ASET and RSET: addressing some issues in relation to occupant behaviour and tenability

DAVID PURSER
FRS, BRE Ltd., Garston, Watford WD25 9XX, UK.

ABSTRACT

Performance-based life-safety design depends on a comparison between the time required for escape (Required Safe Escape Time – RSET) and the time to loss of tenability (Available Safe Escape Time - ASET). Both include a number of stages, involving a variety of processes and requiring a range of input data. A problem for the design engineer is that while all stages need to be addressed to obtain a realistic outcome for the analysis, some aspects are reasonably well understood and quantified, while others are often oversimplified or ignored. For the RSET time line, most emphasis is usually placed upon the travel time component, representing the physical movement of occupants into and through the escape routes. However, the time required for occupants to engage in a range of behaviours before the travel phase (pre-movement time), often represents a greater component of the total escape time. Pre-movement time distributions are dependent upon key features such as occupancy type, warnings, occupant characteristics, building complexity and fire safety management strategy. It is proposed that a practical solution for the engineer is to apply pre-movement time distributions measured from monitored evacuations, fire incidents, or derived using behavioral models, and specified in terms of a number of “design behavioural scenarios” analogous to “design fire scenarios”, classified according to the key features listed.

A problem with the evaluation of travel time, is that most calculation methods assume no interaction between the occupants and the fire effluent. If occupants are exposed to irritant smoke, then movement speeds are likely to be reduced. A calculation method is proposed, relating predicted travel speed to smoke and irritant concentrations.

The ASET time line ends when occupant incapacitation is predicted from exposure to fire effluent. This depends upon the time-concentration curves for the main toxic fire effluents, requiring inputs on smoke and toxic product yields under different fire conditions. Existing engineering calculations use only smoke density and/or carbon monoxide, with yields often treated as constants, usually for the well-ventilated fire case. A method is proposed, whereby yield data for major toxic effluent species can be obtained over a range of fire conditions, expressed in relation to the global equivalence ratio. Results are illustrated for carbon monoxide and hydrogen cyanide.

KEYWORDS: behavior, evacuation, pre-movement, travel speed, smoke, irritants, yield

INTRODUCTION

Comparison of time required for escape (RSET) with time available for escape before conditions become untenable (ASET) is often the basis of a life safety assessment [1,2]. RSET depends upon a series of processes consisting of :

- Time from ignition to detection
- Time from detection to the provision of a general evacuation warning to occupants
- Evacuation time, which has two major phases:
    - Pre-movement time (the time between that when occupants become aware of the emergency and that when they begin to move towards the exits), which consists

of the time required to recognise the emergency and then carry out a range of activities before travelling to exits
- Travel time (the time required for occupants to travel to a place of safety)

For detection, warning and pre-movement recognition and response times, most research on human behaviour has been essentially qualitative [3,4]. This has revealed the complexity of occupant behaviour during fire emergencies and the importance of these behaviours with respect to escape time. In many situations they comprise the greatest part of the time required for escape [3,4,5]. Despite this, there has been little attempt to quantify the wide range of behavioural phenomena and the interactions between them, so that it is difficult to apply them to escape time calculations. Attempts have been made to develop scoring systems for the qualitative evaluation of different occupancies with regard to the ease with which efficient evacuation can be achieved [4], but these have not provided data usable by engineers for escape time calculations. In recent design standards, attempts have been made to relate pre-movement time to the type of warning system used (sounder, recorded voice message or direct personal address message) [1,2], but in many situations the fire safety management system and occupant characteristics are more important [5].

Engineers tend to evaluate travel time, with often only a token consideration of pre-movement time and pre-movement time distributions. This involves physically-based processes more amenable to design calculation methods [6]. However, travel times interact with pre-movement times and can be affected by behaviours such as wayfinding and exit choice [3,4,5]. Also, certain physical phenomena such as merging flows, have not been adequately solved.

The occupant behaviours involved in escape depend upon a range of factors including building characteristics (particularly occupancy type, method for detection and the provision of warnings, fire safety management systems and building layout), occupant characteristics (particularly occupant numbers, alertness [waking or sleeping] and familiarity with the building and its systems) and in situations where occupants are exposed to fire effluent, the fire dynamics [1,2]. Since fire scenarios are extremely variable, design fire scenarios are often used to represent a range of typical fire behaviours. For this paper, a method for the quantification of escape and evacuation times is proposed, whereby a set of key qualitative features of occupant behaviour is used to specify a small number of basic “design behavioural scenarios” analogous to design fire scenarios. Quantitative data for phases of behaviour, particularly warning and pre-movement times, have been obtained by observations of fire safety management and occupant behaviour during monitored evacuations and fire incidents, for the main categories of design behavioural scenarios [1,5]. These are then combined with travel time calculations to provide a simple but robust method for the estimation of escape and evacuation times.

Effects of non-irritant and irritant smoke on walking speed

A problem the evaluation of travel time is that most calculation methods assume no interaction between the occupants and the fire effluent. If occupants are exposed to irritant smoke, then movement speeds are likely to be reduced. Jin [7] showed that walking speed is reduced by non-irritant smoke in proportion to smoke density and that the effect was considerably increased by irritant smoke. A calculation method is proposed, relating predicted travel speed to smoke and irritant concentrations.

Toxic product yields and global equivalence ratios for input to ASET calculations

For the ASET time line, tenability is lost when occupant incapacitation is predicted from exposure to fire effluent. This depends upon the time-concentration curves for the main toxic fire effluents, requiring inputs on smoke and toxic product yields under different fire conditions [8]. Existing engineering calculations use only smoke density and/or carbon monoxide, with yields often treated as constants, usually for the well-ventilated fire case [1,2]. The yields of some key toxic products, particularly carbon monoxide, hydrogen cyanide and organic irritants, have been shown to be highly dependent upon combustion conditions, while others, particularly most acid gases and to some extent smoke particulates, are considered relatively insensitive to changes in combustion conditions [8,9]. For flaming fires, an important yield determinant is the fuel/air ratio, represented by the equivalence ratio (ϕ), expressed in terms of the actual fuel/air ratio divided by the stoichiometric fuel/air ratio [9,10]. For example, it has been shown that the yield of carbon monoxide can vary by up to a factor of approximately 50 between well-ventilated flaming conditions ($\phi < 1$), and fuel rich conditions ($\phi > 1$) [9]. An inability to control or determine the equivalence ratio during most small-scale tests or to allow for its effects on toxic product yields in engineering calculations can therefore lead to large variability in toxic product yields and toxic potency estimations [8,11].

It is proposed that the relationships between equivalence ratio and toxic product yields should be considered in engineering calculations, that large and small-scale combustion tests should be conducted over a range of equivalence ratios, and that the product yields should be expressed in relation to equivalence ratio. Results are presented for yields of CO from PMMA tested in large-scale experiments [9,10] and two small-scale test methods, the Factory Mutual apparatus [9] and the BRE tube furnace [11]. For CO and HCN, comparisons of fractional conversion of fuel carbon to CO and fuel nitrogen to HCN have been made for data obtained in full-scale fire experiments [12,13] and for rigid polyisocyanurate foam (PIR) in the BRE tube furnace.

While no bench scale test can re-create exactly the decomposition conditions in a full-scale fire, the BRE tube furnace method [11] has been developed specifically to overcome some of the problems of existing tests by decomposing materials under a range of non-flaming and flaming combustion conditions. A key feature of the test method is that the test material in strip form is introduced into a tube furnace at a constant rate under a stream of air, providing control over the equivalence ratio and hence the combustion conditions. The furnace system provides two main reaction zones, firstly the flame zone, where pyrolysed fuel mixes with air and primary combustion takes place, and secondly the heated plume zone, where the effluent/air mixture downstream of the flame zone passes through the heated furnace tube enabling secondary reactions to occur [11].

METHODS

Design behavioural scenarios

Research into occupant behaviour during emergency evacuations has been carried out at BRE over many years [5]. This has involved monitored evacuations, with video analysis of pre-movement and travel behaviours, and fire incident investigations of occupant and management behaviours, in a range of occupancy types. The results obtained, with other published data [3,4], have been used to develop behavioural scenario categories and also to develop calculation and computer simulation methods for evacuations [14]. Some actual pre-movement and evacuation times for design scenarios are presented in references [5 and 14], while further data are being compiled. Generic times are mentioned here.

Modelling walking speeds in non-irritant and irritant smoke

Fractional walking speeds in non-irritant smoke were estimated by fitting a curve directly to Jin's data on walking speed against smoke optical density [7,15]. For irritants, it was assumed that very low concentrations had no effect, while walking speed became zero at concentrations causing incapacitation. A curve has been fitted between these two extremes, such that change of walking speed with concentration follow a sigmoid relationship (using a Weibull function).

Toxic product yields and global equivalence ratios for input to ASET calculations

Data for CO yields from PMMA against equivalence ratio were taken from Tewason et al. [9] and from the work of Beyler and Gottuk as presented in Pitt [10]. These were compared with data obtained using the BRE tube furnace method [11]. Specimens of PMMA were introduced into the tube furnace at a rate of 1 g/min per minute under a range of air flow rates from 2.3 to 15.8 l/min to provide a range of equivalence ratios from 0.44 to 3. The decomposition temperature was 650°C, producing constant flaming conditions. Samples of polyisocyanurate foam (PIR) were also decomposed under similar conditions to provide equivalence ratios between 0.5 and 2.3. Data for full-scale conversion of fuel carbon and nitrogen have been obtained from full-scale furniture fire experiments in an enclosed domestic dwelling [12] and from rigid polyurethane wall lining fires in a two-room calorimeter rig [13]. These are compared with BRE tube furnace data for PIR.

IDENTIFICATION OF DESIGN BEHAVIOURAL SCENARIOS

The variables driving the responses of individual building occupants in emergency situations and the interactions between them are extremely complex. But, although each individual has a unique experience, when groups of building occupants are considered, a range of common situations and developing scenarios can be identified. These are of sufficient simplicity that they can be useful to predict generic evacuation times for design purposes. The main drivers of evacuation differ in different situations, so that somewhat different management and control strategies are appropriate. Building characteristics also affect evacuation in different ways in different scenarios. Based upon these considerations, a set of design behavioural scenarios summarized in Table 1 has been identified. For each of these behavioural scenarios it is considered that default design times can be derived for alarm and pre-movement times depending mainly upon the fire safety management strategy and warning system in place. Certain building characteristics are also important, particularly spatial complexity, travel distances, occupancy factors, exits and escape routes. These mainly affect travel times. The basic scenarios may be further subdivided into more closely defined scenarios in each class. Although all the occupant and building characteristics can affect escape times, the most important drivers are:

For occupants:
- number and distribution
- alert/asleep
- familiar and trained or unfamiliar
- physical ability

For buildings and building systems:
- warning system
- fire safety management and staff/ occupant training
- single or multiple enclosures, physical means of escape and spatial complexity

Based upon these key occupant and building characteristics, a system has been developed for classifying escape behaviour into a set of typical “design behavioural scenarios”. For each scenario category, factors are described affecting occupant behaviour and the time required for various activities to be carried out during different phases of an evacuation.

The basic behavioural scenario categories are: A: awake and familiar (e.g. office or industrial occupancy). B: awake and unfamiliar (e.g. retail or assembly occupancy). C: asleep and familiar (e.g. a dwelling) or asleep and unfamiliar (e.g.a hotel) and also (D and E) medical care and transportation categories. From the observations made, it is considered that each basic category has certain general requirements and ranges of likely alarm and pre-movement times. Each design behavioural scenario is defined primarily from the perspective of the occupants rather than the building, but a number of examples of occupancy types for each category are shown. The occupancy types have also been mapped onto the "purpose groups" used in UK prescriptive guidance [16].

Table 1: Design behavioural scenario categories

Category	Occupant alertness	Occupant familiarity	Focal point	Enclosures/ complexity	Occupancy type (ADB purpose groups)	Occupant density
A	Awake	Familiar	No	One or many	Office or industrial (3,6,7a)	Low
B1	Awake	Unfamiliar	No	One or few	Shop, restaurant, circulation space (4)	High
B2	Awake	Unfamiliar	Yes	One	Cinema, theatre (5)	High
Ci	Asleep Long term: individual occupancy.	Familiar	No	Few	Dwelling (1a-c) Without 24 hour on site management.	Low
Cii	Managed occupancy:				Serviced flats halls of residence etc	
Ciii	Asleep	Unfamiliar	No	Many	Hotel, hostel (2b)	Low
D	Medical care	Unfamiliar	No	Many	Residential (institutional) (2a)	Low
E	Transport	Unfamiliar	No	Many	Railway station Airport (5)	High

Within each category evacuation times are further dependent upon the quality of the alarm system (classified into levels A1 to A3) the complexity of the building (classified into levels B1 to B3) and in particular, on the quality of the fire safety management (classified into levels M1 to M3).

Alarm system **Level A1** consists of automatic detection throughout the building, activating an immediate general alarm to occupants of all affected parts of the building. **Level A2** consists of automatic detection throughout the building providing a pre-alarm to management or security, with a manually activated general warning system sounding throughout affected occupied areas and a general alarm after a fixed delay if the pre-alarm is not cancelled. If a voice alarm system is used for either an A1 or A2 system the time taken for the message to be spoken twice should be added to the alarm time. Alarm system **Level A3** consists of local automatic detection and alarm only near the location of the fire or no automatic detection, with a manually activated general warning system sounding throughout all affected occupied areas.

With regard to building complexity, **Level B1** represents a simple rectangular single storey building, with one or few enclosures and a simple layout with good visual access, prescriptively designed with short travel distances, and a good level of exit provision with exits leading directly to the outside of the building. Building **Level B2** represents a simple multi-enclosure (usually multi-storey) building, with most features prescriptively designed and simple internal layouts. Building **Level B3** represents a large complex building. This includes large building complexes with integration of a number of existing buildings on the same site, common with old hotel or department stores, also large modern complexes such as leisure centres, shopping centres and airports. Important features are that internal layout and enclosures involve often large and complex spaces so that occupants may be presented with wayfinding difficulties during an evacuation and the management of an evacuation therefore presents particular challenges.

Classification of Fire Safety Management characteristics and effects on evacuation time

In many situations the time taken to begin the travel phase of an evacuation (i.e. the pre-movement time), and the subsequent conduct of the travel phase, has been found to very dependent upon the implementation of the fire safety management strategy. This depends upon elements such as staff training and emergency management practice, but is also dependent upon the quality of the tools at the disposal of management to carry out an efficient and timely evacuation. The most important of these tools are the alarm system and certain building features. In order to assess the influence of fire safety management on evacuation time, a classification system of three levels of fire safety management has been developed. This can be linked with the classification of the alarm system and the classification of the building complexity.

For **Level M1**, the normal occupants (staff or residents) must be trained to a high level of fire safety management with good fire prevention and maintenance practice, floor wardens, a well-developed emergency plan and regular drills. For “awake and unfamiliar” there must be a high ratio of trained staff to visitors. The system and procedures are subject to independent certification, including a regular audit with monitored evacuations for which the performance must match the assumed design performance. Security videotapes from any incidents or unwanted alarms are made available for audit under the certification scheme. This level would usually also imply a well-designed building with obvious and easy to use escape routes (to level B1 or at least B2), with automatic detection and alarm systems to a high level of provision (level A1). If used by the public, a voice alarm system should be provided. **Level M2** should be similar to level 1, but have a lower staff ratio and floor wardens may not always be present. There may be no independent audit. Building features may be level B2 or B3 and alarm level A1 or A2. The design escape and evacuation times will be more conservative than for a Level M1 system. **Level M3** represents standard facilities with basic minimum fire safety management. There is no independent audit. The building may be Level B1 to B3 and alarm system A1 to A3. This is not suitable for a fire engineered design unless other measures are taken to ensure safety, such as restrictions on fire performance of contents, high levels of passive protection and/or active systems.

It is proposed that this scheme provides a rational approach for the assessment of escape and evacuation times in a range of occupancy types for application to performance-based design. The feature most affected by the scenario category is the pre-movement time distribution. Travel time depends principally upon travel distances within the starting enclosure, the horizontal and vertical escape routes, the mobility of the occupants, occupant numbers, exit choice and the flow capacities of the escape routes. These features are common to all behavioural scenarios, but high or low occupant densities tend to be features of particular scenarios, with important implications for interactions between pre-movement and travel times, and hence total evacuation time.

Where occupant densities are high in relation to aggregate exit width (as in retail and assembly enclosures), evacuation times tend to be dominated by exit flow capacity once the first few occupants start to move. The most important feature in a design context is then the pre-movement times of the first few occupants to move to the exits and form queues. In premises where occupant densities tend to be low (such as offices or sleeping accommodation), queue formation at exits is less likely to occur so, that flow capacity often does not restrict travel time. In these scenarios evacuation time depends on the later stages of pre-movement distributions (the pre-movement times of the last occupants to move) and the travel distances to and through the horizontal and vertical escape routes.

In the following sections further details of three of the main scenario categories are described to illustrate the principles of the categorisation.

Category A: Occupants awake and familiar: Examples of this scenario include offices or workshops. In this scenario occupants are in small groups in single or multiple enclosures, usually with low occupant densities. Occupants are involved in variety of activities and are awake and familiar with the building features including the alarm system and fire safety management procedures. They have well defined roles, carry some responsibility for the building, its operation and emergency strategy, and are trained in emergency procedures. Floor wardens and other staff have special responsibilities to ensure a rapid and efficient evacuation if alarms sound. Occupants are staff and may expect to be disciplined if they fail to follow emergency procedures and evacuate in an efficient manner

In well-managed office buildings, with good management procedures and well-trained staff, pre-movement times should be very short, even with a sounder alarm system. An important consideration is the pre-movement time of the slowest occupants to respond, especially isolated individuals, particularly in a multi-enclosure system. Travel times depend mainly on travel distance unless occupant densities are high, when queuing at exits and in stairs may occur and flow times may dominate. Poor fire safety management may lead to long pre-movement times. Office buildings are most likely to fit into building levels B1 or B2, and since occupants are familiar with the building, spatial complexity should be less important unless outside visitors are commonly present. Reported pre-movement times from offices during well managed evacuations tend to be very short, between a few seconds and a few minutes [5] and times for occupants to reach a protected escape route are rarely more than a few minutes from general alarm [5].

Category B: Occupants awake and unfamiliar: **Examples: No focal point:** shopping enclosure, restaurant, bar, supermarket, department store floor, mall area, airport check in or lounge areas, circulation space, restaurant, day centre **Focal point**: assembly, cinema, theatre. The main scenario features are that occupants may be present at high densities and are largely unfamiliar with the building and systems, but authority figures are present consisting of sales staff, security, managers and stewards who are trained in the building emergency systems and emergency management procedures. Customers lack a feeling of responsibility to respond to alarms, announcements, or other cues if they do not feel directly threatened. Their main commitment is likely to be to the shopping activity or show and to family members or friends. A rapid sweep of the area by staff can be used to ensure a rapid customer evacuation, otherwise alarms may not trigger an evacuation, although voice alarms or personal address messages may be effective [4].

Sales areas may be large with complex layouts and visibility limited by stock. Restaurant areas may also be present. There is also likely to be a wider range of physical and mental abilities (including children, the elderly and family groups who may be scattered at the time of the emergency). Customers may be reluctant to leave goods they have collected or paid for (e.g in supermarkets). In theatres, occupants are attending to the stage or screen, but this provides a focal point, which can be used by management to control an evacuation. During a number of monitored evacuations and incident investigations [5] pre-movement times have been short, with narrow distributions (of around 2 minutes), when management was efficient and staff acted quickly to encourage occupants to evacuate. On at least one occasion when staff did not act quickly, much longer pre-movement times occurred [5]. When design occupant densities are high, evacuation times are mainly dependent upon exit flow capacity, especially if exit choice is not optimal (as is often the case).

Category C: Sleeping: **Examples**: **Familiar**: apartment block, house, residential home **Unfamiliar:** hotel, hostel. Important features include low occupant densities and mixed ability and age residents, who may be sleeping. For residences, occupants should be familiar with warning and evacuation procedures. Fire safety management is often basic in residences but may be more developed in managed accommodation. Dwellings are small, with simple layouts and are familiar to occupants. When one member of a household detects a fire cue or alarm their first actions are usually to investigate, but warning others is often a high priority, so that once detection has occurred, warnings to other occupants may be delivered within a short time. Pre-movement times can be long, especially with sleeping occupants or when cues are ambiguous, or occupants inebriated. For hotels and hostels, occupants are largely unfamiliar with the building and systems and are dispersed among a large number of enclosures. Some authority figures may be present consisting of staff, security and managers who are trained in the building emergency systems and emergency management procedures. Non-staff occupants may lack a sense of responsibility for the building and systems, and may not respond to alarms. Their main commitment is activities such as sleeping. Layout is likely to be complex and escape routes hard to identify quickly. For these reasons a rapid and efficient evacuation is unlikely to be achieved. If there are sufficient well-trained staff present, and if they act quickly, then a rapid sweep might be used to secure a local evacuation of an affected area. In many situations evacuation may be counterproductive, since occupants are likely to be relatively safe in their rooms. Pre-movement times for even the first few occupants to respond may be very long (up to an hour), and the distribution of pre-movement times is likely to be very wide. Evacuation times are likely to be dependent on maximum pre-movement times and walking times, flow restrictions at potential “pinch” points are unlikely to occur. Occupants may be reluctant to leave their belongings and the temporary refuge of their rooms. For these reasons passive fire protection should be a major strategy.

EXAMPLES OF SUGGESTED PHYSIOLOGICALLY DERIVED EXPRESSIONS FOR THE EFFECTS OF SMOKE AND IRRITANTS ON WALKING SPEED

Effects of smoke on walking speed

Based on Jin’s work [7] it is possible to derive a simple expression for the effect of smoke optical density on walking speed. Fig. 1 shows the relationship between fractional walking speed and smoke optical density for Jin’s data between the limits of 0.13 (below which movement speed is normal) and 0.55 (above which movement speed is as in darkness at 0.3 m/s). Actual walking speed is given by multiplying the unexposed walking speed by the fractional value for any given non-irritant smoke density. This expression does not allow for other delaying effects resulting from reduced visibility, such as erratic walking direction and effects on wayfinding. Fractional walking speed in non-irritant smoke is then given by the expression:

Fractional walking speed = -1.738 x OD/m + 1.236

For an OD/m above 0.55 the walking speed fraction is reduced to a minimum of 0.3 m/s, since it is still possible to move at this speed in total darkness. However it is likely that in some situations occupants will be unwilling to move at all when in dense smoke or darkness, and may be unable to find their way to an exit (and hence to save themselves) at lower smoke concentrations.

Effects of irritants on walking speed

Walking speed in smoke is strongly affected by sensory irritancy as well as simple optical density, as Jin’s work clearly illustrates [7]. Jin used smoke from non-flaming wood, but did not report the composition of the irritant smoke. Smoke produced by a variety of materials contains a wide range of irritant products at different yields depending upon the decomposition conditions. A method is required for assessing the effects of sensory irritants on movement speed independently from optical density, and then to assess the interaction between the two effects. One approach is to consider the fractional effects of smoke and irritants on walking speed as essentially additive.

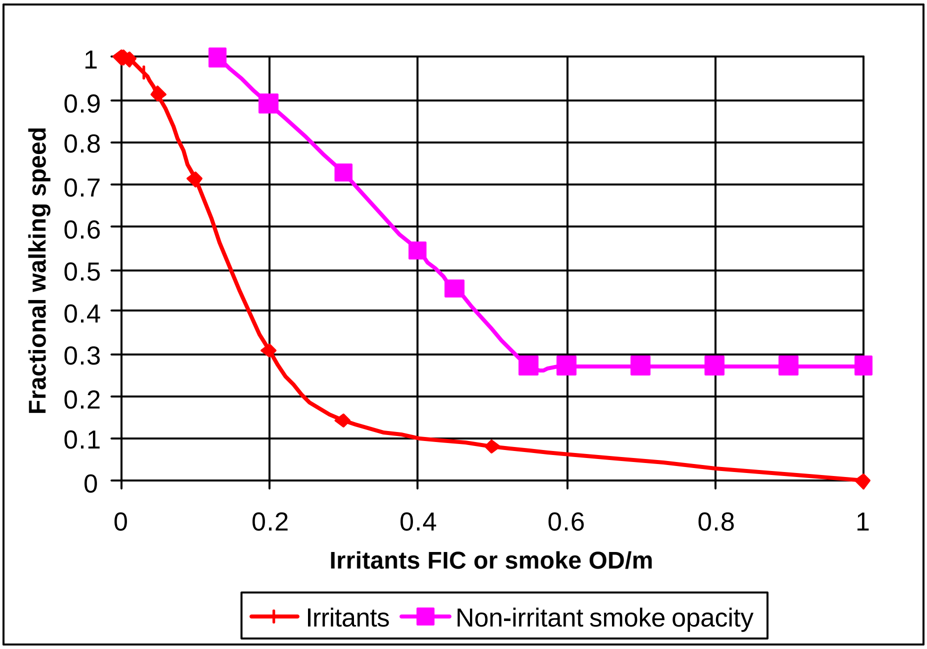

Fig 1-Relationship between visual obscuration by non-irritant smoke and fractional walking speed and suggested relationship between fractional irritant concentration and fractional walking speed.

Exposure to irritants at low concentrations should not reduce movement speed. In fact speed may even be increased due to discomfort or if occupants are anxious. At higher concentrations, the effects of eye pain, blepharospasm and lacrymation, together with respiratory tract pain and breathing difficulties [8,15] are considered to reduce movement speed, as shown by Jin [7]. Over a critical range, increasing concentrations are likely to have profound effects on movement ability, but at still higher concentrations (partly due to the logarithmic relationship between concentration and sensation) [8,15] it is likely that the rate of reduction of velocity with concentration will decrease. This suggests a sigmoid relationship between concentration and walking speed. Very high concentrations may cause all effective movement to cease, representing a point of incapacitation. The effects on movement speed will lie between these limits. On this basis, an attempt to derive a relationship between concentration and fractional movement speed for a sensory irritant is shown in Figure 2. The effect for any specific irritant depends upon the fractional irritant concentration (FIC), the concentration of the irritant expressed as a fraction of the concentration predicted to cause incapacitation [8,15]. For mixtures of irritants, the individual FIC values are summed to provide an overall FIC value. When the FIC value reaches 1.0 incapacitation is predicted.

Figure 1 shows a general case for the effect of exposure to any irritant gas or mixture or irritant gases on fractional walking speed. The ordinate shows the fractional irritant concentration (FIC). Unlike the situation for non-irritant smoke, the curve reaches a fractional speed of zero when FIC is 1.0 and incapacitation is predicted. The expression for the curve shown in the Figure 1, which can be applied to any individual irritant compound, or to the fractional irritant concentrations for a mixture of compounds, is given by:

$$F_{wvirr} = 1 - ((1 - e^{-(x/b)^a}) + (-0.2x + 0.2)/1.2)$$

Where: a = 2, b = 160, x = FIC

The overall effect of exposure to an irritant smoke on walking speed (F_{wv}) would then be given by:

$F_{wv} = 1 - (1 - F_{wvsmoke}) - (1 - F_{wvirr})$

Where: F_{wv} = Overall fractional walking speed
$F_{wvsmoke}$ = Fractional walking speed due to smoke effects on visibility
F_{wvirr} = Fractional walking speed due to irritant effects for compounds 1 to n

TOXIC PRODUCT YIELDS AND GLOBAL EQUIVALENCE RATIOS FOR PMMA AND NITROGEN-CONTAINING MATERIALS

For the BRE tube furnace, yields of CO, CO_2, smoke OD/m, smoke particulates, unburned organics, acid gases, hydrogen cyanide, and oxygen consumption were measured, but only CO and HCN are considered here. Tewarson [9] has expressed the effect of equivalence ratio on CO yield in large-scale fires and in the Factory Mutual apparatus by plotting yield ratio (in terms of the ratio of the mass of carbon monoxide generated per unit mass of fuel for ventilation controlled to well ventilated fires) against equivalence ratio. The left side of Figure 2 shows the BRE tube furnace data plotted on the Tewarson data. The results are very similar for the two different types of apparatus

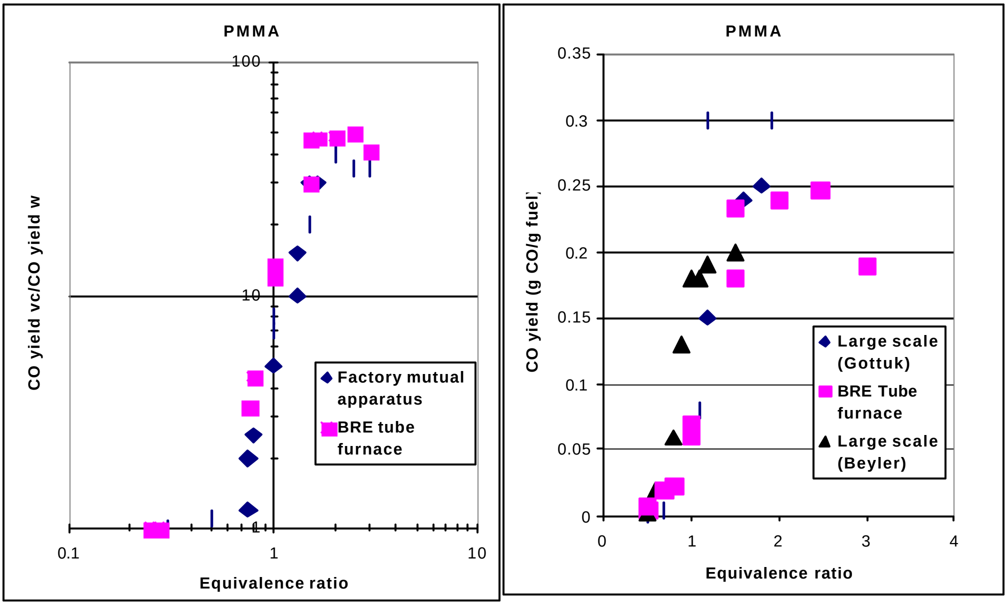

Figure 2: Comparison of CO yield ratio (left figure) and CO yield (right figure) as a function of equivalence ratio for PMMA in the BRE tube furnace, compared with the Factory Mutual apparatus and large-scale compartment fires

and fires. The right side of Figure 2 shows the same BRE tube furnace data plotted on large-scale compartment fire data from Gottuk and Beyler (taken from Pitt [10]).

For HCN it is also possible to produce plots of yield against equivalence ratio, but another useful parameter to consider for both CO and HCN is the efficiency of conversion of fuel carbon to CO and fuel nitrogen to HCN. Figure 3 shows the relationship between % conversion efficiencies for these two gases, obtained from full-scale ventilation-controlled furniture fires conducted at BRE using polyurethane foam-filled furniture with acrylic or cotton covers [12] and in two-room large scale fires conducted at NIST using rigid polyurethane foam [13]. The results show an almost 1:1 relationship between the two parameters, so that HCN concentrations and yields could be reasonably well predicted from CO alone if the respective elemental proportions of carbon and nitrogen in the fuel combusted were known. Also show are similar data for another rigid foam (polyisocyanurate - PIR) from the BRE tube furnace. These show a similar relationship to that found in the full-scale fires.

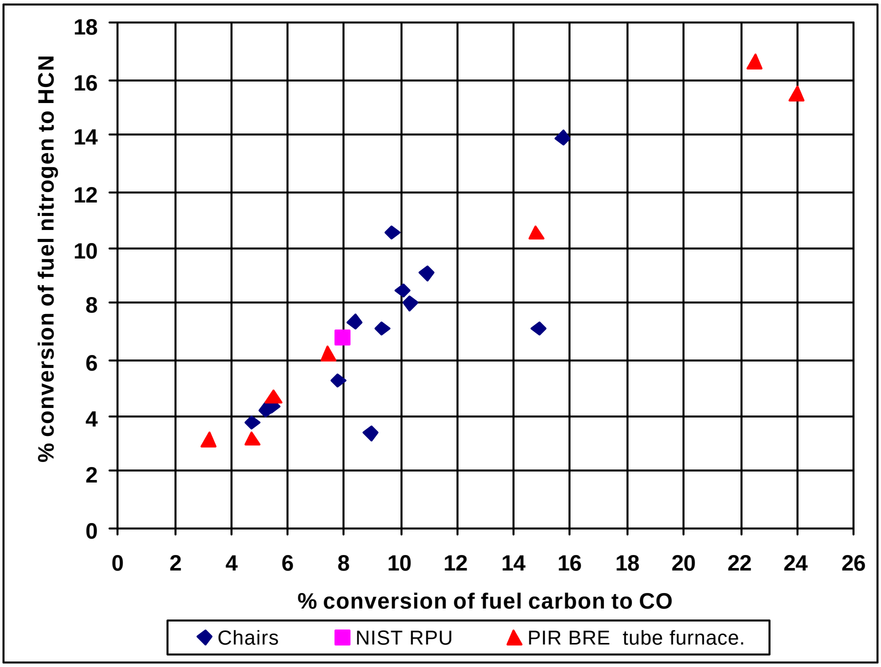

Fig. 3 - Relationship between % conversion of fuel carbon to CO and fuel nitrogen to HCN for full-scale ventilation-controlled furniture fires (BRE) rigid polyuretethane (NIST) and BRE tube furnace results for PIR

CONCLUSIONS

Some terms in ASET and RSET estimations are routinely quantified using simplified abstractions of complex phenomena. Standardised t^2 fire growth curves provide one example. Others terms receive only rudimentary consideration, yet can have serious effects on outcomes. In this paper an attempt has been made to provide a pragmatic approach to the quantification of three such neglected terms. The concept of design behavioural scenarios provides a basis for the classification of occupant evacuation characteristics, particularly pre-movement times, into a small number of types for which quantitative data can be measured or modelled. The development of expressions for movement speed in irritant smoke, which separates obscuration effects from effects of irritants, enables effects on movement speed to be related to the specific chemical composition of effluent in terms of smoke particles and irritant compounds. The use of the global equivalence ratio as metric for the measurement and prediction of the yields of key toxic products in fire effluent provides a method for application to the estimation of time-concentration curves for a variety to toxic products in fires, which in turn can be used with fractional effective dose models to predict ASET times [8].

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