A BRIEF REVIEW ON THE TIME LINE CONCEPT IN EVACUATION

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ABSTRACT

In studying evacuation, different components of evacuation time have to be well understood. These include evacuation time, Required Safe Egress Time (RSET), Available Safe Egress Time (ASET) and Total Evacuation Time (TET). In this paper, definitions and calculation methods for those time components will be reviewed. A time line of fire development and evacuation process with all those components reported in the literature is presented.

1. INTRODUCTION

Crowd movement is a concern in dealing with safety. There had been many hazards in extremely crowded spaces, such as the Lan Kwai Fong tragedy in Hong Kong [1] and Beijing incident in 2004 [2]. Those incidents were only in open areas without any hazards or terrorist attack. An accidental small fire in a crowded building could be very serious. Much greater damages would occur due to terrorists. Therefore, building evacuation should be dealt with carefully in fire safety provisions, especially for mass transport with large number of passengers staying inside.

Evacuation time is an important time concept in the evacuation process for recognizing the time required by the occupants to move from the hazard area to a safe region when they recognize the danger and start to evacuate. The margin of safety, which is the difference between the calculated value of the required evacuation time and available time for occupants to escape from the building, i.e. Required Safe Egress Time (RSET) and Available Safe Egress Time (ASET), can be used to determine the life safety in building. Real evacuation time for all occupants to evacuate from the building safely and reach a place of safety, i.e. Total Evacuation Time (TET), was highly concerned. However, TET of occupants in real fires is difficult to obtain. Therefore, it is likely to be achieved by simulations through different evacuation models in the commercial market.

Evacuation time, RSET, ASET and TET [e.g. 3-16] were studied extensively in the past decades. A literature review on evacuation time, RSET, ASET and TET was outlined to give a better understanding of the development of those time components and the other time components, i.e. pre-movement time, recognition time, response time, travel time, walking time and flow time, included in evacuation. A time line relating evacuation with the fire development is shown in Fig. 1.

In case of an emergency, different occupant groups from different areas would be merged before the exits [17]. Due to the reduction of flow rate at exits, congestion is likely to occur before the exits if large numbers of occupants evacuate at the same time. Queuing would be occurred and several steps are involved, i.e. approaching the queues, standing in queues, moving forward and passing through the exit [18]. The term “standing in queues” can be understood as the occupants wait in the queues. Waiting effects in queues should not be ignored as it will affect the movement of occupants and consequently lengthen the evacuation time.

Extensive work has been carried out on evaluating the waiting time in queues. Queuing time is further elaborated from the term “Time to queue formation” in BS 7974 [19]. Both the waiting time and moving time are involved. However, waiting time of occupants can be altered by the crowd density, selection of exits and number and width of the exits used.

2. EVACUATION TIME

The term “maximum emptying time” \( t_m \) (in min), being the time for clearing the occupants within the building, was introduced in the Engineering News Record by the NFPA Committee on Safety to Life in 1917 [20]. It was the earliest time concept involved in the evacuation process and was considered to be the evacuation time as reviewed by Pauls [12]. According to the National Bureau of Standards [21] on building exits, \( t_m \) can be reduced by utilizing a high flow rate in the exit design.
Fig. 1: Time line analysis

BSI = British Standards Institution, NFPA = National Fire Protection Association
Based on the purported successful evacuation time in a 1911 theatre fire in Edinburgh, $t_{ev}$ for buildings was specified to be 2.5 min [22].

Evacuation time is defined as the elapsed time between the instant that occupants receive an alarm or become aware of a fire and their arrival at a destination where it is normally a safe location inside or outside the building [e.g. 8,12,23,24]. It is now understood as the time interval between raising of alarm and completion of evacuation [19].

Evacuation was studied extensively by Togawa [3]. Examples were on mass evacuation of buildings across openings of department stores, theatres and station premises; moving out from elevators; and getting off from buses and trains. Railway station was observed to have high passenger loading during rush hours. Scenarios of passengers escaping from the train, moving in platform and passing through the exit were analyzed in determining the evacuation time of passengers in the railway station by Togawa [3].

A formula for calculating the evacuation time $t_{e1}$ (in s) for passengers to escape from the station platform was derived [3]. Taking a train with total number of escaping passengers $N_a$ and $n$ doors of width $B_i$ (in m) for the $i^{th}$ door (where $i = 1, ..., n$) as an example. Time $T_o$ (in s) is the period between the occupants moving out from the train and the queues start to form at platform exit. The number of passengers $N$ who can escape can be expressed in terms of the flow rate of people moving out from the $i^{th}$ train door $f_{pi}$ (in person m$^{-1}$s$^{-1}$), and percentage $\phi_i$ (in %) of the number of passengers gathering at the $i^{th}$ train door to the number of passengers going to other train doors:

$$N = \sum_{i=1}^{n} \int_{0}^{T_o} f_{pi}(t) B_i \phi_i(t) \, dt$$

After $T_o$, flow time $t_{f1}$ (in s) of passengers who can pass through the platform exit is in terms of the width of platform exit $B'$ (in m) and flow rate $f_p'$ (in person m$^{-1}$s$^{-1}$) passing through the exit:

$$t_{f1} = \frac{1}{f_p'} B' \left( N_a - N \right)$$

The evacuation time $t_{e1}$ can then be expressed as a sum of the time period $T_o$ for passengers to move out the train and begin to queue up before the platform exit, and flow time $t_{f1}$ of passengers who can pass through the platform exit after $T_o$ as:

$$t_{e1} = T_o + t_{f1}$$

A relatively simple expression can be derived for $T_o$ and $t_{f1}$ by assuming all passengers escaped from the furthest train door away from the platform exit (i.e. the last train door) [3]. Suppose the distance from the last train door to the platform exit is $k_e$ (in m) and the walking velocity of the crowd is $v$ (in ms$^{-1}$), $T_o$ is taken as the walking time $t_{w1}$ (in s) of passengers travelling to the platform exit:

$$T_o \approx t_{w1} = \frac{k_e}{v}$$

Equation (2) on $t_{f1}$ can be simplified by taking all passengers passing through the platform exit without jamming:

$$t_{f1} = \frac{N_a}{f_p'B'}$$

An approximate formula of $t_{e1}$ can be expressed as:

$$t_{e1} = t_{w1} + t_{f1}$$

The above expression on $t_{e1}$ derived by Togawa [3] was pinpointed on the station platform. It is only applicable to platforms with a single floor. In applying $t_{e1}$ to tall buildings, travel time in staircases should be considered.

Evacuation of multi-story buildings was studied by Galbreath [4]. Two time periods were defined in the evacuation time $t_{e2}$ (in s), i.e. the walking time $t_s$ (in s) of occupants to travel the staircase, and the flow time $t_{f1}$ required for occupants to discharge from the base of stairs and pass through the exit.

$$t_{e2} = t_s + t_{f1}$$

This equation holds when $T_o$ is shorter than $t_s$.

The effect of different occupant loadings on evacuation in multi-story buildings was considered by Melinek and Booth [5]. Consider a building that has $i$ floors, where $i = 1, ..., m$, the flow time $t_{f1}$ (in s) for the occupants on the $i^{th}$ floor and above to enter the staircase can be expressed by the number of occupants $Q_j$ on the $i^{th}$ floor and above, where $j = r, ..., m$; flow rate $f$ (in person m$^{-1}$s$^{-1}$) per unit width of the staircase and width of the staircase $b$ (in m) as:

$$t_{f1} = \frac{\sum_{j=r}^{m} Q_j}{f \times b}$$

Evacuation time $t_{e3}$ (in s) of occupants from the $i^{th}$ floors and above can be expressed in terms of the
flow time $t_{f1}$ (in s) and the walking time $t_{w1}$ (in s) for the unimpeded crowd on the $r^{th}$ floor to reach the ground floor.

$$t_{e3} = t_{w1} + t_{f1}$$

(9)

Psychological effects of occupants during evacuation were not considered in $t_{e1}$, $t_{e2}$ and $t_{e3}$. Once the occupants recognized the occurrence of fire, they are assumed to escape immediately. However, the response time $t_{r}$ (in s) of occupants to the warning prior to beginning the evacuation was considered by Smith [8] in determining the evacuation time $t_{e4}$ (in s) of occupant in an analytical queuing network. $t_{e4}$ in the algorithm will be regulated by the longest time path of an occupant to exit the building. The longest time path included $t_{r}$, walking time $t_{w2}$ (in s) and waiting time $t_{w1a1}$ (in s) at each queue to exit.

$$t_{e4} = t_{r} + t_{w2} + t_{w1a1}$$

(10)

Psychological effects of occupants during evacuation were further elaborated by Pauls [12]. Two major components, pre-movement time $t_{pr1}$ (in s) taken up by relatively complex behaviour that precedes or accompanies egress, and time for some individuals in the evacuating crowd to move along the most direct egress route, i.e. travel time $t_{t1}$ (in s), should be included in the calculation of evacuation time $t_{e5}$ (in s).

$$t_{e5} = t_{pr1} + t_{t1}$$

(11)

$t_{pr1}$ can be expressed in terms of the evaluation time $t_{ev}$ (in s) of recognizing the fire and deciding to take action, and the coping time $t_{c}$ that diverts the occupant from the most direct egress route once that person’s movement is initiated, e.g. inform others, assist others or fight the fire.

$$t_{pr1} = t_{ev} + t_{c}$$

(12)

The calculation of $t_{t1}$ is similar to $t_{e1}$ [3], which involved the walking time $t_{w1}$ to move along the egress route and flow time $t_{f1}$ through the opening of the egress system.

$$t_{t1} = t_{w1} = t_{w1a1} + t_{f1}$$

(13)

An evacuation model was established by Løvås [25]. The components of evacuation time $t_{e6}$ (in s) input into the model are similar to $t_{e4}$ [8], which are expressed in terms of $t_{r}$, $t_{w2}$ and $t_{w1a1}$.

$$t_{e6} = t_{e4} = t_{r} + t_{w2} + t_{w1a1}$$

(14)

Human behaviour, queuing effect and occupant loading had been considered by the British Standard [19] in calculating the evacuation time $t_{e7}$ (in s). Two cases are specified for $t_{e7}$ with respect to different occupant density [e.g. 26,27].

Case 1: Lower occupant density

The enclosure is sparsely populated with a population density, say, less than 1/3 of the design population [26,27]. Due to the low occupant density, walking speed to exits is unimpeded. Pre-movement time is longer in lower occupant density as occupants may not be aware of the fire or get the information from others to escape [26,27]. Therefore, $t_{e7}$ is expressed in terms of the pre-movement time $t_{p99}$ (in s) and walking time $t_{w3}$ (in s) of the last few occupants, which is equal to the unimpeded walking speed multiplied by the average or maximum travel distance.

$$t_{e7} = t_{p99} + t_{w3}$$

(15)

Case 2: Higher occupant density

The enclosure contains the maximum design population. At such high occupant loading, pre-movement time is shorter as occupants can recognize the occurrence of fire easily through the communication with others and evacuate together [26,27]. Therefore, $t_{e7}$ can be expressed in terms of the pre-movement time $t_{p1}$ (in s) and walking time $t_{w4}$ (in s) of the first few occupants, and flow time $t_{f1}$ for the total number of occupants to pass through the available exits.

$$t_{e7} = t_{p1} + t_{w4} + t_{f1}$$

(16)

3. REQUIRED SAFE EGRESS TIME (RSET)

Several definitions for the “Time required for escape” were reported in the literature [3,6,7,28]. It is the time taken for an individual or building population to reach safety, which can be understood as the target time for ensuring complete evacuation and all occupants remain safe for any portion of the time spent inside the building. Psychological effects of occupants were considered by Marchant [6,7] in determining the “Time required for escape” $t_{e1}$ (in s). $t_{e1}$ can be expressed in terms of the elapsed time from ignition to perceive that a fire exists, i.e. perception time $t_{p}$ (in s), elapsed time from recognition to the beginning of safety action, i.e. response time $t_{r}$ and elapsed time from initiation of action to reach a safe place, i.e. travel time $t_{t1}$:

$$t_{e1} = t_{p} + t_{r} + t_{t1}$$

(17)

The term “Required Safe Egress Time” (RSET) was identified by Pauls [29]. Three terms were
involved in the calculation of RSET $t_{R1}$ (in s) [29], i.e. recognition time $t_{rc}$ (in s) from being alerted by a cue to know that there is a fire, response time $t_r$ from knowing that there is an emergency to begin escape and travel time $t_{t1}$ for beginning escape to leave the building.

$$t_{R1} = t_{rc} + t_r + t_{t1}$$

RSET $t_{R2}$ (in s) was illustrated by Stahl et al. [10]. $t_p$ and $t_r$ utilized in $t_{re1}$ [6,7] were further divided into a number of discrete time intervals [10]. $t_p$ can be expressed in terms of the detection time $t_{de}$ (in s) required for sensation of a stimulus from fire environment, notification time of sensation $t_a$ (in s) and recognition time $t_{rc}$ required to become aware of this sensation as a potential life threat, while $t_r$ was understood as the time $t_d$ (in s) required to evaluate the quality and extent of life threat and coping time $t_c$ required to initiate effective actions. The travel time $t_{t1}$ needed to escape from the building was represented by the time required to follow-through and complete actions leading to safety.

$$t_{R2} = t_{de} + t_a + t_{rc} + t_d + t_c + t_{t1}$$

RSET was defined by Cooper [11] as the length of time, subsequent to alarm, which is actually required for safe occupant egress from threatened spaces. It can also be understood as the overall time needed for occupants to evacuate the building in response to a cue [30-32]. According to Sime [33], RSET $t_{R3}$ (in s) can be divided into two parts, i.e. psychological time component $t_{ps}$ (in s) and physical time component $t_{ph}$ (in s).

$$t_{R3} = t_{ps} + t_{ph}$$

Times involved in $t_{ps}$ are related to human behaviour when there is a fire occurred, i.e. recognition time $t_{rc}$ from people being alerted by a cue to recognize that there is a fire, decision time $t_d$ related to the decisions to take which actions, and coping time $t_c$ which includes actions after recognition, such as warn the others and fight fire.

$$t_{ps} = t_{rc} + t_d + t_c$$

The time components involved in $t_{ph}$ are the physical movement of occupants during evacuation. $t_{ph}$ can be expressed in terms of the walking time $t_{w1}$ and flow time via exits $t_{f1}$, which is similar to $t_{re1}$ [3].

$$t_{ph} = t_{w1} + t_{f1}$$

RSET $t_{R4}$ (in s) was sub-divided by Buchanan [34] into a number of discrete time intervals. As occupants have undergone hazards once a fire started, detection time $t_{de}$ and notification time $t_a$ were involved in the calculation of $t_{R4}$. Except $t_{de}$ and $t_a$, recognition time $t_{rc}$, response time $t_r$, movement time $t_{w2}$ and waiting time $t_{wa1}$ were also considered in the calculation.

$$t_{R4} = t_{de} + t_a + t_{rc} + t_r + t_{w2} + t_{wa1}$$

RSET $t_{R5}$ (in s) raised by Harold et al. [35] was similar to that by Buchanan [34]. $t_{R5}$ involved the time from fire ignition to detection $t_{de}$, time from detection to notification of occupants in case of fire $t_a$, time from notification until occupants decide to take action $t_{tc}$, and time from decision to take action until evacuation commences $t_r$. $t_{de}$ and $t_a$ are affected by the performance of fire detection devices and fire alarm equipment, while $t_r$ and $t_c$ are related to the individual and collective responses of occupants until they start to evacuate. Instead of walking time and waiting time, the travel time $t_{t1}$ of occupants from the initiation of evacuation until it is completed would be comprised in $t_{R5}$ as:

$$t_{R5} = t_{de} + t_a + t_{rc} + t_r + t_{t1}$$

The term RSET was only involved in BS 7974 [19]. For the earlier versions, such as draft code of practice [36] and technical report [37], it only included the term “escape time” rather than RSET. The escape time [19] is the interval between ignition and the time in which all occupants are able to reach a place of safety. It is the real time that the occupants needed to evacuate. For the calculated escape time of occupants, i.e. RSET, it is the calculated time available between ignition of a fire and the time at which occupants in a specified place of building are able to reach a place of safety [19]. RSET $t_{R6}$ (in s) of occupants [19] depended upon series of processes. It is similar to $t_{R5}$ [35], which also included the terms $t_{de}$, $t_a$, $t_{rc}$, $t_r$ and $t_{t1}$.

$$t_{R6} = t_{R5} = t_{de} + t_a + t_{rc} + t_r + t_{t1}$$

4. AVAILABLE SAFE EGRESS TIME (ASET)

“Time available” $t_{av}$ (in s) was identified before the establishment of Available Safe Egress Time ASET. $t_{av}$ was pointed out by Caravaty and Haviland [28] to be the time required for toxic environment to reach a critical or untenable state. $t_{av}$ was also stated by Marchant [6,7] as the elapsed time from ignition of fire to develop to untenable environmental conditions.

Later, the term ASET was developed by Cooper [11]. It is the time interval between the initiation of alarm and the time of onset of hazardous conditions. “Time available” aspects were worked out with a
The fire zone model by Cooper [11] accounts for the length of time after initiation of an alarm to carry out a safe egress from threatened spaces. Occupants would be safe under fire conditions if they successfully escape from threatened spaces prior to the time when hazardous conditions start to prevail. ASET \( t_A1 \) (in s) can be expressed in terms of the detection time \( t_{de} \), notification time \( t_a \), and the time of onset of hazardous conditions \( t_h \) (in s) as:

\[
t_A1 = t_h - t_{de} - t_a \quad (26)
\]

ASET \( t_A2 \) (in s) [19] can be expressed in terms of \( t_{R6} \) and the time difference between \( t_A2 \) and \( t_{R6} \), which is known as the margin of safety \( t_{ma} \) (in s):

\[
t_A2 = t_{R6} + t_{ma} \quad (27)
\]

The time taken for an individual or building population to reach a place of safety, should not exceed the time required for the environment to reach a critical or untenable state [e.g. 6,7,11,28]. Relative to a potential hazardous fire, a building is of safe design if ASET \( > \) RSET, whereas \( t_{ma} \) should be at least 0 s. It is essential to identify \( t_{ma} \) for ensuring life safety, provided that occupants are evacuated in a safe condition without causing incapacitation. All occupants should be able to evacuate before ASET is reached.

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\[
t_{A2} = t_{R6} + t_{ma} \quad (27)
\]

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\[
SI = \frac{t_{ma}}{t_{R6}} \quad (28)
\]

SI is used as a benchmark to identify the life safety of occupants in a building. The increasing values of index indicate the increased levels of safety, while the increased levels of risk are indicated by the decreased values of SI.

5. TOTAL EVACUATION TIME (TET)

ASET and RSET are the calculated values for assessing the safety of occupants in a building. However, it is necessary to determine the time for all occupants to evacuate from the building safely and reach a place of safety [e.g. 9]. The term TET constituted is to assess the evacuation time required for all occupants to leave the building [e.g. 9]. It is the travel time of the last evacuee from the top floor to the final exit [e.g. 5,9,14,38,41].

TET \( t_{T1} \) (in s) raised by Kendik [41] is expressed in terms of the flow time \( t_{f2} \) (in s) required for the flow to be terminated at the \( (r - 1)^{th} \) floor, where \( r = 1,…….m \); walking time of the occupants \( t_{er} \) (in s) coming from the overcrowded areas at the \( (r - 1)^{th} \) floor and the waiting time \( t_{wa2} \) (in s) due to congestion in the escape routes. The calculation has a great emphasis on the jamming conditions occurred in the crowd movement, while the pre-movement time, such as recognition time and response time, was not included.

\[
t_{T1} = t_{f2} + (r - 1) t_{er} + (r - 2) t_{wa2} \quad (29)
\]

Psychological effects of occupants were considered by Sime [38] in TET \( t_{T2} \) (in s). The time to recognize a dangerous situation \( t_{rc} \), response time to decide for evacuation \( t_r \) and travel time \( t_{t1} \) were involved in the calculation as:

\[
t_{T2} = t_{rc} + t_r + t_{t1} \quad (30)
\]

TET of occupants escaped in real fires is difficult to obtain. Therefore, it is likely to be achieved by simulations through different evacuation software, e.g. EXIT 89, EGRESS, buildingEXODUS and SIMULEX. TET simulated by those commercial models can act as a reference for recognizing the time taken for all occupants to pass through available exits [16]. A rough estimation of TET \( t_{T3} \) (in s) [15] can be determined by the time for one person to traverse the maximum travel distance \( t_{wa2} \), time taken for the entire population to pass through the available exits \( t_q \) (in s) and average response time \( t_r \) as:

\[
t_{T3} = t_r + t_{wa2} + t_q \quad (31)
\]

6. PRE-MOVEMENT TIME

Pre-movement time \( t_{pr1} \) (in s) can be understood as the time taken up by relatively complex behaviour during evacuation as identified by Pauls [12]. Two components, i.e. the period of recognition time and decision time \( t_{rc} \) and coping time \( t_c \), are involved in calculating \( t_{pr1} \).
Pre-movement time is the time interval between the warning of fire being given (by an alarm or by direct sight of smoke or fire) and first move being made towards an exit [19,37]. The time will affect the flow of people in a building. For example, the rate of people entering the exits will be different when the occupants are moving together or at different times. Pre-movement time \( t_{pr2} \) (in s) [19] can be expressed in terms of the recognition time \( t_{rc} \) and response time \( t_r \) as:

\[
t_{pr2} = t_{rc} + t_r
\]

(33)

The pre-movement time distribution [19] is consisted of three phases.

- The time from alarm to the movement of the first few occupants to begin their travel phase, i.e. pre-movement time of first occupants \( t_{p1} \).

- The subsequent distribution of pre-movement times for the population of occupants to begin their travel phase. This can be expressed as a distribution of individual times or represented by a single time, i.e. pre-movement time occupant distribution \( t_{p50} \) (in s).

- The time from raising of a general alarm to the movement of the last few occupants to begin their travel phase, i.e. pre-movement time of last few occupants \( t_{p99} \).

\( t_{pr2} \) for total occupants [19] can also be expressed in terms of \( t_{p1} \) and \( t_{p99} \) as:

\[
t_{pr2} = t_{p1} + t_{p99}
\]

(34)

It was pointed out by Spearpoint [42] that for short values of pre-movement time, evacuation time is dominated by travel time, where waiting effects are significant. If pre-movement time is long, travelling and waiting effects become a smaller percentage and hence appear to be less important. For very long pre-action, pre-movement time dominates evacuation time even when the occupant loading is high. When pre-movement time lies between these two extremes, evacuation time is affected by occupant loading and pre-movement time of each occupant [42].

Pre-movement time of occupants is a factor affecting the formation of queue [42]. Rate of people joining the queues will be different when the occupants are moving together or at different times [42]. If the people are moving together with identical travel speed, more occupants would arrive at the exit simultaneously and hence constitute the jamming situations.

7. TRAVEL TIME

Definitions of travel time in those literatures [12,15,43] are similar, i.e. time for the person in evacuating crowd who moves from a point of origin where his/her evacuation is considered complete. As mentioned in BS 7974 [19], travel time is the time needed once movement towards an exit has begun, for all occupants in a specified part of the building to reach a place of safety. Travel distance is an important factor in affecting the travel time. It can be used to calculate the travel time when the travel speed is known.

As mentioned in BS 7974 [19], three components were considered in travel time \( t_t \). These are the walking time \( t_{w1} \), i.e. average time required for occupants to move from their starting location to a protected escape route or outside of the building; time to queue formation at exits \( t_{qf} \) (in s), i.e. time from raising of a general alarm to that when queues are formed at exits; and flow time \( t_f \), i.e. time required for people to pass through a particular exit.

\[
t_t = t_{w1} + t_{qf} + t_f
\]

(35)

Travel time \( t_2 \) (in s) mentioned by Spearpoint [42] is expressed only in terms of the walking time \( t_{w1} \) and queuing time \( t_q \), where the flow time was not included.

\[
t_2 = t_{w1} + t_q
\]

(36)

8. OTHER TIME COMPONENTS

- Recognition time

Recognition time was mentioned by Sime [38] as the time to recognize the dangerous situation. It is also the time before the occupants start to move [44]. In British Standards [19,37], recognition time is defined as the period after an alarm or cue is evident but before the occupants begin to respond. The time will be ended when occupants have accepted that there is a need to respond [e.g. 19,37,38,44].

Before activation of an alarm, occupants may engage in activities such as waiting for check-in or check-out, working and shopping. Length of recognition period can be varied seriously, depending on the types of building, nature of occupant and alarm and management system [19,37].
• Response time

After the occupants have accepted that there is an emergency occurred, they need to take time to respond [5]. Response time is defined as the time taken to receive and interpret the information of emergency and make preparations for evacuation [e.g. 5,8,41]. As mentioned in the British Standards [19,37], response time is the period after occupants recognize the alarms or cues and begin to respond to them before the start of the travel phase of evacuation.

Occupants near the emergency location may be more aware of the risk, they would react and evacuate earlier than those far away from the hazardous areas [5]. Response time can be significantly reduced by providing clear, prompt and accurate information to occupants [43]. Many factors will affect the response of occupants. For instance, the level of occupants committed to other activities, their mental and physical state, extent to which they are trained to respond to warnings, the level they feel endangered by fire, their role and responsibilities [19,37].

• Walking time

Walking time is the time for the movement towards safety [38]. According to Thompson and Marchant [45], it is the time to walk from the most remote point in a building to the exit. Walking time is the time needed for all occupants in a specified part of a building to move to an exit [37], which depends upon the walking speed of each occupant and their distance from an exit [e.g. 46].

According to BS 7974 [19], walking time is the time taken for a person to walk from their starting position to the nearest exit, assuming the walking speed is unrestricted. It represents the minimum time required to walk to the exit as no allowance is made for the possibility of impeded walking due to high levels of occupant density within the enclosure [19].

• Flow time

Flow time [e.g. 5,41,46] is the total time taken for a number of people to pass an element in the egress route. It is simply a function of the crowd flow capacity of usable width of a particular circulation element and the number of people to be moved through it [12].

Flow time mentioned in BS 7974 [19] is the time for occupants to evacuate an enclosure, assuming all occupants are available at exits and the use of exits is optimal. It is determined by the flow capacity of exits and represented by the total time required for the occupant population to flow through exits.

9. QUEUING

When people arrive at the exit and identify that it is obstructed by others, a change in the speed of movement would be resulted. Occupants will slow down their pace and reduce the walking velocities gradually to keep a comfortable distance between themselves and the others, and avoid treading on the heel of the front person [47,48]. They will shuffle along slowly if getting close [12,47]. Finally, occupants will become stationary when there is no space for them to move [45]. Waiting period of occupants then commences. They will wait in the queues until there is room for them to move forward.

• Occurrence of queuing

Waiting lines are formed when the current demand for service exceeds the current capacity to provide services [49,50]. Applying this concept in evacuation, queues are developed when the rate of occupants passing through the exit is slower than the arrival rate of people trying to get out [51].

Occupants from different areas would be merged before the exit [52]. If the rate of people arriving at the exit is larger than the maximum flow rate that can be sustained through the exit, queues would be developed [52].

Two types of queues, i.e. ordered queue and bulk queue, may be formed before the exits. For an ordered queue, priority of queuing is on the basis of ‘first come, first served’, while bulk queue is characterized by the unordered and deficiency of the queue discipline [46]. Some people may lack patience and want to overtake the front person to reach the exit [53,54]. They may side-step the blockage, move faster and then walk in front of the slower person [15]. If occupants cannot overtake the front person, they may only stand around the ordered queue, wait for a chance to pass the queue and enter the exit [47]. Formation of bulk queues affects the flow rate of exit such that occupants are needed to use a longer time to pass through the exit [42]. On the other hand, close pack bulk queue of occupants will cause people anxiously waiting or competing to enter the exit [12]. Crushing force between people is increased, thus giving rise to panic when they cannot leave the building rapidly or enter a safe area [5].
Background of waiting time

As mentioned by Togawa [3], “waiting time” can be understood as the delaying time for the crowd to pass through the platform exit. A formula of the number of passengers \( \varphi \) who would be jammed before the platform exit was indicated [3]. It is the difference between the number of passengers escaping from the train with respect to time \( T \) (in s), say \( y_1 \), and the passengers who can pass through the platform exit, say \( y_2 \). \( y_1 \) and \( y_2 \) are expressed in terms of \( f_{p_i}, B_i, \phi_i \) and \( T \), for \( i = 1, \ldots, n \); while \( f_{p_i}', B' \) and \( T_0 \) are also included in \( y_2 \).

\[
y_1 = \sum_{i=1}^{n} \int_{0}^{T} f_{p_i}(t) B_i \phi_i(t) \, dt \tag{37}
\]

\[
y_2 = \sum_{i=1}^{n} \int_{0}^{T} f_{p_i}(t) B_i \phi_i(t) \, dt - \left( \sum_{i=1}^{n} \int_{0}^{T_0} f_{p_i}(t) B_i \phi_i(t) \, dt + (T - T_0) f_{p_i}' B' \right) \tag{38}
\]

\( \varphi \) can be expressed in terms of \( y_1 \) and \( y_2 \) as:

\[
\varphi = y_1 - y_2 = \sum_{i=1}^{n} \int_{0}^{T} f_{p_i}(t) B_i \phi_i(t) \, dt - \left( \sum_{i=1}^{n} \int_{0}^{T_0} f_{p_i}(t) B_i \phi_i(t) \, dt + (T - T_0) f_{p_i}' B' \right) \tag{39}
\]

By differentiating \( \varphi \), two values of \( T \), i.e. the time \( T_0 \) that the crowd begins to wait at the platform exit, and the time \( T_m \) (in s) when maximum number of passengers queue up at the exit, can be obtained.

\[
\frac{d\varphi}{dT} = \sum_{i=1}^{n} f_{p_i}(T) B_i \phi_i(T) - f_{p_i}' B' = 0 \tag{40}
\]

\( \frac{d\varphi}{dT} \)

Taking the occupants travelled from the corridor to a wider staircase as an example, traffic capacity of occupants in corridor and staircase are \( C_c \) (in \( m^2 \text{min}^{-1} \)) and \( C_s \) (in \( m^2 \text{min}^{-1} \)) respectively. \( \tau \) with respect to \( C_c \) and \( C_s \) can be expressed as:

\[
\tau = Q \times H \left( \frac{1}{C_c} - \frac{1}{C_s} \right) \tag{44}
\]

Delaying time in queues was interpreted by Fruin [46] as the period of occupants required to stand in a stationary position as a result of queuing. It is included in the calculation of \( t_q \) by Smith [8] and TET by Kendik [41]. Delay time at queues can also be understood as the time that a person has to wait to enter the exit [51]. Occupants are forced to remain stationary and standing exactly behind the front person until that person moves [45]. A term “Cumulative Waiting Time” (CWT) was defined by Owen et al. [15] as the total amount of time occupants remain stationary as a result of conflicts or queuing due to crowding, i.e. the time that occupants have to occupy in congestion [53,54].

Consideration of the components in queuing time

Queuing time \( t_q \) is not solely included the waiting period in queues. Movement in queues should also be considered [e.g. 5,12,46]. \( t_q \) is suggested to involve two components, i.e. waiting time \( t_{wa3} \) (in s) and moving time \( t_{mo} \) (in s). \( t_{wa3} \) can be understood as the stationary time in queuing, while \( t_{mo} \) is the time taken for a person to move in a queue before reaching the exit [46].

\[
t_q = t_{wa3} + t_{mo} \tag{45}
\]

10. CONCLUSIONS

Key terms and components in evacuation time including RSET, ASET, TET are reviewed. A clearer picture of the evacuation process was illustrated. Development of those time components was also discussed. For example, evacuation time of occupants (such as \( t_e \)) was only applicable to single-story buildings at the beginning. Effects of occupant loading in multi-story buildings and psychological effects of occupants were considered later.

Components with psychological effects, such as recognition time and response time, were included in RSET and TET. Those components were
generalized as the term “pre-movement time” of occupants before starting to evacuate.

Psychological effects of occupants are very important in case of emergency. All actions of occupants taken in evacuation would be affected. Therefore, human behavior should be studied more carefully. However, this cannot be studied only by fire engineers and scientists. Psychologists should be involved.

Waiting time would be a dominant factor in evacuation time under crowded condition. This will be addressed separately.

NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>b</td>
<td>exit width, m</td>
</tr>
<tr>
<td>B</td>
<td>width of train door, m</td>
</tr>
<tr>
<td>B'</td>
<td>width of platform exit, m</td>
</tr>
<tr>
<td>C</td>
<td>traffic capacity of occupants, m²/min⁻¹</td>
</tr>
<tr>
<td>Cc</td>
<td>traffic capacity of occupants moved to a section in corridor, m²/min⁻¹</td>
</tr>
<tr>
<td>Ci</td>
<td>traffic capacity of occupants moved to a section in staircase, m²/min⁻¹</td>
</tr>
<tr>
<td>D</td>
<td>density of flow, m³/min⁻¹</td>
</tr>
<tr>
<td>f</td>
<td>flow rate, person m⁻¹s⁻¹</td>
</tr>
<tr>
<td>fp</td>
<td>flow rate of people moving out the train door, person m⁻¹s⁻¹</td>
</tr>
<tr>
<td>fp'</td>
<td>flow rate of people passing through the platform exit, person m⁻¹s⁻¹</td>
</tr>
<tr>
<td>H</td>
<td>area of horizontal projection of people, m²</td>
</tr>
<tr>
<td>kₙ</td>
<td>shortest distance from the last train door to platform exit, m</td>
</tr>
<tr>
<td>l</td>
<td>length of the flow, m</td>
</tr>
<tr>
<td>m</td>
<td>number of floors</td>
</tr>
<tr>
<td>n</td>
<td>number of train doors</td>
</tr>
<tr>
<td>N</td>
<td>number of passengers who can escape through various train doors</td>
</tr>
<tr>
<td>Nₙ</td>
<td>total number of passengers inside the train</td>
</tr>
<tr>
<td>Q</td>
<td>number of occupants</td>
</tr>
<tr>
<td>s</td>
<td>speed of flow, ms⁻¹</td>
</tr>
<tr>
<td>t'</td>
<td>thickness of a person, m</td>
</tr>
<tr>
<td>tₕ</td>
<td>time from detection to notification of occupants, s</td>
</tr>
<tr>
<td>tₜₑ</td>
<td>time required for toxic environment to reach a critical or untenable state, s</td>
</tr>
<tr>
<td>tₐ₁</td>
<td>ASET by Cooper (1983), s</td>
</tr>
<tr>
<td>tₐ₂</td>
<td>ASET by British Standards Institution (2004), s</td>
</tr>
<tr>
<td>tₜ</td>
<td>time component due to any behaviour that diverts an individual from the most direct egress route once that person’s movement is initiated, s</td>
</tr>
<tr>
<td>tₙ</td>
<td>time required to evaluate quality and extent of life threat, s</td>
</tr>
<tr>
<td>tₕₑ</td>
<td>detection time required for sensation of a stimulus from fire environment, s</td>
</tr>
<tr>
<td>tₑ₁</td>
<td>evacuation time by Togawa (1955), s</td>
</tr>
<tr>
<td>tₑ₂</td>
<td>evacuation time by Galbreath (1969), s</td>
</tr>
<tr>
<td>tₑ₃</td>
<td>evacuation time by Melinek and Booth (1975), s</td>
</tr>
<tr>
<td>tₑ₄</td>
<td>evacuation time by Smith (1982), s</td>
</tr>
<tr>
<td>tₑ₅</td>
<td>evacuation time by Pauls (1987), s</td>
</tr>
<tr>
<td>tₑ₆</td>
<td>evacuation time by Lovás (1995), s</td>
</tr>
<tr>
<td>tₑ₇</td>
<td>evacuation time by British Standards Institution (2004), s</td>
</tr>
<tr>
<td>tₑ₉</td>
<td>walking time of the occupants coming from the overcrowded areas at the (r - 1)th floor, s</td>
</tr>
<tr>
<td>tₑ₀v</td>
<td>evaluation time of recognizing the fire and deciding to take action, s</td>
</tr>
<tr>
<td>tₑ₁</td>
<td>flow time of passengers passing through the exit, s</td>
</tr>
<tr>
<td>tₑ₂</td>
<td>flow time required for the flow to terminate at the (r - 1)th floor, s</td>
</tr>
<tr>
<td>tₑ₅o</td>
<td>time of onset of hazardous conditions, s</td>
</tr>
<tr>
<td>tₑ₅n</td>
<td>maximum emptying time, min</td>
</tr>
<tr>
<td>tₑ₆ₐ</td>
<td>margin of safety, s</td>
</tr>
<tr>
<td>tₑ₉₀</td>
<td>time taken for a person to move in a queue before reaching exit, s</td>
</tr>
<tr>
<td>tₑ₇p</td>
<td>elapsed time from ignition to perceive that a fire exists, s</td>
</tr>
<tr>
<td>tₑ₈₁</td>
<td>pre-movement time for the first few occupants, s</td>
</tr>
<tr>
<td>tₑ₉₅₀</td>
<td>subsequent distribution of pre-movement times for the population of occupants to begin their travel phase, s</td>
</tr>
<tr>
<td>tₑ₉₉₉</td>
<td>pre-movement time for the last few occupants, s</td>
</tr>
<tr>
<td>tₑ₉₉₈</td>
<td>physical time component, s</td>
</tr>
<tr>
<td>tₑ₉₁₈</td>
<td>pre-movement time by Pauls (1987), s</td>
</tr>
<tr>
<td>tₑ₉₉₂</td>
<td>pre-movement time by British Standards Institution (2004), s</td>
</tr>
<tr>
<td>tₑ₉₈</td>
<td>psychological time component, s</td>
</tr>
<tr>
<td>tₑ₉₉₈</td>
<td>time taken for entire population to pass through available exits, s</td>
</tr>
<tr>
<td>tₑ₉₉₉</td>
<td>time to queue formation at exits, s</td>
</tr>
<tr>
<td>tₑ₉₉₈</td>
<td>response time of occupants to the warning prior to beginning the evacuation, s</td>
</tr>
<tr>
<td>tₑ₉₉₉</td>
<td>recognition time from people being alerted by a cue, s</td>
</tr>
<tr>
<td>tₑ₉₁₈</td>
<td>time required for escape by Marchant (1976), s</td>
</tr>
<tr>
<td>tₑ₉₁₈</td>
<td>RSET by Pauls (1980), s</td>
</tr>
<tr>
<td>tₑ₉₂₈</td>
<td>RSET by Stahl et al. (1982), s</td>
</tr>
<tr>
<td>tₑ₉₃₈</td>
<td>RSET by Sime (1996), s</td>
</tr>
<tr>
<td>tₑ₉₄₈</td>
<td>RSET by Buchanan (2001), s</td>
</tr>
<tr>
<td>tₑ₉₅₈</td>
<td>RSET by Harold et al. (2002), s</td>
</tr>
<tr>
<td>tₑ₉₆₈</td>
<td>RSET by British Standards Institution (2004), s</td>
</tr>
<tr>
<td>tₑ₉₉₈</td>
<td>walking time of occupants required to travel the staircase, s</td>
</tr>
<tr>
<td>tₑ₉₉₉</td>
<td>walking time for the unimpeded crowd in the rth floor to reach the ground floor, s</td>
</tr>
<tr>
<td>tₑ₉₁₈</td>
<td>travel time needed to reach a safe place, s</td>
</tr>
<tr>
<td>tₑ₉₂₈</td>
<td>travel time by Spearpoint (2004), s</td>
</tr>
<tr>
<td>tₑ₉₃₈</td>
<td>TET by Kendik (1983), s</td>
</tr>
<tr>
<td>tₑ₉₄₈</td>
<td>TET by Sime (1986), s</td>
</tr>
<tr>
<td>tₑ₉₅₈</td>
<td>TET by Owen et al. (1996), s</td>
</tr>
</tbody>
</table>
\( t_{w1} \) walking time of occupants travelling to the exit, s
\( t_{w2} \) walking time for one person to traverse the maximum travel distance, s
\( t_{w3} \) walking time of the last few occupants, s
\( t_{w4} \) walking time of the first few occupants, s
\( t_{w5} \) waiting time at each queue to exit, s
\( t_{w6} \) waiting time due to congestion in the escape routes, s
\( t_{w7} \) stationary time in queuing, s
\( T \) time, s
\( T_m \) time for the delaying crowd to form the maximum mass at the platform exit, s
\( T_o \) time for the crowd to start to form at the exit in platform, s
\( v \) walking velocity of the crowd, ms\(^{-1}\)
\( w \) width of a person, m
\( y_1 \) number of passengers escaping from the train with respect to time \( T \)
\( y_2 \) number of passengers flowing out the platform exit

Greek symbols
\( \phi \) percentage of the number of passengers gathering at one of the train doors to the number of passengers going to other train doors, %
\( \varphi \) formula of delaying crowd
\( \tau \) duration of delay of movement during queuing, min
\( \delta \) width of the flow, m

REFERENCES

52. P.A. Thompson and E.W. Marchant, “Testing and application of the computer model 'SIMULEX'"

