Chapter 2
Developments in Tenability and Escape Time Assessment for Evacuation Modelling Simulations

David A. Purser

2.1 Introduction

Fire safety in any built environment depends on the integrated performance of a system comprising many components relating to the building systems, fire scenarios and occupant behaviour.

Life-safety outcomes should a fire occur are essentially time-based:

- Fires grow through a series of stages so that fire and fire effluent spread to progressively larger building areas with time
- Escape processes involve a time series of components including detection, warnings and occupant evacuation (or protection in place)

The ultimate evaluation of the performance of the system from a life-safety perspective is to compare the time available for escape with the time required for escape (or tenability time in refuges), since this incorporates the performance of all the separate elements involved in fire development, occupant evacuation and survival [1–4].

For fire engineers this is summarized in the essential principle of performance-based design:

Available Safe Escape Time > (Require Safe Escape Time + an appropriate safety margin)

Where:

ASET = time from ignition to loss of tenability
REST = time from ignition to escape

D.A. Purser (✉)
Hartford Environmental Research, Hatfield, Hertfordshire, UK
e-mail: david-purser@ntlworld.com

A. Cuesta et al. (eds.), *Evacuation Modeling Trends*,
DOI 10.1007/978-3-319-20708-7_2

In this context, tenability limits are exceeded when exposure conditions are such that occupants are no longer able to save themselves. For a defend-in-place strategy it would mean exposure to conditions threatening significant injury or death.

With regard to RSET assessment and simulation it is important to recognise the distinction between "escape" and "evacuation". The evaluation of escape processes and escape time involves everything that happens from the ignition of the fire to the time that all occupants have reached a place of safety. Evacuation processes are a sub-set of escape, consisting of the time from when a warning is presented to occupants to that when they have reached a place of safety. Evacuation time therefore includes pre-travel activities (pre-movement time) including the recognition time (the time taken for occupants to recognise fire cues or warnings and stop their pre-fire behaviours) and Response time (the time taken for occupant to engage in a range of activities related to the fire emergency but before they begin to travel towards the exits). This includes activities such as stopping work processes, seeking information, gathering belongings and warning others.

Since the time periods from ignition before warnings are given (the times from ignition to detection and from detection to warning), and the pre-movement period of evacuation, are most often the greatest part of both total escape time and evacuation time it is very important that these are included in escape or evacuation analysis or simulation. Yet most simulations are limited to the last and shortest process—that of travel to exits and through escape routes.

Although RSET/ASET comparison is usually thought of in the context of performance-based design it is in fact not a new concept but goes back to UK Post War Building Studies and beyond [5, 6].

Around that time committees developing fire safety guidance for buildings considered a number of fire incidents (including the famous Empire Palace Theatre incident, Edinburgh in 1911) [5, 6], and decided that in most cases approximately 2.5 min were available for occupants to escape from when a fire was of a size that it became obvious (a simple estimate of ASET).

They then carried out a performance-based design of escape route capacity, requiring that the aggregate flow capacity (hence width) of available exits should be sufficient to enable the maximum occupant population of an enclosure to evacuate into a protected escape route within 2.5 min [6]. This thereby provided a simple estimate of RSET.

This is still the basis of the prescriptive guidance for exit, escape corridor and stair widths in England and Wales (Approved Document B [7]).

For performance-based design the ASET/RSET methods have become somewhat more sophisticated than the original 1930s application, with more terms in the ASET and RSET expressions and more detailed methods for evaluation of the individual terms and the interactions between them [3, 4].

The original estimates for fire hazard development did not consider methods of and times to detection, fire growth dynamics, or calculation of smoke, heat, effluent toxicity and spread. The original RSET methods did not consider detection, warnings and occupant behaviour times, but only the physical "hydraulic" travel phase of occupant evacuation.

The current Building Regulations for England and Wales (2010) [8], as well as those for Northern Ireland and Scotland are Performance-Based, and the ASET/RSET principle forms the basis of the requirements for means of escape [7]:

"The building shall be designed and constructed so that there are appropriate provisions for the early warning of fire, and appropriate means of escape in case of fire from the building to a place of safety outside the building capable of being safely and effective used at all materials times".

In practice an acceptable design performance can be achieved either by following a set of prescriptive design guidance or by a fire engineering performance-based design.

The same principle is also applied in part to the requirements for fire spread of linings in that they should "have if ignited a rate of heat release or rate of fire growth which is reasonable in the circumstances" and for Internal fire spread (structure) for which "…in the event of fire, its stability will be maintained for a reasonable period."

So the ASET/RSET principle is absolutely fundamental to the required performance of buildings and other structures (such as transport vehicles). Yet almost all aspects of current fire safety design and regulation are based on simple prescriptive requirements for individual features, with limited consideration of interactions between parameters or performance-based evaluation. In the context of this book it is useful to consider how fire safety objectives have been approached and evaluated in the past and what opportunities are presented by current and future performance-based modelling approaches. It is also important to examine the limitations and inadequacies of current methods and how these may be improved by future developments.

Historically most fire safety regulation has been based on changes to individual features in response to particular incidents. Probably the first requirements related to passive fire protection, such as those relating to building construction and separation following the great fire of London in 1666. Passive protection in buildings has been based on fire-resisting materials, initially on an *ad hoc* basis, but increasingly during the last century based upon a testing and certification regime. Furnace tests performance has been used for certification, but originally the relationship between fire-resistance time in a standard test and that in a real fire scenario was only loosely established (2 h fire resistance in a furnace test does not ensure 2 h fire resistance in all potential building fires). In practice the main way to evaluate the success of the standard has been to examine fire statistics over a period since the introduction of the standard, rather than by any performance-based engineering analysis. During the last century there was an increasing progression towards the development of tests designed to provide data for input into fire engineering calculations for structural performance and for the use of "natural" fire curves, more representative of actual fire conditions in buildings. These methods can also be applied to several different structural features so as to enable engineering calculations to predict interactions between different structural elements and the performance of entire structural systems.

So structural fire protection is developing from a set of somewhat *ad hoc* requirements and tests to a more mature and integrated engineering discipline, at least with regard to structural integrity performance. When it comes to parameters affecting occupant escape performance and hazard evaluation such progress has been less obvious. Here there is still a tendency to focus on individual aspects in isolation and to rely on simplistic test and certification criteria rather than obtaining data that can be used for engineering hazard calculations and that can be integrated with data for other elements to enable prediction of the behaviour of building and occupant systems during fires.

An example relates to available and required escape time from dwelling fires. Although the performance-based requirement in the UK is to provide safe means of escape, engineering assessment methods for calculating ASET and RSET are very limited, both with regard to the identification and assessment of individual human behaviour and fire hazard parameters and their integration to assess overall performance. In practice, when problems have arisen, the response had been rather simplistic, with changes to individual features, with the hope of improving performance, but without any performance-based assessment of the extent to which the new features will actually improve safety or interact with other aspects.

Has this approach worked? Well, two examples are changes to furniture flammability requirements and the introduction of smoke alarms, each introduced with the intention of improving fire safety in domestic dwellings. Information on the effects of these changes is revealed in the historical annual United Kingdom fire statistics data for deaths per million population shown in Fig. 2.1. The fourfold increase in deaths resulting from toxic smoke exposure between 1955 and 1970, together with concerns and research on the fire behaviour of upholstered furniture, led to the introduction of the Furniture Regulations in 1988. These introduced controls on the ignitibility of furniture from cigarettes and small flaming ignition sources, which lowered the probability of sustained fires occurring from the application of small fire sources. Fortuitously (but not by design), the changes in covering and filling materials needed to satisfy these test requirements (often involving the use of flame retardants), also resulted in a slower flaming fire growth following exposure to ignition sources large enough to overcome the designed level of ignition resistance. This thereby increased the ASET time available for occupants (especially occupants of domestic dwellings) to escape before conditions became untenable.

Also, from around this time there was an increasing market penetration of domestic smoke detector/alarms, increasing from 9 to 74 % of dwellings between 1987 and 1994. By providing early warning of fire these thereby decreased the RSET time required for escape, when they were effective.

Figure 2.1 shows that the combination of these two measures has fortuitously had a beneficial outcome, so that the fire death rate/million has decreased from 18.01 in 1988 to 7.64 in 2010. However, a more detail examination of the fire deaths and injury statistics reveals a more complicated pattern. The changes to upholstered furniture requirements had no immediate effect, since only a small proportion of householders replace their furniture and beds each year. Despite this, the annual death rate from dwellings fires, especially deaths from smoke exposure, did in fact start to decrease continually from around 1988, but the numbers of fires and the incidence of smoke exposure injuries continued to increase over the next 10 years. After this both the annual numbers of fires and the annual numbers of deaths and injuries continued to decrease up to the present day.

Although other factors may be partially responsible for these improvements in fire deaths and injuries it seems likely that the initial decrease in death rates may have been mainly due to the increasing use of smoke alarms. Occupants received earlier warning of fires and were more likely to survive and escape, but due to the ease of ignition and rapid fire development of the older style furniture, producing large volumes of highly toxic smoke, there was a high probably of building occupants suffering significant smoke exposure while escaping, hence the continued increase in smoke injuries. Once there was significant market penetration of the new-style furniture, the combination of a lowered probability of ignition, coupled with slower fire growth and early warning of fire from the smoke alarms, resulted in a synergistic interaction: increased ASET coupled with decreased RSET, leading to the observed continued decrease in smoke injuries and deaths.

Despite the improvements since the high point of fire deaths in the 1970s and 1980s Fig. 2.1 shows that toxic smoke is still the major cause of fire injuries and deaths, and that we have only succeeded in almost getting back to the rates of injuries and deaths occurring in the 1950s, which represents rather limited progress.

Rather than waiting for the results of these changes to show up in the fire statistics, another way to examine the likely benefits of different interventions could have been to carry out a full ASET-RSET analysis of domestic fires. This has been done for some domestic fire scenarios by carrying out full-scale fire tests in fully furnished test houses coupled with studies of human response behaviour during actual

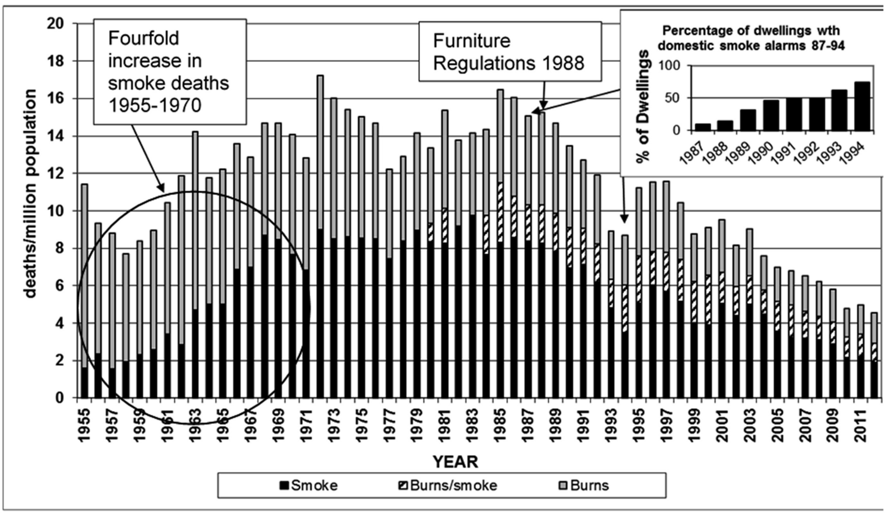

Fig. 2.1 UK Fire deaths per million population [9]

fire incidents. These have revealed the very short time window available for occupants to become aware of alarms and escape before conditions in typical domestic fires can become untenable. However from a design perspective it would be preferable if we could assess such situations by carrying computer simulations of fire development and occupant escape. In order to carry out such a simulation it is necessary to identify each parameter in the ASET and RSET in a fire and escape scenario, determine which parameters have a significant effect on the outcome, quantify them and incorporate them into a simulation. An example of such an analysis is presented later in this chapter for the Rosepark Nursing Home fire.

Attempting such simulations immediately shows that we have some problems, even for a deterministic simulation of a single fire scenario. Firstly, even if we assume flaming ignition of an item has occurred, we have a very limited ability to calculate the subsequent heat release rate and fuel mass loss rate curve in a defined building enclosure. Although attempts are being made to model pyrolysis rates in flaming fires these are still at an early stage and cannot be applied accurately to complex fuel packages such as upholstered furniture, even if the detailed composition and construction are known.

So currently it is usual to rely on standard heat release rate curves or experimental data from large-scale calorimeter tests, the data from which are limited only to the item tested and for which the test boundary conditions are likely to differ considerably from those in a real enclosure fire.

Another vital parameter in fire hazard development is the changing yields of smoke and toxic products from burning fuels under the different changing combustion conditions occurring in full-scale building fire scenarios. Ability to model these in fire simulations is currently very limited. Experimental studies have shown that yields of key toxic gases including CO and HCN vary considerably depending upon fuel composition and combustion conditions, and this topic is discussed with examples later in the chapter.

One area where considerable progress has been made in both zone and CFD simulation models is the movement and mixing of fire effluents plumes through building enclosures once formed. This means that once problems or fire growth, combustion conditions and toxic product yields are solved it is possible to simulate changing smoke, heat and toxic product concentrations with time within enclosures, and hence the conditions to which occupants may be exposed.

Another area where good progress has been made is in assessing effects of concentrations and doses of smoke, toxic gases and heat on escape capability of exposed subjects, for assessment of time to incapacitation in specified fires with known time-concentration curves for key parameters.

Alternatively, as stated, it is possible to carry out and measure all the relevant fire parameters in full-scale building fires, but again the results are somewhat limited to the specific fuels, enclosures and conditions. Such methods are very useful for validation of modelling predictions.

Even when these issues are solved we are left with the enormous problem of the wide varieties of fuels, building contents, structures and configurations occurring in practice and the probabilistic aspects of fires involving them. Our ability to make realistic assessments of fire hazard scenarios and their probability of occurrence could be considerably improved by more assiduous collection of some fairly basic data. For example, in different building occupancy categories, what proportion of interior doors and windows to the exterior are open or closed at different times, and at what times during actual fire incidents—a parameter having an enormous effect on tenability time during fires? What are the average and range of compositions of television sets or washing machines in terms of the chemical elements important in toxic fire hazard, or for whole contents of different rooms or vehicle interiors? It is noticeable in relation to all these parameters, that efforts to collect data, develop calculation and simulation methods all tend to be heavily directed at some parameters, while others are largely ignored.

Similar issues arise when RSET parameters are considered. Quite a lot of effort has been directed at measuring and modelling the response of smoke and heat detectors during compartment fires. However very little research or data are available for the probability and timing of occupant recognition and response to warnings. As the Dusseldorf Airport example described later illustrates, this is especially a problem when occupant warnings depend on the response of security personnel to pre-alarms or warning. In many such incidents, security and management personnel were aware of fire detection for many minutes before evacuation warnings were delivered to other occupants, sometimes resulting in multiple deaths.

In contrast to this, much effort has been directed over the years to the physical design of means of escape and the calculation and simulation of the travel phase of escape and evacuation. Although it is important to develop a good basic travel and flow simulation component as the basis for any evacuation model, it seems to me that we are approaching diminishing returns in this area, in that almost all research and development in human behaviour is devoted to small improvements in simulating this parameter, while other equally important terms on the RSET equation are almost ignored. A prime example is the World Trade incident, for which evacuation travel capacity was not the main limitation on escape and survival, but the very long delays in warning occupants to evacuate and in their response to the developing fire cues, which resulted in delays of around and hour before many occupants decided to start evacuation travel.

If we consider for example a large building, or tunnel incident in which warning and pre-movement can be estimated as 20 ± 15 min and physical evacuation travel time as 5 ± 0.1 min, how much are we going to improve our total escape time simulation accuracy by improving our travel time calculation accuracy to 5 ± 0.01 min?

Of course it is much easier to simulate physical movement than human response, and it is much easier to conduct and measure experimental evacuation travel drills than to set up and perform unannounced escape and evacuation experiments to collect this vital data.

So what are the challenges for future development of fire hazard, escape and evacuation simulations?

- Examination of the entire escape and hazard development process involving all interactions between the occupants, built systems and fire scenarios.

- Identification of those parameters having the greatest effect on safety outcomes.
- Design studies and experiments to collect the necessary data on the key ASET and RSET parameters and to design functions and simulation methods to replicate their behaviours.
- Design simulation methods that replicate the main features of each key parameter and integrate them into a functioning system enabling prediction of outcomes for specified deterministic scenarios.
- Collect data on the range of variability of each key parameter to facilitate probabilistic analysis of simulation outcomes.

Specific issues relating to escape simulations that require research and improvement are:

- Measurement of response behaviours and decision times in reporting chains from persons first discovering a fire, and through management, leading to general evacuation warnings to occupants. Development of simulation functions for these behaviours and incorporation into simulation models.
- Measurement of recognition and response pre-movement behaviours of people in different kinds of occupancies in relation to different warning systems and fire safety management practices. Development of simulation functions and probability distributions for these behaviours and incorporation into simulation models.
- Measurement from experiments and collection of data from fire incidents on behavioural responses and decision making in response to seeing or being enveloped in smoke. In particular, under what conditions are occupants likely to take refuge rather than escape (for example remaining in a bedroom when the landing is smoke-filled, or in their vehicle during a tunnel fire)? Under what conditions (at what smoke densities) and in what scenarios are they likely to decide to travel through smoke? What are probability distributions for such decisions, for example as a function of smoke density or proximity to the fire?
- Vital aspects such as these are usually ignored in simulations, although some useful experimental research has been carried out on the effects of smoke density on travel speed once occupants decide to evacuate, especially in tunnels. Although these data can be incorporated into evacuation simulations, they may be of limited relevance if most occupants would in fact remain in their vehicles as occurred during the Mont Blanc tunnel fire. Criteria are therefore needed for this decision process for incorporation into simulation models.
- With regard to travel and flow simulations for occupant populations through escape routes, existing physical simulations models are very effective, but further development and validation are needed with respect to merging behaviour and flows. This has been shown to be partly a physical problem and partly dependent on aspects of social behavioural interactions. Another aspect of travel which is behavioural rather than physical, but which can have a large effect on evacuation flows is exit choice and wayfinding behaviour. In addition to collecting data on this aspect there is need for the development of a functional basis for application in simulations.

So as I see it, the twentieth century saw the birth of performance-based analysis and the development of engineering calculation methods for individual fire parameters. The challenge for the first part of the twenty-first century is

- To recognise and improve understanding and methods for calculations of important parameters previously neglected in simulations.
- Develop improved and more comprehensive simulation methods to integrate the effects of different parameters interacting in systems.
- Collect and apply sufficient data on variability of input data to improve the capability of probabilistic simulations.

The remainder of this chapter discusses the benefits and possible alternatives to ASET/RSET comparisons and simulations and presents three examples of the investigation and application of ASET/RSET components and interactions. The text is the basis for the 2013 Rasbash Medal Lecture presented by the author at the Institution of Fire Engineers 2013 Conference, Stratford-upon-Avon 10–11 July 2013.

2.2 Is There an Alternative to ASET/RSET Comparisons?

So given that ASET/RSET comparisons form the basis of the prescriptive guidance and the performance–based engineering standards, I was somewhat surprised and concerned to come across a 2010 paper published in Fire and Materials entitled " RSET/ASET, a flawed concept for fire safety assessment". I have also found that some international colleagues in the fire safety engineering standards arena seem to have a limited understanding or appreciation of the importance of this principle.

This gave me pause for thought—have the codes and engineering standards been wrong all this time and what possible alternative might there be to ASET/RSET analysis for the fire safety performance of buildings?

The paper cited above recounts a number of fire incidents in dwellings in which occupants have failed to escape in safety or have attempted to re-enter burning buildings, and more importantly, design cases for which the ASET/RSET methods have been incorrectly applied. The paper concludes by recommending ASET/RSET calculations with use of appropriate safety margins—which is of course the original basic concept. So perhaps the title is somewhat misleading in that it is not so much the basic concept that is flawed as its application, and the paper does a useful job in drawing attention to such misuse.

Considering the whole issue I feel that there are alternative methods for improving life-safety other than the application of ASET/RSET comparisons. As mentioned with respect to the Furniture Regulations one method is to introduce measures that target specific issues and reduce the probability of occurrence of specific failure modes. Thus the implementation of the furniture regulations reduced the probability of occurrence of furniture fires in general. The introduction of domestic smoke alarms reduces the probability that domestic fires will remain undetected until conditions become untenable. However, risk overall is the product of probability of occurrence and severity of the ensuing hazards. Also, when considering the overall performance of built systems, there is a general probability of fires starting in a variety of components for a variety of reasons. For any situation in which a fire does occur it then becomes important to consider the time-based performances of the entire system to evaluate fire safety, hazards and risks to occupants.

2.3 Benefits of ASET/RSET Comparisons

I am convinced that, carried out correctly, time-based ASET/RSET comparison provides a very powerful method for evaluating and improving fire-safety for the following reasons:

- It evaluates the overall performance of the whole system
- It forces the designer and regulator to identify and consider the performance of each individual component of fire hazard and means of escape—and justify any assumptions
- It enables the influence of each parameter on the performance of the whole system to be evaluated. Areas of weakness can then be addressed
- It enables identification of parameters having a large influence on system performance and where redundancies or overlaps occur. (For example time to detection is an additive term in RSET and therefore very important. Pre-movement and travel times, although additive for individual occupants, overlap for evacuating populations—Fig. 2.2)
- It enables trade-offs between different components to achieve desired overall performance
- It enables development and evaluation of defence-in-depth, to determine effects on overall safety outcomes when one or more components fail.

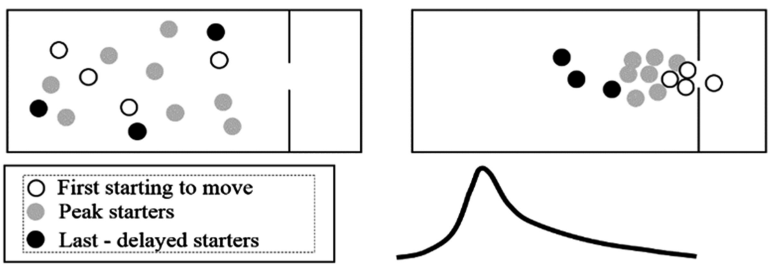

Fig. 2.2 Pre-movement time distributions for occupant populations follow log-normal distributions but for a crowded enclosure the evacuation time depends upon the pre-movement time of the first few occupants (who form the queue at the exit) plus the travel flow time for the population. Late starters simply join the end of the queue at the exits [12, 13]

- It highlights important parameters for which we have insufficient knowledge—providing a focus for meaningful research (e.g. merging flows at storey exits), or for the application of safety margins.
- For fire incident investigation the construction of a time-line for fire development and occupant behaviour is vital to understand what happened—the majority of cases involve ASET/RSET failures in terms of fire and escape design and management

Comparing the interactions between different parameters as in Fig. 2.2 enables optimisation of means of escape and effects of trade-offs to be calculated.

2.4 Three Examples of the Investigation and Application of ASET/RSET Components and Interactions

In order to illustrate the benefits of investigation and application of ASET/RSET components and system interactions I have chosen three different examples from different topics I have worked on:

1. RSET topic: "pre-warning" delays in evacuations of large buildings with two-stage alarm systems resulting in life loss in major fire incidents
2. ASET topic 1: Using comparisons of forward-calculated Fractional Effective Dose and carboxyhaemoglobin concentrations with measurements in incident victims to validate fire test or computer modelling incident reconstructions
3. ASET topic 2: combustion chemistry: Non-conservative constant values are often used in fire dynamics models for heats of combustion and toxic gas yields. The ISO/TS19700 tube furnace—developed at BRE—can be used to measure these variables as a function of fuel/air equivalence ratio [14–16].

2.4.1 RSET Topic: Pre-warning Delays in Major Fire Incidents

The basic RSET expression for a simple building is as follows:

$$RSET\left(\Delta tesc\right) = \Delta tdet + \Delta ta + \Delta tpre + \Delta ttrav$$

Where

RSET (Δtesc) = escape time (time from ignition for all occupants to reach a place of safety)
Δtdet = time from ignition to detection
Δta = time from detection to alarm
Δtpre = pre-movement time
Δttrav = travel time

For many smaller buildings a simple (Level 1) automatic detection and alarm system is used whereby detection usually results within a few milliseconds in a general evacuation alarm or warning to all occupants. In such a simple system alarm time is effectively zero. After a pre-movement period during which occupants recognise and respond in various ways to the alarm they then travel towards the exits and evacuate [2, 3].

Larger building often have two-stage alarms (Level 2 systems). Detection activates a pre-alarm to security after which a general alarm is sounded to all affected occupants. The time from ignition to the general alarm is the simple sum of the detection and alarm times. But in many larger and more complex buildings, when the initial detection of the fire (either automatic or by a person) provides a pre-alarm to security staff, they then have to decide if and when to activate a general evacuation alarm to occupants of affected enclosures (or the entire building). Sometimes there is an automatic protocol for a general alarm (for example after a fixed delay unless cancelled, or if more than one detector is activated by the fire), but in some serious incidents either there has not been such a back-up or it has been cancelled. When staff receive the pre-warning they enter their own pre-movement sub-routine, taking time to recognise that an alarm has been received and then responding in some way. In almost all cases the first response is to send someone to investigate. Further time is then spent for investigators to travel to the fire site, appraise the situation and report back. Investigation and reporting may take a significant time as the fire grows before it may be considered sufficiently serious to recommend evacuation. Information on the developing scenario and instructions may pass up and down a management chain. Eventually, if the fire becomes more serious, a decision may be made to active a general evacuation warning to affected occupants, but in some incidents this has occurred too late, so that members of the occupant population suffer a serious exposure while attempting to escape.

In such a situation the RSET expression might be represented as follows:

$$RSET\left(\Delta tesc\right)=\begin{pmatrix}\Delta tdet+\Delta tpre\\ \uparrow\longleftarrow\downarrow\end{pmatrix}\longrightarrow\Delta ta+\Delta tpre+\Delta ttrav$$

Where

Δtpre represents the pre-warning time

In practice in such incidents it is possible to recognise a kind of sub-routine consisting of a sequence of different "detection" stages or events leading to a sequence of different "pre-warning" events before the final pre-warning leads to an alarm [17, 18].

Issues such as these have made an important contribution to the consequences of a number of serious fire incidents including:

- Dusseldorf Airport
- Manchester Woolworths,
- Summerland Holiday Centre
- Nagasikiya store fire, Amagasaki City, Japan

- Bradford Stadium,
- Rosepark Nursing Home
- Dupont Plaza and MGM Grand Hotel Fires
- Daegu Korea and London Kings Cross Underground Stations
- Channel Tunnel and Mont Blanc tunnel
- World Trade Centers
- Stardust Disco
- Lakanal House

The Dusseldorf Airport Germany 11th April 1996 [19] provides an example of one such incident: (Table 2.1). This fire started as a result of "hot work" (welding) on an access roadway above one of the terminals, with the fire penetrating down into a void and then through the terminal ceiling of the Arrivals hall near a flower shop (Fig. 2.3). The fire was detected as a smell of smoke and visible sparks by a taxi driver waiting on the taxi rank. He reported the fire to airport control by telephone. Two minutes later, two airport firefighters were sent to investigate. They called an electrician to investigate an electrical burning smell, but the fire and smoke gradually worsened so that after 12 min a full attendance of the airport fire service was requested. After 16 min a firefighter saw a rapidly spreading glowing area over the suspended ceiling and instructed 20 persons to leave the nearby cafeteria, but no general alarm is given. After approximately 27 min a flashover occurred and the automatic general evacuation alarm was triggered, as well as a fire shutter, which descended too slowly to prevent fire spread to an adjacent hall. The evacuation alarm consisted of a taped message instructing occupants to evacuate towards the fire area. There were 16 deaths including eight in the Air France VIP lounge, five in a lift which descended from the car park and opened on the arrivals hall fire, one person in a toilet and two in the main arrivals hall.

So for this incident:

ASET

Arrivals hall = ~16 min ceiling collapse 30 min flashover
Air France lounge = 23 min smoke blocks escape routes
Departures hall = 31 min smoke spreading at walking speed

Table 2.1 Timeline for Dusseldorf Airport incident

15:31	0	Taxi driver reports smell of smoke and sparks on taxi rank roadway
15:33	2	Two airport fire fighters send to investigate. They called electrician
15:40	9	Electrician attempting to identify source of smoke
15:43	12	Smoke worse: full airport fire service requested
15:45	14	Occupants notice strong stench of burning rubber some leave
15:47	16	Firefighters sees rapidly increasing area of glowing to 20 m^2 of suspended ceiling, shouts to 20 people in Cafeteria to leave (no alarm sounds) then ceiling collapses
15:50	19	Occupants see large cloud of black smoke above arrivals level parking garage
16:06	27	Flashover in hall activates fire alarm and shutters. Automatic voice alarm message directs occupants to evacuate towards the fire

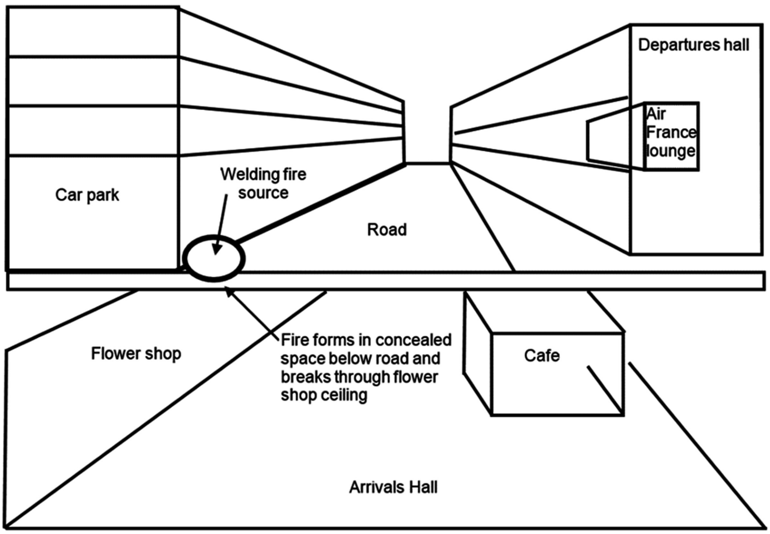

Fig. 2.3 Dusseldorf Airport

$$RSET\left(\Delta tesc\right) = \begin{pmatrix} \Delta tdet + \Delta tpre \\ \uparrow \longleftarrow \downarrow \end{pmatrix} \longrightarrow \Delta ta + \Delta tpre + \Delta ttrav$$

Δtdet + Δta Taxi driver 0 min, before or soon after flaming ignition?
Δtdet Airport Fire fighters 2–16 min (long pre-warning period)
Δtpre Airport Fire fighters 26 min Tell airport security to clear terminal
Δta Voice alarm message 35 min (5 min after flashover and directs towards fire)

The general findings from this and other incidents are that both “detection” and “pre-warnings” are not simple processes, even when sophisticated detection systems are present. For the transport case described, and others, the affected enclosures contained many occupants (travellers) or involved staff, so that cues to all fires were observed by some persons soon after ignition, when the fires were quite small [17, 18]. In two cases (King’s Cross and Dusseldorf) the first person to discover the fire very quickly reported it to the local authority, but in other cases (Channel tunnel, Daegu, Mont Blanc) they either failed to communicate quickly or as in the case of several incidents, were slow to interpret the fire or smoke cues as representing a potentially serious fire and issue timely evacuation warnings, so that there was an extended “detection” period interspersed with an extended “pre-warning” period. A complication with Mont Blanc was that the “opacimeters” providing cues to the fire in the control room were not intended as a fire detection system.

Designer issues: For enclosures such as stations or train carriages, toilets etc., occupancy cannot be guaranteed, so automatic detection is necessary, but for normally occupied enclosures obvious manual means of reporting a fire and raising an alarm should be provided. For large enclosures with high ceilings early detection by occupants is even more likely. Careful consideration needs to be given to the likely series of cues that occupants and staff will become aware of, and how they will and should be trained to interpret and act on the information received, especially what constitutes “detection” of a serious fire.

With regard to the provision of general evacuation warnings it is very important at the design stage (and in simulations) to consider the nature and timing of information regarding a fire that will become evident to security and control staff.

It is then necessary to consider the sequence of investigation activities the staff will be expected to engage in and the sequence of communication and decision making up and down the management chain.

- How serious does an incident need to be before security staff can activate a general evacuation warning?
- What autonomy do passengers or staff at the fire scene, or receiving information directly from it, have to initiate a general evacuation?
- Given that fires in transport incidents may develop from minor to severe fires within a few minutes, how long should be allowed in the design for the detection and warning processes to take place? How can effective firefighting resources be activated to arrive at a fire scene within a few minutes of the first detection?
- For transport situations how is fire information provided to station and train or tunnel operation management to enable facilities to be closed so that no further trains or vehicles enter the danger area?

2.4.1.1 ASET TOPIC 1: Validation of Rosepark Full-Scale Reconstruction Fire Using Fractional Effective Dose Modelling and Forensic Incident Analysis

The Rosepark nursing home fire occurred at 04:28 h on 31st January 2004 and resulted in 14 deaths [20]. As part of the investigation on behalf of the Scottish Office and the Procurator Fiscal a full-scale test reconstruction of the fire was carried out by BRE [21]. The author participated in this work and also investigated the fire time-line and effects on decedents and exposed survivors using documentation related to the incident.

As part of the BRE work time-concentration curves for smoke, toxic gases and temperature from the fire test data were used to calculate (simulate) the uptake by exposed occupants in different locations and the predicted toxic effects and burns. This analysis took the form of Fractional Effective Dose (FED) calculations, whereby the received dose of each toxic gas (or heat) during the fire is expressed as a fraction of the dose predicted to cause incapacitation. The FED of an occupant increases with time during the fire as they are exposed to a toxic gas until a point is reached when the FED exceeds 1, at which time incapacitation is predicted. As part of the analysis the uptake of carbon monoxide was also calculated in terms of calculated percentage carboxyhaemoglobin (%COHb) in the blood, and also the extent of predicted pain or burns from heat exposure. By this means forward-calculated

%COHb concentrations were predicted for each occupant at the time of incapacitation or rescue (for survivors) and the time at which a lethal concentration was achieved (for decedents). This information was used to estimate hazard development during the incident, but in practice the findings were only as good as the extent to which conditions in the reconstruction fire were similar to those in the actual incident, and the extent to which the FED calculation input data and models were representative of the uptake of toxic gases and effects on the actual occupants.

In practice considerable care had been take to replicate the important structural features, fire fuel sources and boundary conditions of the actual incident, and the pattern of fire damage in the experimental rig after the test was very similar to that found during investigation at the incident site.

Another source of information used to validate the test results was the measured %COHb in the blood of incident decedents and survivors. For the 10 persons dying at the fire scene during the incident the %COHb levels represented those at the time of death. For the 8 persons rescued alive from the fire scene the %COHb levels were those recorded from blood samples taken soon after arrival at hospital. After rescue these subjects were treated with oxygen, which gradually washes CO from the blood, but if the time of rescue, subsequent treatment and time of blood sampling are recorded it is possible to back-calculate from the %COHb concentration measured in hospital to that in the blood at the time of rescue.

The extent to which the forward calculated %COHb from the fire test data agrees with the %COHb at death and the back-calculated %COHb in the blood of survivors (and the extent of predicted burns compares with actual burns) therefore provides an indication of the extent to which the fire test conditions and FED calculations are representative of the actual fire incident conditions and effects.

Figure 2.4 shows a plan of the upper (ground) floor of the nursing home which was built on a sloping site. The fire occurred in an open cupboard marked with a star on the plan. A brief violent fire occurred which filled the dog-leg corridor and open bedrooms off it with a dense toxic effluent. Figure 2.5 shows the short high temperature fire in the cupboard, and there was a similar temperature profile in the corridor. However as Fig. 2.6 shows the temperature in the open rooms did not exceed 150 °C at bed height and then only for a brief period. The fire self-extinguished after approximately 6 min as the oxygen in the enclosed system became depleted.

Figure 2.7 shows the time-concentration curves for the smoke and toxic gases in the corridor, which were similar to those in the open rooms off the fire corridor. The FED analysis and calculated %COHb concentrations for an occupant of the fire corridor are shown in Fig. 2.8. The analysis shows that a corridor occupant would be seriously affected by dense irritant smoke from 4 min (as the FIC smoke curve crosses 1 on the Y-axis). Incapacitation (loss of consciousness from the effects of asphyxiant gases) is predicted at 5.5 min (6.5 min in the open bedrooms at bed height). Pain from heat exposure is predicted after 6 min in the corridor, but neither pain nor burns in the open bedrooms. The %COHb increases rapidly after 6 min and in the occupied open bedrooms is calculated to exceed lethal threshold levels (50 % COHb) after 7.9 min.

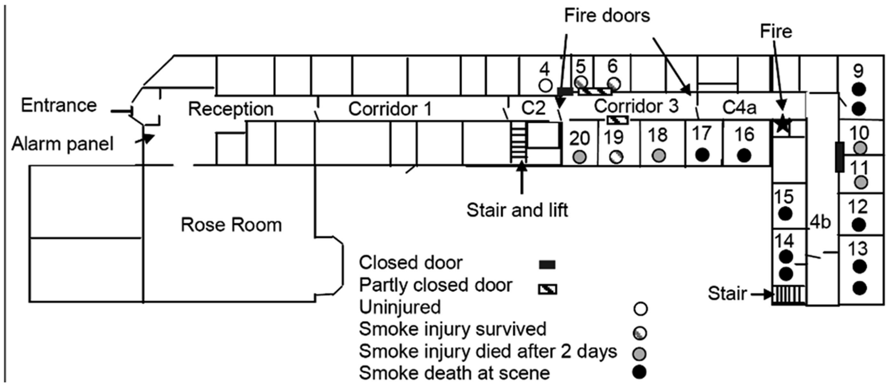

Fig. 2.4 Rosepark Nursing Home ground floor showing locations of exposed residents

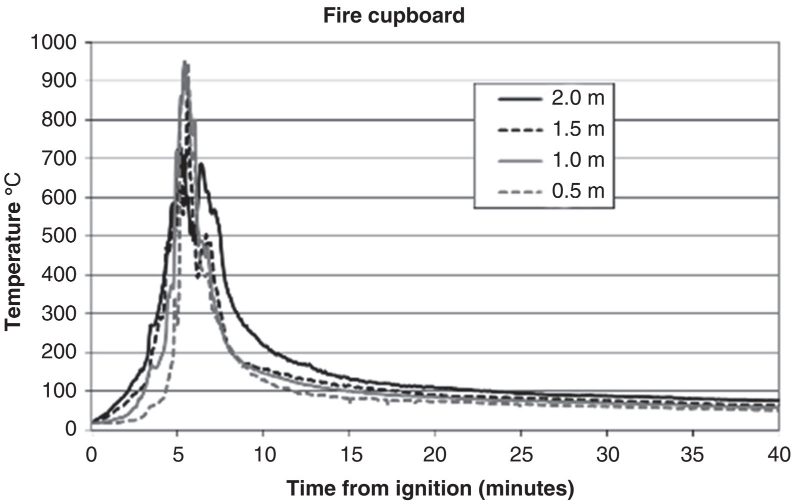

Fig. 2.5 Temperature profile in fire cupboard

From this analysis it was predicted that all occupants of the open bedrooms of the fire corridor would have been incapacitated after 6.5 min and dead by around 8 min. They were predicted to have no burns (at least before death) and that the %COHb concentrations in the bodies would be at lethal levels, exceeding approximately 50 % COHb but with final concentrations depending upon when each individual stopped breathing (ranging from approximately 50–85 % COHb).

In practice all the open room occupants were found dead at the fire scene when the fire service personnel entered the rooms 30–60 min after ignition. They were not burned (apart from some minor superficial, probably post-mortem, burns in a room close to the fire area) and all had very high %COHb concentrations ranging from 48–82 % COHb (mean 63 %). These results were therefore consistent with the

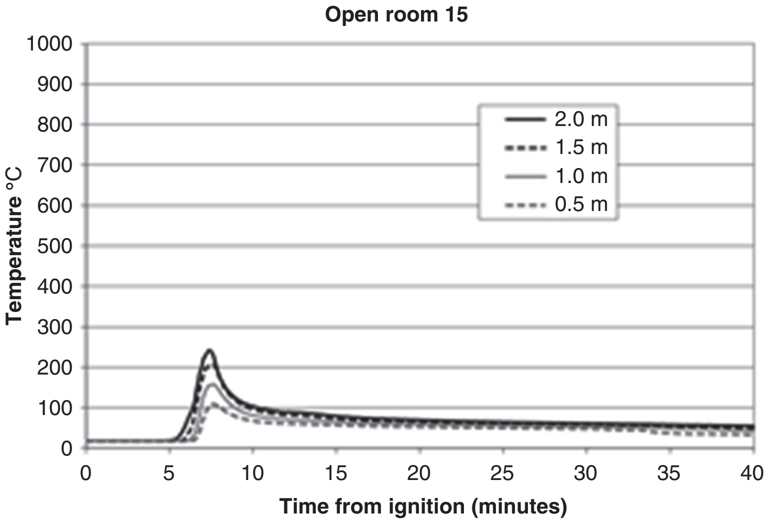

Fig. 2.6 Temperature profile in open bedroom

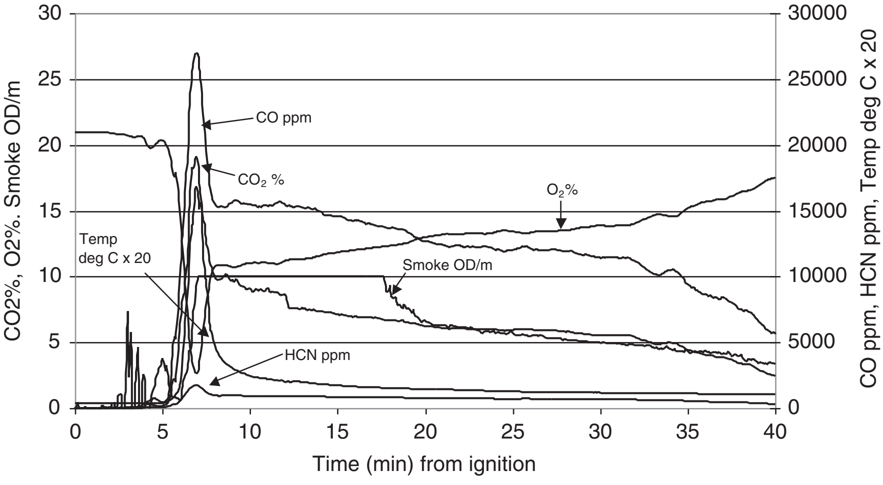

Fig. 2.7 Smoke, toxic gases and temperature profile in the fire corridor during the BRE full-scale recreation of the Rosepark Nursing Home fire. Conditions in the open bedrooms off this corridor were similar except that temperature at bed height was considerably lower

findings predicted from the fire test and FED modelling. However, because the exact times of death could not be established from the forensic data it was not possible to fully validate the CO concentrations and uptake in the test against the actual fire incident conditions.

As indicated in Fig. 2.4, two occupants were in closed rooms (10 and 11) off the fire corridor. The door to Room 10 remained intact, while that of Room 11 was

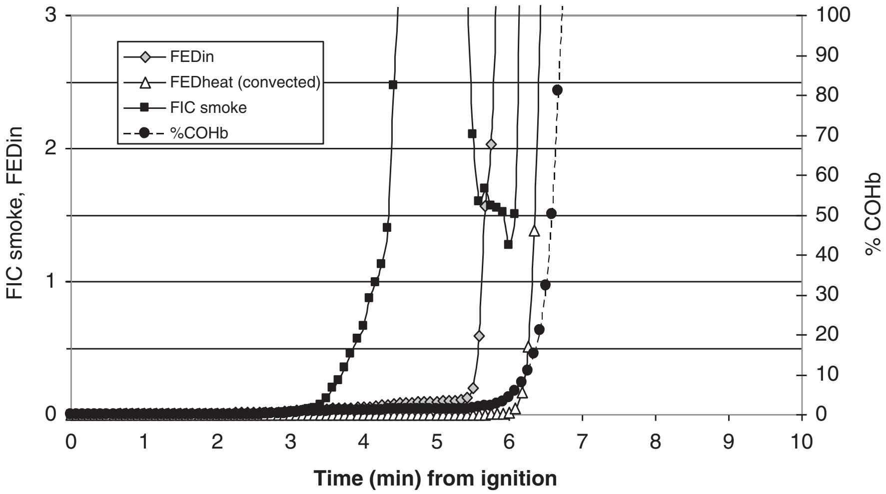

Fig. 2.8 Fractional effective dose hazard analysis for the corridor fire profile in Fig. 2.7

partly burned through during the fire. Since the time of rescue was known it was possible to forward calculate the predicted %COHb at rescue for these occupants from the CO concentration curve measured in a closed room during the fire test, and compare it with the back-calculated values from the blood levels measured after arrival at hospital. Adjacent to the fire corridor was another corridor protected by a fire door which closed when the fire was detected. Unfortunately, the fire cupboard contained some aerosol cans. Each time one of these exploded during the fire the resultant pressure pulse blew open the fire door enabling some toxic smoke to enter the corridor beyond and the open rooms off it. Five occupants were rescued from the rooms off this corridor, with varying degrees of exposure and measured blood %COHb concentrations depending upon the extent to which their bedroom doors were fully or partially opened, or closed during the fire. Similar comparisons could therefore be made between the %COHb concentrations calculated for these individuals from the test data and their concentrations at rescue, back-calculated from the hospital blood data.

Figure 2.9 shows the smoke, toxic gases and temperature profiles measured in a closed room off the fire corridor during the BRE test. Figure 2.10 shows the forward calculated blood %COHb concentration for the occupant of Room 10 up to her rescue after 70 min. The figure shows two uptake curve estimations. These represent the range of uncertainty in the uptake calculation depending upon the respiration of the subject. The lower curve is for a subject at rest breathing 6 L of air each minute (for example a subject resting or sleeping in bed). The upper curve is for a more active subject awake and sitting of standing during the exposure period. The two estimates range from 42 to 56 % COHb at the time of rescue. In practice it is known that this subject got up from her bed and moved around briefly and then sat on a chair, awaiting rescue, before becoming unconscious. Since she was rescued

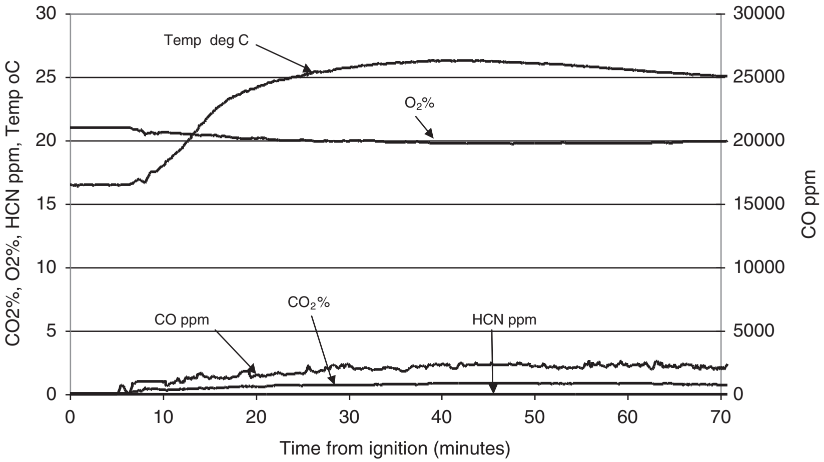

Fig. 2.9 Smoke, toxic gases and temperature profile for a closed room off the fire corridor during the BRE full-scale recreation of the Rosepark Nursing Home fire

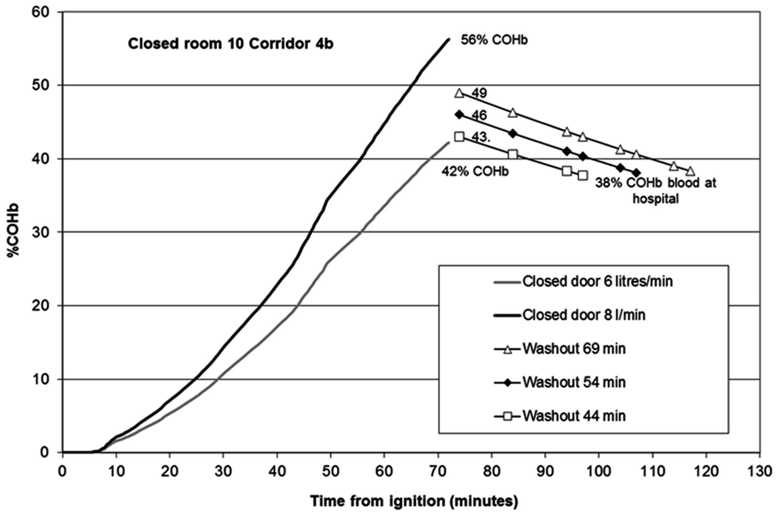

Fig. 2.10 Forward calculated %COHb level for the occupant of closed room 10 from the CO and CO2 gas profiles in Fig. 2.9, assuming sleeping and standing VE values of 6 and 8 L/min compared with %COHb levels back-calculated to the time of rescue using three estimates of the time when the blood sample was taken after arrival at hospital

alive and recovered consciousness in the ambulance it is considered unlikely that she could have had a blood level exceeding 50 % COHb at rescue, so the best estimate would be around 45 % COHb. When a sample was taken at hospital she had a blood level of 38 % COHb. Unfortunately the exact time the blood sample was taken was not recorded, but from other cases it is considered that a sample would have been taken soon after arrival and three estimates of 44, 54, and 69 min after rescue have been made. From the washout back calculations these give a %COHb range at the time of rescue between 44 and 49 % COHb. The best estimate based upon 54 min is 46 % COHb (excluding the 49 % COHb estimate which would most likely have been lethal at the fire scene).

Although both the forward and back-calculated values have some ranges of uncertainty it is considered that the values predicted from the test are very close to those calculated from the blood data and therefore provide a considerable degree of confidence that:

- The conditions in the BRE test fire (the fire size and gas concentrations in the fire corridor) were similar to those in the actual incident
- The leakiness of the closed bedroom doors in the BRE test rig were similar to the leakiness of the actual Rosepark closed bedroom doors, so that the time-concentration curve for CO in the closed test room was similar to that in the actual Room 10
- The FED and %COHb uptake calculations, and burns model, are validated to the extent that the calculated and measured %COHb concentrations were close to those calculated from the measured gas concentrations and the effects on the exposed subject were as predicted (loss of consciousness but survivable at the fire scene with no burns or reported heat pain)

For the occupant of Room 11 forward calculations are complicated by the fact that her room door burned through partially during the fire, which would have allowed the CO concentration in the room to increase considerably to a level close to that in the corridor. Also, since she was rescued at a time when the corridor CO concentrations were still high, she would have suffered some exposure while being carried out along the corridor. When her blood level was forward calculated to the time of rescue plus an additional value for the brief, high concentration, exposure in the fire corridor (but assuming her room door remained intact before rescue) then the calculated value of 34–40 % COHb was somewhat lower than the back-calculated blood value of 43–57 % COHb (Table 2.2). However, when allowance was made for partial door burn through, with increased CO leakage from 34 min to the time of rescue at 41 min, the calculated value increased to around 45 % COHb which is consistent the value using the measured blood data. Table 2.2 summarizes the %COHb comparisons for eight subjects in different locations. For each subject the fire test CO data and times exposed have been used to forward calculate the %COHb at the fire scene. The times on oxygen and blood data %COHb at Hospital (shown in the last column) have been used to back-calculate the %COHb range at the fire scene (shown in the penultimate column).

For the occupants of rooms off the corridor beyond the compromised fire door the forward calculations are complicated in that three subjects had room doors party open or open for part of the time, although two had open doors. For all these subjects the forward-calculated values from the BRE test are somewhat lower than the back-calculated values from their measured blood data. It was concluded that the extent of smoke and CO contamination of this corridor and the rooms off it was somewhat greater in the actual incident than in the BRE test. During the BRE test an extract duct system was omitted which had been present at Rosepark, with

Table 2.2 Occupants alive and rescued at the fire scene: outcomes and comparison between actual and calculated %COHb

Subject and location	Room	Time exposed in room (min)	Time on oxygen (min)	COHb at scene		
				From fire test data	From blood data	
					At scene	Hospital
Closed rooms off fire corridor (corridor 4)						
Door closed, unconscious, recovered in ambulance, pneumonia death	10	72	23–33	42–56	43–49	38
Door partly burned, coma, cardiac arrest, no recovery, pneumonia	11	41	44–69	34–40	43–57	25.8
Open, ajar and closed rooms off corridor 3 beyond fire door						
Door open, coma, resp arrest, no recovery, pneumonia	18	38	51–66	22–29	44–53	24.7
Door open, conscious, pneumonia death	20	27	62–73	20–26	42–55	29.6
Door ajar, conscious, survived	5	32	67–82	~12 19–24	29–32	19.6
Door ajar then closed, conscious, survived	6	36	55–70	~12 22–27	35–38	25.5
Door ajar, comatose, recovered, survived	19	32	67–82	~12 18–24	38–41	24.8
Door closed, uninjured	4	29		~12		

openings to the cupboard and this corridor. Subsequent BRE tests established that a significant quantity of smoke would have been extracted from the fire cupboard into this ducting system, and that some of it would have been released into the corridor beyond the fire door (as reported by witnesses at the time of the fire). This would have added to the total CO concentration in this corridor and rooms off it, which may partly explain why the exposure during the incident appears to have been greater than predicted from the original BRE tests.

Taking these results as a whole, it is considered that the application of the FED and %COHb ASET modelling calculations added considerably to the understanding of the fire conditions at Rosepark, and taken together with the fire test results, incident investigation and toxicology data from exposed subjects, provided a set of evidence validated using the different methods applied. The findings also provide validation of the FED calculation methods to predict effects on subjects exposed in incidents such as this.

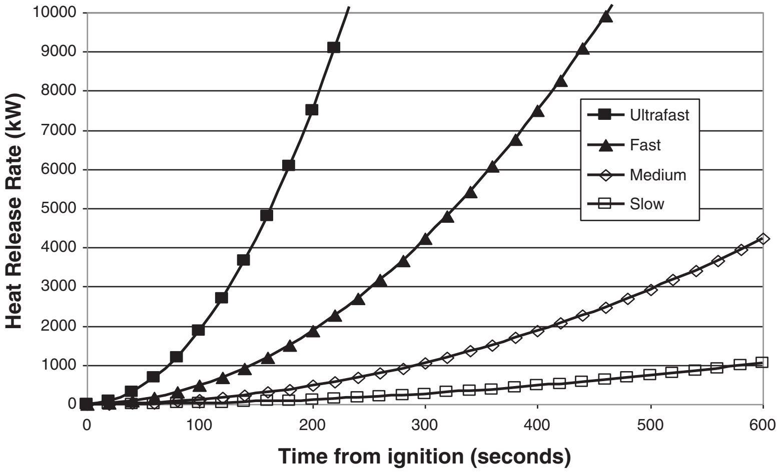

Fig. 2.11 t^2 Heat release rate curves

2.4.1.2 ASET Topic 2: Combustion Chemistry—Measuring Effective Heats of Combustion and Toxic Product Yields as a Function of Combustion Conditions for Input to Fire Dynamics Models

The developing toxic hazard in a compartment fire depends upon the time-concentration curves for the toxic products. This in turn depends on:

- Fire growth curve (mass loss rate of fuel [kg/s])
- Yields of toxic products under a range of combustion conditions (e.g. kg CO/kg material burned)

In fire engineering calculations and computer models the size of the growing fire is often expressed in terms of a t^2 HRR (Heat Release Rate) curve (Fig. 2.11): The mass pyrolysis rate of the fuel is then given by HRR (MW) x heat of combustion (MJ/kg) = kg/s fuel mass pyrolysed. The values used for the heat of combustion are often the constant heats of complete combustion [22, 23]. In practice the actual heats of combustion from burning fuels are likely to be close to these values during the early stages of well-ventilated fires. However, during enclosed or partly enclosed compartment fires typical of fires in buildings, combustion efficiency decreases considerably as the ventilation becomes limited and the combustion fuel-rich. The effective heat of combustion then decreases. This means that to provide a given HRR value inside the fire compartment a greater mass of fuel is pyrolysed.

Similarly, the values for the yields of toxic products commonly used as input to these calculations are often constant values measured during well-ventilated combustion. As the combustion becomes less efficient, the yields of the toxic products of incomplete combustion including smoke particulates, irritant organic species, CO and HCN are considerably increased.

The results of these two common oversimplifications are non-conservative. For example halving the effective heat of combustion results in double the mass production rate of the fuel and toxic products, and when this is accompanied by a tenfold increase in CO yield per kg of fuel mass pyrolysed the result is a 20× increase in the mass production rate of CO.

The ISO/TS19700 tube furnace was developed at BRE to measure heats of combustion and toxic product yields from fuel materials and products over a range of fire conditions. These data can then be used for input to fire simulations to enable calculations of time-concentration curves of fire effluent species [14–16].

The method has been validated for a number of fuels against the yields obtained in large-scale and full-scale compartment fires [24–27].

For flaming combustion, heats of combustion and effluent species yields are measured as a function of the fuel/air equivalence ratio (ϕ). Under well-ventilated combustion conditions ($\phi < 1$), toxic product yields for non-flame retarded materials are low, but increase considerably under fuel-rich conditions ($\phi > 1$).

$$\phi = \frac{Actual\ \ Fuel / Air\ \ Ratio}{Stoichiometric\ \ Fuel / Air\ \ Ratio}$$

The effects of other variables, including temperature, oxygen concentration and non-flaming and flaming decomposition are also measured.

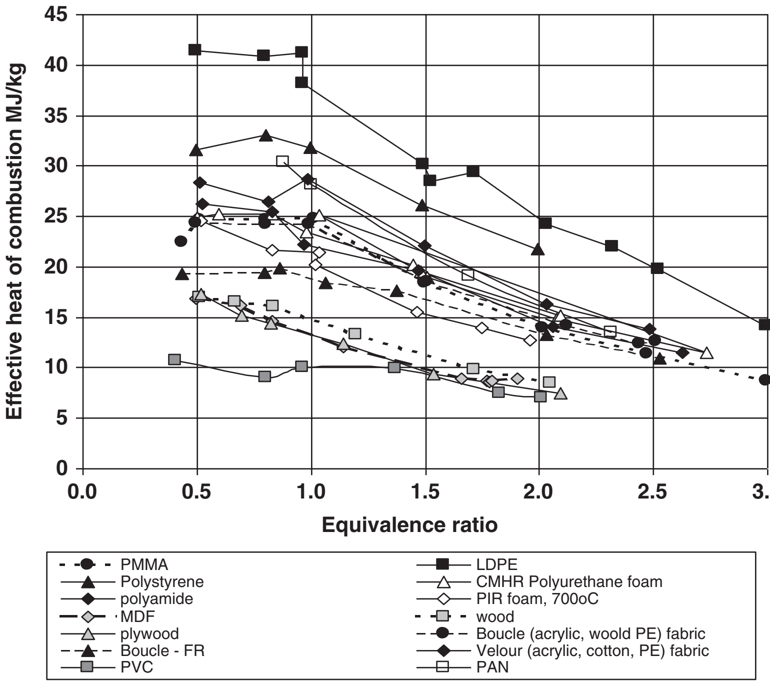

Fig. 2.12 Relationship between equivalence ratio and effective heats of combustion measured using the ISO/TS19700 tube furnace [24, 25]

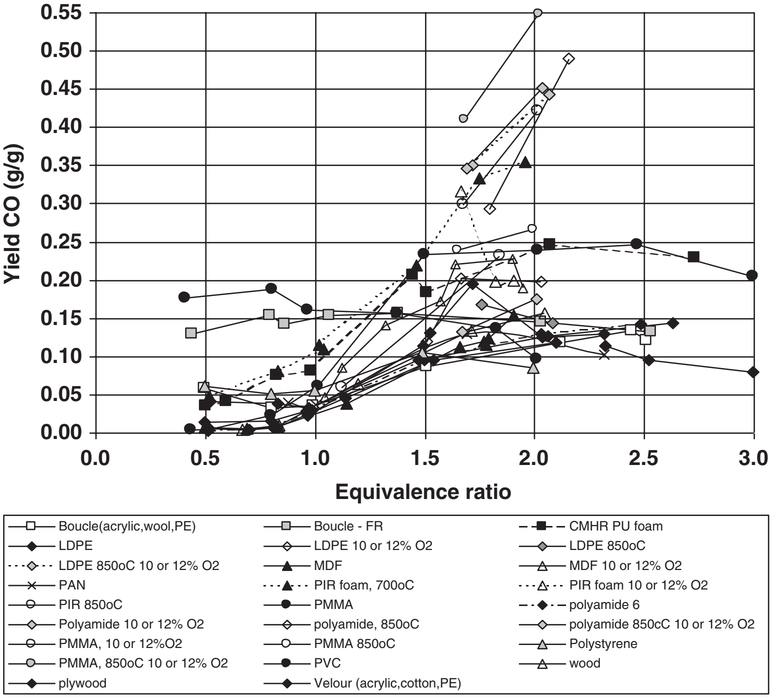

Fig. 2.13 Relationship between equivalence ratio and CO yields measured using the ISO/TS19700 tube furnace [24]

Figure 2.12 shows the relationship between equivalence ratio and effective heats of combustion for a range of common polymers measure using the ISO/TS19700 tube furnace. The effective heats of combustion are maximum under well-ventilated combustion conditions (ϕ 0.5 and 1.0), depending on the polymer composition, but decrease to almost half these levels under fuel-rich condition (ϕ 2.0). For halogenated flame-retarded materials such as polyvinylchloride (PVC) the combustion efficiency is low across the range.

Figures 2.13 and 2.14 show the effects of equivalence ratio on the yields of CO and HCN for the same range of natural and synthetic polymers. For non-flame retarded materials there is a considerable increase in CO yield between well-ventilated and fuel-rich combustion conditions. For example, the CO yield from polymethylmethacrylate (PMMA) increased by a factor of 62 between ϕ 0.5 and 2.0. Under higher temperature (post-flashover, fuel-rich) combustion conditions the CO yields were even higher for some polymers. The presence of halogens as flame-retardants also increased the CO yield under well-ventilated combustion conditions. Figure 2.14 shows similar effects on HCN yields from nitrogen-containing materials, with considerable increases as combustion conditions become fuel-rich. For polyamide-6 the HCN yield increased by factors of between 59 and 101 between ϕ 0.5 and 2.0, depending on temperature and oxygen concentration. It was also found

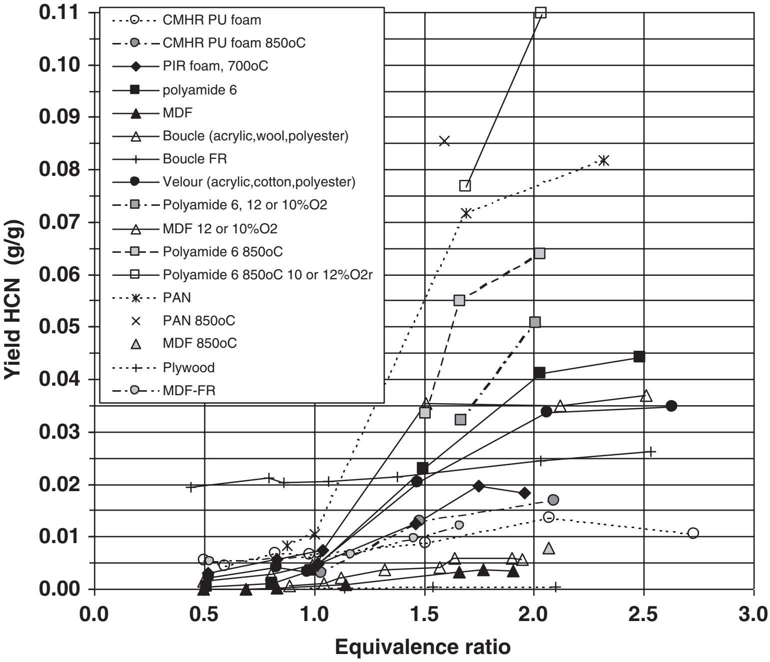

Fig. 2.14 Relationship between equivalence ratio and HCN yields measured using the ISO/TS19700 tube furnace [24, 25]

that there was a close relationship between the efficiency of conversion of fuel carbon to CO and the efficiency of conversion of fuel nitrogen to HCN, which could be useful for modelling applications [25, 26].

The overall findings from this work and complementary studies of full-scale compartment fires and fire investigation statistics is that most flaming fires in buildings are small fires in enclosed dwellings which rapidly become under-ventilated. This results in limited fire damage, usually confined to a limited area of the room of origin, but large volumes of toxic effluents fill open volumes within the structure, resulting in injuries and deaths from toxic smoke exposure. In contrast to this, most large-scale fire tests and fire dynamics models are carried out for well-ventilated combustion conditions involving high heats of combustion and low yields of toxic products. The data obtained using the ISO/TS19700 [16] and the ASTM E2058 flammability apparatus [23], whereby yields are measured as function of equivalence ratio, have been used to derive functions for input to fire dynamics calculations to improve toxic gas concentration calculations for compartment fires, rendering them more realistic and less non-conservative for hazard assessments [1, 24].

2.5 Conclusions

Time-based ASET/RSET analysis is an important and powerful method for evaluating overall fire safety performance.

- For performance-based design, when correctly applied, it enables the engineer to identify and evaluate the effects of each component and their interactions for fire hazard development and fire-safety outcomes.
- It can be applied to scenario analysis with varying levels of sophistication. For example a simple but effective deterministic ASET calculation can be used to determine the tenability time for a single enclosure. A more sophisticated method linked with an evacuation simulation model can be used to calculate the accumulated FED for each individual occupant as they move through building spaces. When such methods are used with variable inputs for different fire and occupant parameters they can be used for Monte Carlo simulation probabilistic risk assessments.
- When the method is applied to the performance-based analysis of prescriptive guidance it can be used to highlight areas requiring modification and provide a means to achieve improvements (pre-empting fire incidents otherwise likely to occur).
- By identifying parameters having a large effect on safety, but for which knowledge is poor, it provides a focus for research needs, the collection of improved data and the development of improved methods.
- It provides a valuable method for incident investigation and forensic fire incident analysis.
- Finally it provides a conceptual framework enabling fire engineers and professionals working on different aspects of fire safety to collaborate to improve overall fire safety knowledge and outcomes.

References

1. Purser, D. A. (2008). Assessment of hazards to occupants from smoke, toxic gases and heat. In P. J. DiNenno (Ed.), *SFPE handbook of fire protection engineering. Chapter 2–6* (4th ed., pp. 96–193). Quincy, MA: National Fire Protection Association.
2. Purser, D.A. (2002). *ASET and RSET: Addressing some issues in relation to occupant behaviour and tenability*. 7th International Symposium on Fire Safety Science (pp. 91–102). Worcester, MA: Worcester Polytechnic Institute. 16–21 June 2002. Fire Safety Science—Proceedings of the Seventh International Symposium. International Association for Fire Safety Science, 2003.
3. British Standards Institution. (2004). *The application of fire safety engineering principles to fire safety design of buildings. Human Factors: Life safety strategies—Occupant evacuation, behaviour and condition* (PD7974-6). London: British Standards Institution.
4. ISO. (2009). *ISO/TR16738 Fire-safety engineering—Technical information on methods for evaluating behaviour and movement of people International Standards Organisation.* Geneva: Author.

5. Reed, R. E. H. (1986). *British fire legislation on means of escape 1774–1974*. BRE Report. Building Research Establishment. Watford, U.K.
6. Joint Committee of the Building Research Board. (1946). *Post-war building studies*. London: The Stationery Office.
7. Communities and Local Government. (2006*). Fire safety: Approved document B* (Vols. 1 and 2). Communities and Local Government. London, The Stationery Office.
8. (2010). *The Building Regulations, England and Wales*. London, The Stationery Office.
9. *Fire statistics in The United Kingdom 2011*. London: Communities and Local Government (published annually). London, The Stationery Office.
10. *Furniture and furnishings (Fire) (Safety) regulations 1988 statutory instrument 1988/No. 1324*. London, The Stationery Office.
11. Babrausakas, V., Fleming, J. M., & Russell, B. D. (2010). RSET/ASET, a flawed concept for fire safety assessment. *Fire and Materials, 34*, 341–355.
12. Bensilum, M, & Purser, D. A. (2002). *GridFlow: An object-oriented building evacuation model combining pre-movement and movement behaviours for performance-based design*. 7th International Symposium on Fire Safety Science (pp. 941–952). Worcester, MA: Worcester Polytechnic Institute. 16–21 June 2002 (Proceedings in press). Fire Safety Science—Proceedings of the Seventh International Symposium. International Association for Fire Safety Science, 2003.
13. Purser, D. A. (2003). Behaviour and travel interactions in emergency situations and data for engineering design. In E. Galea (Ed.)*, Pedestrian and evacuation dynamics 2003: Proceedings of the 2nd International Conference on Pedestrian and Evacuation Dynamics, Greenwich* (pp. 355–370). London: University of Greenwich.
14. Purser, D. A., Fardell, P. J., Rowley, J., Vollam, S., & Bridgeman, B. (1994, January). *An improved tube furnace method for the generation and measurement of toxic combustion products under a wide range of fire conditions*. Proceedings of the 6th International Conference Flame Retardants '94 (pp. 263–274). London: Interscience Communications.
15. ISO/TS 19700. (2007). *Controlled equivalence ratio method for the determination of hazardous components of fire effluents*. Geneva, Switzerland: International Organization for Standardization.
16. Purser, J. A., Purser, D. A., Stec, A. A., Moffatt, C., Hull, T. R., Su, J. Z., et al. (2013). Repeatability and reproducibility of the ISO/TS 19700 steady state tube furnace. *Fire Safety Journal, 55*, 22–34.
17. Purser, D. A. (2011, October 21). *Design behavioural scenarios for escape behaviour modelling in tunnels and underground complexes*. Proceedings of Advanced Research Workshop on Evacuation and Human Behaviour in Emergency Situations (pp. 1–19). Santander, Spain: University of Cantabria.
18. Gwynne, S. M. V., Purser, D. A., Boswelll, D. L., & Sekizawa, A. (2012). Understanding and representing staff pre-warning delay. *Journal of Fire Protection Engineering, 22*, 77–99. doi:10.1177/1042391512436785.
19. Ballard, C. (1996). Düsseldorf Airport tragedy. *Fire International, 152*, 18–21.
20. Rosepark Nursing Home. *Sheriff's inquiry report and appendices*. http://www.scotcourts.gov.uk/opinions/2011FAI18.pdf http://www.scotcourts.gov.uk/opinions/APPENDICES.html
21. Building Research Establishment. (2004, January 31). *Experimental research for Scottish Building Standards Agency following the fire at the Rosepark Care Home,* Glasgow (BRE Project Rep. No. 219132). Retrieved October 2004, fromhttp://www.scotland.gov.uk/Topics/Built-Environment/Building/Building-standards/publications/pubresearch/researchfire/resroprk
22. British Standards Institution. (2003). *PD7974-1 Application of fire safety engineering principles to the design of buildings—Part 1: Initiation and development of fire within the enclosure of origin (Sub-system 1)*. London: British Standards Institution.

23. Tewarson, A. (2008). Generation of heat and gaseous, liquid and solid products in fires. In P. J. DiNenno (Ed.), *SFPE handbook of fire protection engineering* (4th ed., pp. 3-109–3-194). Quincy, MA: National Fire Protection Association.
24. Purser, D.A., & Purser, J. A. (2003, March 28). *The potential for including fire chemistry and toxicity in fire safety engineering* (BRE Rep. No. 202804). Garston: Building Research Establishment.
25. Purser, D. A. & Purser, J. A. (2008). *HCN yields and fate of fuel nitrogen for materials under different combustion conditions in the ISO 19700 tube furnace*. Fire Safety Science—Proceedings of the ninth international symposium (pp. 1117–11128). Karlsruhe, Germany: International Association for Fire Safety Science.
26. Purser, D. A. (2000). Toxic product yield and hazard assessment for fully enclosed design fires involving fire retarded materials. *Polymer International, 47*, 1232–1255.
27. Stec, A., Hull, T.R., Purser, D. & Purser, J. (2014, February 10–14). *Fire toxicity assessment: Comparison of Asphyxiant Yields from laboratory and large scale flaming fires*. 11th International Symposium on Fire Safety Science. Christchurch, New Zealand: University of Canterbury.

http://www.springer.com/978-3-319-20707-0

Evacuation Modeling Trends
Cuesta, A.; Abreu, O.; Alvear, D. (Eds.)
2016, VII, 133 p., Hardcover
ISBN: 978-3-319-20707-0