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An analysis of factors affecting available safe escape time

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Abstract. This paper deals with some of the parameters that affect the available safe evacuation time (ASET), including fire growth rate, enclosure area, and thermal properties of the bounding construction. Although the available safe escape time is a crucial design parameter, it is, or has to be, often generalised to cover a range of scenarios; this is also the case of design codes. It is therefore necessary to be aware in which aspects such generalisation is possible. A set of computer model cases, carried out in CFAST, is analysed and the effect of individual variables quantified. As real fires usually grow exponentially with time, the t^2-fire model was used, employing the standard fire growth rates. By analysing the computer model scenarios, it was found that increasing the size of the enclosure does not bring proportional growth of available safe escape time. It is the rate of fire growth that is the primary factor affecting the safe available escape time. Two different smoke layer height tenability criteria – 0.9m and 1.5m – are also compared; the first derived from literature and the latter represent a more conservative estimate.

Introduction

The basis of all evacuation calculations and escape route design is the available safe escape (egress) time – ASET. In fire engineering calculations (eg. [1]), it is found as a direct input quantity, which the designer must establish in order to be able to assess the feasibility of their means of escape. In other design standards, it may also be used as a direct input value (eg. [2]) or be "hidden" in the maximum allowable length of escape routes and their minimum required width for a given type of occupancy [3], [4].

As such, the available safe escape time may be very difficult to quantify, especially when searching for a general value; for example a single ASET value that should represent an occupancy type in general. Since the available evacuation time is directly connected to the development of a fire it is also dependent on the same variables – compartment geometry, rate at which a fire develops, ventilation conditions to list a few.

In this paper, selected parameters are analysed in respect to their influence on the overall available safe escape time. It should be noted that the analysis herein does not account for delays in fire notification or pre-evacuation movement. These should be accounted for when determining the required safe escape (egress) time – RSET.

Modelling software - CFAST

To carry out the calculations of fire dynamics necessary for establishing the conditions in the modelled enclosure a software model CFAST - *Consolidated Model of Fire Growth and Smoke Transport* by NIST was used. CFAST is a two-zone fire model used to calculate the evolving distribution of smoke, fire gases and temperature throughout compartments of a building during a fire [5].

The model was selected because evacuation is carried out in the development (growth) phase of a fire, i.e. pre-flashover. This phase is characteristic by the presence of two distinct layers or zones – hot (smoke gases) and cold (air). The height and temperature of the upper layer determines for how long the enclosure is tenable.

Further details regarding the governing equations, assumptions and limitations of the modelling software are in [6].

Model description

To determine the available safe escape time it is important to consider a range of parameters. In this paper the effects of the following parameters were analysed:

- size of enclosure,
- thermal properties of construction material,
- fire growth rate.

The above parameters were selected and varied to represent some real-world examples and determine their influence on the available evacuation time.

Two different sizes of enclosure were used – 100 m^2 (10x10 m) and 500 m^2 (25x20 m). These sizes were also selected due to a higher number of occupants expected; although strongly dependent on the occupancy type, the number of occupants would likely start at 20 and 100 occupants, respectively. An example of such occupancy types would be a meeting room or auditoria.

In order to simulate a realistic worst case scenario it was assumed that all openings (doors, windows) were closed and intact. This is a reasonable assumption as the expected temperature profiles are relatively low – under 183°C (see below for discussion). Therefore, the only ventilation of the enclosure is via leakage areas which were assumed to be 0.01% of the enclosure floor area. This represents gaps and leaks around doors and windows which would be normally present.

To analyse the effect of bounding wall materials two distinctive materials were used in the walls and ceiling – normal weight concrete and mineral-fibre insulation (for thermal properties refer to Table 1).

Table 1 Thermal properties of the bounding materials

Material	Density [kg.m^{-3}]	Conductivity [W.m^{-1}.K^{-1}]	Specific heat [kJ.kg^{-1}.K^{-1}]
Normal weight concrete	2200	1.75	1.00
Mineral-fibre insulation	105	0.04	0.72

In general, each scenario comprised a single undivided enclosure with the above stated dimensions. Centrally in the enclosure the source of fire was placed. It was of square footprint – 1x1m – and located at floor level. The clear height of the room was set to 3m.

Since, the monitored parameters were the smoke layer height and its temperature (see section *Tenability criteria* for further discussion), it was therefore possible to model the fire as a relatively simple source emitting heat and combustion gases.

The final parameter, varied in the individual simulations, was the fire growth rate. As it primarily affects the development of a fire, it is necessary to take it into account when estimating the available evacuation time. Four standard fire-growth regimes [7],[8] were considered, all of them based on the t^2-fire described above, which grows exponentially with time. The characteristic parameters of the fire growth regimes are listed in Table 2. Fuel specific data (e.g. [9], [10]) should be used when more detailed analysis is to be carried out.

Table 2 Fire growth regimes for t^2-fire [1]

Fire growth regime	Time to reach 1MW [s]	Coefficient α_i [kW.s^{-2}]	Example building use [8]
Slow	600	0.00293	Picture gallery
Medium	300	0.01172	Office
Fast	150	0.0469	Shop
Ultra-fast	75	0.1876	High rack storage

The second criterion is the height of smoke layer itself. The difficulty lies with the wide range of effects smoke can cause, depending on its density and composition. It is therefore difficult to generalise any pass/fail criteria. Cooper uses the 0.91 m layer height as the tenability criterion in his work [11]; no reference is given to the toxicity of smoke, however. The value (0.91 m) from Cooper's work was refered to by Reichel in his work [13] on the means of escape part of Slovak and Czech standards (eg. [2]) and more recently was included in Chapter 3. *Compartment Fire-Generated Environment and Smoke Filling* of [14]. Despite the above referencing, an additional smoke layer height of 1.5m was also monitored. This is due to the fact, that should the smoke layer height drop to 0.91m and be considered as the tenability limit, it would be very dependent on the composition (irritants, toxic gases and soot content) of the smoke.

Results and discussion

Following the simulations for the individual cases in which the above mentioned parameters were varied, the results were analysed. For each case, the onset of untenable conditions was monitored; the smoke layer temperature or height, whichever was achieved earlier. This was considered the available safe escape time for the given case. The results for the critical smoke layer height of 0.91 m are in Table 3 and for 1.5m in Table 4.

Table 3 Available safe escape times for critical smoke layer height 0.9m

Enclosure area [m^2]	Available safe escape time for given fire-growth rate [min]			
	Slow	Medium	Fast	Ultra-fast
Insulated walls				
100	4.2	3.1	2.2	1.5
500	9.4	6.4	**3.1**	**2.3**
Concrete walls				
100	4.3	3.1	2.2	1.6
500	9.8	6.7	4.4	**2.7**

*values in bold mean that the smoke layer temperature criterion was achieved first

Table 4 Available safe escape times for critical smoke layer height 1.5m

Ensclosure area [m^2]	Available safe escape time for given fire-growth rate [min]			
	Slow	Medium	Fast	Ultra-fast
Insulated walls				
100	2.8	2.2	1.6	1.2
500	7.3	5.1	**3.1**	**2.3**
Concrete walls				
100	2.8	2.2	1.7	1.2
500	7.4	5.3	3.6	2.5

*values in bold mean that the smoke layer temperature criterion was achieved first

The above results clearly confirm the expected dependency of the available safe escape time on the size of the enclosure and fire-growth rate. The ratio of smoke production rate to the size of an enclosure is the primary factor determining the safe available escape time.

Due to the exponential nature of the t^2-fire model, the safe available escape time does not increase linearly with the area of the enclosure. Increasing the area of the enclosure, thereby effectively increasing the volume of the smoke reservoir, by a factor of 5 (from 100 m^2 to 500 m^2) the available safe escape time increases only by a factor of approximately 1.4-2.6. The greater the fire growth rate is, the less the available safe escape time grows with the size of the enclosure. Since real fires do also grow exponentially rather than linearly, the above is a very important design consideration.

The influence of the thermal properties of bounding walls was also found to have a certain effect on the available safe escape time. With the exception of the cases when the critical temperature criterion is reached first, the effect of the thermal properties is negligible, particularly for the 100 m^2 enclosure. For the fast and ultra-fast fire growth rates in the larger enclosure, the onset of untenability is faster in the insulated enclosure, approximately by 15-30% when compared to the uninsulated enclosure. This effect grows in significance as buildings are progressively more energy efficient, which usually involves an increased proportion of insulating materials in construction.

Since the smoke is modelled as a simple layer of hot gases, tenability is based on the height of this layer, i.e. how deep it descends during a fire. Although in agreement with [11] and [14], the tenability criterion of 0.91m seems overly optimistic. Thus a smoke layer height of 1.5 m was selected since it would represent significantly better escape conditions. Despite the approximately 80% increase in the smoke layer height the actual safe available escape times decreased only by 10-35% when compared to the 0.91m cases. Where the temperature of the hot layer was the tenability criterion, no change in safe available escape time is recorded. It is therefore recommended that for available safe escape time the height of smoke layer of 1.5m is used instead of 0.9m due to safety reasons.

Conclusions and future work

The series of computer simulations carried out in this work provide an insight on the basic parameters affecting the available safe escape time (ASET). Utilizing the standardised fire-growth rates in conjunction with the t^2-fire model instead of a universal fire provide a good compromise between too much generalisation and too much detail. Since occupants evacuate the affected area during the development phase and due the tenability limits (temperature and smoke layer height), ventilation does not affect the fire significantly in this period; it also represent a conservative assumption that the doors and windows to the enclosure and are closed and intact.

From the analysed parameters, the most significant one is the growth rate of a fire. This further supports the use of the above mentioned t^2-fire model with an appropriate growth rate instead of a universal value.

The area of an enclosure does not affect the available escape time in a linear fashion due to the exponential growth of the fire. Similar effect is expected to be present with increased enclosure heights as both area and height effectively change the smoke reservoir volume. For a longer available safe escape time reducing the fire growth rate, for example by sprinklering, is more efficient than increasing the area or height of the enclosure.

The effect of higher values of thermal resistance of the bounding construction was found to advance the onset of the critical temperature within the smoke layer, thereby reducing the available safe escape time.

The final comparison was made between the available safe escape times for the critical smoke layer heights (i.e. the height to which the smoke descends during afire) of 0.91 m and 1.5 m. The results show that, although yielding shorter available safe escape times (when compared to 0.91 m), the 1.5 m use of is not overly conservative and provides a good margin of safety especially when the toxicity of smoke is not modelled.

To conclude, the above describes the ways in which the individual fire and enclosure variables affect the available safe escape time. Certain important conclusions have been drawn, but it is desirable to expand the set of cases to include a wider range of compartment geometries, both area- and height-wise, and incorporate toxicity assessment in the future work.

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