assume that those interviewed had enough technical knowledge about the systems to make informed guesses is reckless. Secondly, the actual layout of the individual concept sheets could have affected the perception of the quality of the product. And thirdly, the circumstances surrounding each individual interview (whether it was in an individual or group setting, whether the criteria used to determine the 'best' idea were different between surveys, etc.) could have changed the results drastically. In essence, the most that this particular part of the product research cycle is most useful in gauging user comfort with the idea of each concept.

Concept Scoring

The final test for the last three ideas was a concept scoring matrix, whereby various design considerations were weighted in relation to one another. Each item was weighted on a 10-point scale, while each item was rated on a 5-point scale. In the end, while the slide achieved the highest rating points-wise, the team made the executive decision to go forward with the Personal Rail Descent concept. This is due, first and foremost, to the fact that the practicality of such a slide system housed inside of existing stairwells is questionable at best.

In addition, there were a few intangible yet unsettling factors that couldn't quite be explained but were well-understood by a number of members in the group. At the core of it all, however, there was the understanding that this whole project was designed to be a learning experience. A slide-stair mechanism for an escape system did not pose as much of a challenge and did not present as much of a learning opportunity as a rail-based descent system. As a result, the Personal Rail Descent concept was used as the final direction for the product.

Owing to the widely diverse nature of each of the concepts that were generated, it wasn't really possible to combine ideas from the concepts into the final concept that was chosen. However the concept that was chosen slowly evolved over time, in the sense that, initially when the idea was chosen, there was only a rough idea about how the system would function. However more time was spent analyzing the pros and cons of the system in order to minimize risks and maximize effectiveness and by doing so, a few areas which had earlier been considered negative aspects were eliminated.

For instance, one of the major areas of concern initially established with this system was the inability of the system to control the flow of people. Brainstorming and improvisation lead to the addition of lighting systems and a computer controlled program into this system in order to make it more effective.

	Weight	Slide		Bridge		Personal Rail Descent	
		Raw	Weighted	Raw	Weighted	Raw	Weighted
Safety	10	3	30	3	30	4	40
Reliability	8	4	32	2	16	3	24
Practicality	8	4	32	3	24	4	32
Speed of mass escape	8	5	40	3	24	4.5	36
Ease of use	7	3	21	5	35	2	14
Accessibility from all floors	7	5	35	3	21	5	35
Retrofit Ability	6.5	4	26	3	19.5	5	32.5
Congestion	5.5	4	22	2	11	3	16.5
Speed of Individual Escape	5	3	15	1.5	7.5	3	15
Non-intimidating	4	3	12	5	20	1	4
Inexpensive	3	4	12	1	3	3	9
Protection from externality	3	3	9	0	0	3	9
Usability for other purpose	0.5	3	1.5	5	2.5	1	0.5
Total			287.5		213.5		267.5

Table 4 – *Concept Scoring Matrix*

Final Concept

The final concept for a high-rise emergency egress system is a Personal Rail Descent System (Figure 2). It features a small device – the car, which runs along a vertical I-beam shaped track, located on the interior walls of elevator shafts or on the exterior of the building. The car operates through retractable wheels that attach to the I-beam track and a set of centrifugal brakes (Figure 3) to control the speed. The user secures to the car via a hip-cradle harness around the waist. The harnesses and their corresponding cars will be issued to each occupant of the floor, and additional devices will be stored next to the vertical tracks for people who do not have their own – such as visitors to the building or people who are in a different floor than where they usually are.

Figure 2 – *The car and track*

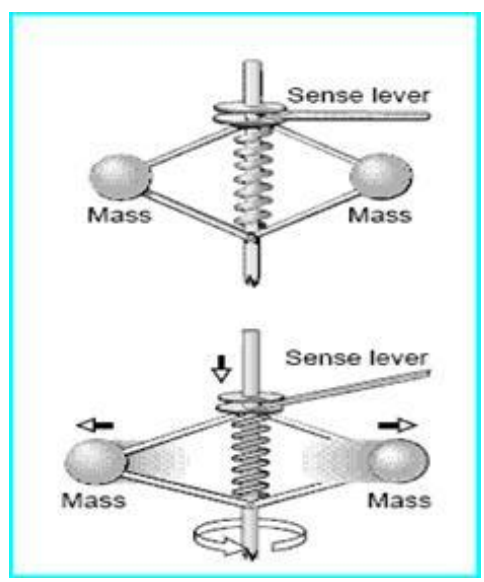


Figure 3 – *The centrifugal brake system* [5]

Detailed description of the final concept

- **The Car**

The car (Figure 2 and Appendix 4) itself consists of two major parts – a set of retractable wheels which lock around the I-beam track and the centrifugal brake. The retractable feature allows the car to easily be connected to the track. The centrifugal brake runs by the spinning of the wheels, which are connected to a shaft that spins as they do. This, in turn, operates the centrifugal brake.

As the brake spins faster, the masses move further out from the shaft, compressing the spring and applying friction. This allows the car to maintain a specific speed. If the car goes beyond a certain speed, the brake is applied and the car slows down. The brake releases once the specified speed is achieved again.

Additionally, a manual brake will be employed to allow the user to slow the car down. The car also has a headlight and a taillight. The headlight is a white light on the bottom and the taillight is a red light on the top. The positions of the lights are analogous to the standard orientation of vehicle lights to indicate the relative positions of other users. Once the user has descended to the ground floor, the car simply slides off the bottom of the track, which ends several feet above the floor. This makes for a fast and easy exit from the building.

- **The Harness**

The harness the user has to wear consists of a standard hip-cradle (Figure 4) and a Spandex lining. The hip-cradle supports the user's weight and connects to the car via a short tether. The Spandex lining aids in donning the harness by reducing entanglement. Also adjustable, the harness accommodates most users and larger or smaller sizes can be made available if needed.

Figure 4 – *The hip-cradle harness* [6]

Speed Analysis

In order to get a rough idea of the spectrum of speeds at which the system could be operated, calculations were carried out. Kinematics calculations determined optimal speed of descent for the system. In order to determine what a safe, yet efficient, speed would be to descend from even the tallest of buildings, a comparison baseline was established.

$$V_f^2 = V_i^2 + 2a\,(x_f - x_i)$$

Equation 1: ***Final velocity equation***

Distance Fallen (ft)	Velocity (ft/s)
1	08.00
2	11.31
3	13.86
4	16.00
5	17.89
6	19.60
7	21.17
8	22.63
9	24.00
10	25.30

Table 5 – ***Baseline velocities based on distances of free fall***

Equation one calculates a final speed given an initial speed, acceleration and displacement. Baseline speeds were created by selecting distances of free fall, in other words with only the force of gravity and no initial velocity, i.e. $V_i = 0$. These baseline speeds seen in Table 5 serve as a means of determining safe speeds of descent. For example, it is fairly safe to jump from a one foot height. A one foot descent results in an impact speed of 8 ft/s or 5.45 mph. This can be used as 'safe' speed to make further calculation of the system's operation.

$$T = D/V$$

Equation 2: ***Time equation***

Velocity (ft/s)	Time (min) to Descend 2683ft
2.53	17.68
3.58	12.50
4.38	10.21
5.06	8.84
5.66	7.90
6.20	7.22
6.69	6.68
7.16	6.25
7.59	5.89
8.00	5.59
9.80	4.56
11.31	3.95
12.65	3.54

Table 6 – *Velocities and times to descend The Burj Dubai Building, Dubai*

Equation 2 calculates time given a distance and constant velocity. Table 2 displays the time it would take to descend from the top of the Burj Dubai building in Dubai, while traveling at the baseline speeds established. These calculations show that it is possible to quickly descend great heights that can be encountered at relatively safe speeds and provide a basic idea of the operational speeds an emergency evacuation system could operate at.

Effectiveness Analysis

In order to elucidate on the effectiveness of this system, calculations were carried out regarding how this emergency egress system might be employed in an existing building, by estimating the time it would take to completely evacuate this entire facility. The building for which this system was evaluated against was The Chrysler Building in New York, which ranks as the 32nd tallest building in the world. It stands 1064ft tall with 77 stories and approximately 195 people per floor. [7]

Two tracks will be placed in each of the 33 elevator shafts, making for less than three people per track on any given floor. A well coordinated system will have the upper most floor and the middle floor open at the same time for approximately 2 minutes. Then the floors immediately below these ones would open up following the evacuation of the floors above. Given these metrics, it would take approximately 2.32 hours to evacuate the entire building at full capacity. Table 7 gives a floor by floor breakdown of this calculation. This time is less than half the estimated time of 6.17 hours to evacuate The Chrysler Building using only the current stairs and elevators. [8]

Floors		Height of upper floor (ft)	Time to evacuate floors and reach ground (min)
77	39	1046.00	4.18
76	38	1032.41	4.15
75	37	1018.82	4.12
74	36	1005.23	4.09
73	35	991.64	4.07
72	34	978.05	4.04
71	33	964.46	4.01
70	32	950.87	3.98
69	31	937.28	3.95
68	30	923.69	3.92
67	29	910.10	3.90
66	28	896.51	3.87
65	27	882.92	3.84
64	26	869.33	3.81
63	25	855.74	3.78
62	24	842.15	3.75
61	23	828.56	3.73
60	22	814.97	3.70
59	21	801.38	3.67
58	20	787.79	3.64
57	19	774.20	3.61
56	18	760.61	3.58
55	17	747.02	3.56
54	16	733.43	3.53
53	15	719.84	3.50
52	14	706.25	3.47
51	13	692.66	3.44
50	12	679.07	3.41
49	11	665.48	3.39
48	10	651.89	3.36
47	9	638.30	3.33
46	8	624.71	3.30
45	7	611.12	3.27
44	6	597.53	3.24
43	5	583.94	3.22
42	4	570.35	3.19
41	3	556.76	3.16
40	2	543.17	3.13
		Total Evacuation Time (hours)	**2.315077431**

Table 7 – *Floor-by-floor evacuation time estimation for Chrysler Building, New York*

Cost Analysis

Part of system	Estimated cost (in US dollars)
The car	200 (per person)
The harness	150 (per person)
The track	Dependent on building

Table 8 – *Cost Analysis*

The estimated cost of the complete system is approximately $400 per person, and includes a $50 per person amount for the cost of the track. However this number could vary depending on the building in question.

Conclusion

Analysis of the design suggests that the possible risks involved with the usage of this system would be the improper use of the harness leading to congestion during evacuation and the failure of individual harness/car systems. However improper usage can be prevented by training the occupants of the building with a routine similar to a regular fire drill in order to maintain calmness even under tense situations.

But apart from that, the design is feasible considering factors of manufacturability and practicality. It is cost effective and should be affordable by a larger section of society. There are no complicated procedures involved during the use of the harness making it user friendly. The device combined with a programming system to control the flow of people evacuating the building could further improve its ability to evacuate large numbers of people safely and quickly.

The design meets most of the initial needs established making it a feasible concept, however, the mechanics of how the centrifugal brake and the retractable wheels will operate needs to be worked on. The customization of this system to each building is another important aspect. The number of tracks and their locations tailor to meet the needs of a specific building based on its physical size and number of occupants. By changing the spring on the centrifugal brake, the speed of descent can be adjusted, and set to meet the needs of a specific building.

Resources

1. http://www.saferamerica.com/productDetail.asp?categoryID=15&productID=65
2. http://irc.nrc-cnrc.gc.ca/pubs/cbd/cbd174_e.html
3. http://www.emporis.com/en/bu/sk/st/tp/wo/
4. http://www.delmar.ca.us/NR/rdonlyres/0265A761-A223-47F7-9A29-26550A89ED5F/0/CH1004.pdf
5. http://howthingswork.virginia.edu/supplements/elevators.pdf
6. http://rescue-equip.com.au/REharnPETind.html
7. http://www.vintageviews.org/vv-ny/Ko/cards/nyc032.html
8. http://jfe.sagepub.com/cgi/content/abstract/14/1/33

Appendices

Appendix -1 (*Needs Metrics Matrix*)

Needs metrics	Still usable 95% of time after 4ft drop x 100	Cost <$750 per person	>99% survival rate	Can withstand 800^{o}F for > 5mins	Evacuates >50 people per minute	Total system occupies < 5% of floor space	>20 year shelf life	Requires < 1 hour of training per person	Requires < 10 mins to figure out how to use without prior instruction	Takes < 1 min to reach	Single person can escape < 5 mins
Robustness	X	X	X	X		X					
Cheap	X	X	X	X	X	X	X				
Safe	X	X	X	X	X						
Fire resistant		X	X	X							
Accommodates large volumes					X	X		X		X	X
Compact	X	X		X	X	X				X	
Long service life		X	X	X			X				
Easy to use			X		X			X	X	X	X
Accessible					X					X	X
Fast individual escape			X		X					X	X

Appendix 2 (*Concepts Generated*)

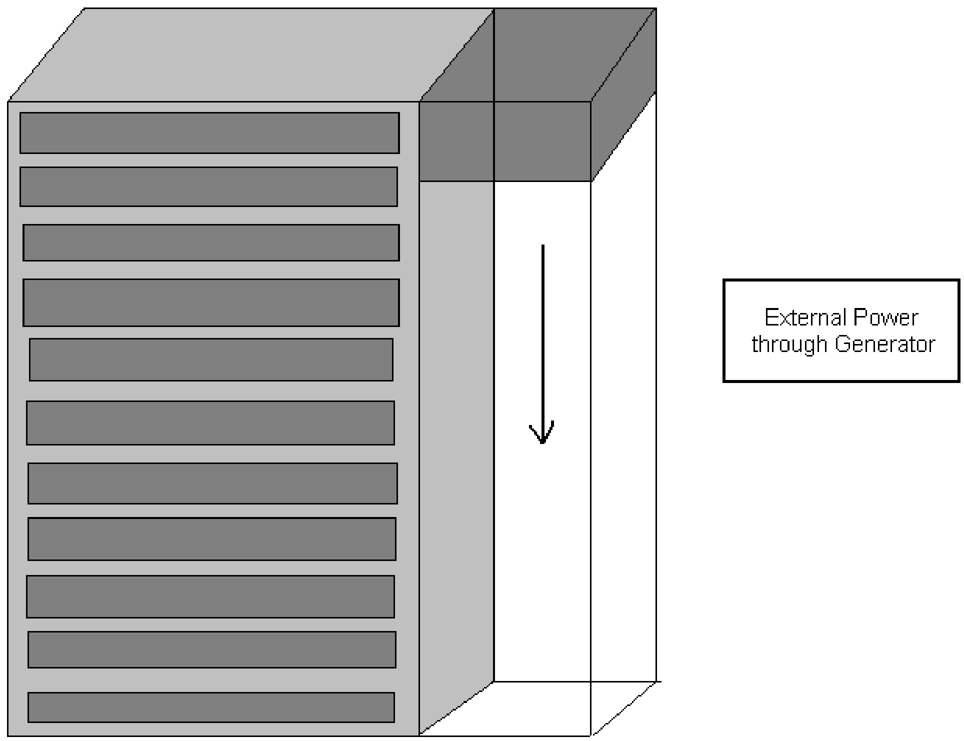
Inflatable tubular slide	Magnetic cushioning device
Indoor parachute channel	Zip Line
External Elevator	Abseil
Swirly Slide	Suite that inflates to Zorb
Bridges to adjacent buildings	Gliders on roof
Parachutes	Helicopters
Safe rooms	Hard external track with harness attached
Trampoline	Trap doors between floors
Ladders/Escalator/Escalator Ladder	Slip and Slide
Sky hook	Hot air balloon/Hovercraft
Device that hooks onto elevator cables to descend	Rocket shoes
Bungee jump stopping at bottom	Stun man bag

Appendix 3 (Individual Concept Surveys)

Survey 1	Elevator	Slide	Personal Rail Descent	Safe room	Bridge	Total wins
Elevator	X	4	7	6	5	22
Slide	6	X	8	5	4	23
Personal Rail Descent	3	2	X	2	3	10
Safe room	4	5	8	X	7	24
Bridge	5	6	8	3	X	22
Survey 2	Elevator	Slide	Personal Rail Descent	Safe room	Bridge	Total wins
Elevator	X	7	4	4	7	22
Slide	3	X	2	4	4	13
Personal Rail Descent	6	8	X	5	9	28
Safe room	6	6	5	X	5	22
Bridge	3	6	1	5	X	15
Survey 3	Elevator	Slide	Personal Rail Descent	Safe room	Bridge	Total wins
Elevator	X	1	2	3	0	6
Slide	10	X	8	9	7	34
Personal Rail Descent	9	3	X	9	4	25
Safe room	8	2	2	X	1	13
Bridge	11	4	7	10	X	32

Concept Sheets used in the survey follow

EXTERNAL ELEVATOR MECHANISM



An external elevator located along at least 2 sides of the building would be a pretty effective evacuative procedure. The elevator should be powered by a generator which doesn't derive power from the general mechanism of the building. In order to facilitate rescue workers and firefighters to move up the building, we could have a separate elevator so that the outflow of people isn't affected by the time it takes for the elevator to move back up to get people in.

Alternating the movement of the elevator could also help the people get to safety much quicker. It's advantageous as it could be built alongside construction and can carry a large load of people per drop off depending upon the capacity to which it's built.

SKYWALK EMERGENCY ESCAPE MECHANISM

Similar to the sky walk present in the Petronas Towers, Kuala Lampur, Malaysia, a sky walk system could be established between buildings. A passage way between two buildings once every 15 floors or so could help people reach a safer place without having to go to ground level.

Bridges would be constructed using materials that can withstand high wind pressure and turbulence owing to the upward deflection of winds that strike the base of the building.

The bridge shall merely consist of a metallic or concrete beam that is attached to both the buildings through diagonal supports spanning the height of roughly 5 to 6 floors. This way, irrespective of where the fire is, the people will be able to get to a floor of safety without having to go through the area that is affected by the fire.