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Assessment of pre-warning, pre-travel and travel behavior interactions with smoke and toxic gases during fire incidents

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ABSTRACT

Evaluation of potential fire scenarios and escape outcomes involves data and calculations for many different parameters and their interactions, with uncertainties regarding application to real systems. Assessment of fire development, occupant behaviors and effects of toxic smoke exposure during actual incidents can provide a reality check on engineering methods, data quality, assumptions and limitations. Because incidents encompass the performance of entire occupied built systems, they enable witness accounts, survival, medical and pathology outcomes and evidence of fire development and toxic smoke spread to be combined with fire, evacuation and toxicity modelling calculations. Since outcomes are known, they constrain the predictions derived, revealing previously unidentified parameters and enabling validation of current methodology. Examples from incidents highlight the following findings.

- Pre-warning delays – neglected parameter, high consequence.
- Effects of fire cues and warnings on occupant behavior and pre-travel times, and stair descent speeds in relation to visibility – generally validate current methods.
- Probability of evacuation through irritant smoke– high consequence, needs more consideration.
- Times to incapacitation from asphyxiant gases as a function of fuel composition and smoke density – useful assessment method.
- Using smoke and carbon monoxide exposure toxicology to estimate fire development and exposure history - Useful method for fire scenario validation, confirms FED method validity.

1. Introduction

Fire safety management and emergency evacuation design methods have mainly been developed for application to non-residential premises (such as hotels, stores, businesses and transport), usually with 24 h security and automated detection and warnings [1,2]. Scenarios generally assume evacuation without smoke exposure and both travel and pre-travel data from experimental studies provide a good basis for evacuation evaluation in well-managed scenarios [1,3,4]. However, a number of incidents have revealed cases where escape times have been fatally prolonged by pre-warning delays resulting from inadequate fire safety management responses to initial fire detection, with extended periods before evacuation warnings were provided to affected occupants [5]. Incidents involving extensive fire spread between compartments in high rise residential buildings, including Lakanal House [6] and Grenfell Tower [7] in the UK have revealed issues in fire safety and evacuation management for buildings designed with a "stay put" (shelter in place), strategy with no on site fire security, communal warning system or simultaneous evacuation plan (no "Plan B″ for when fire development exceeds expected limits). Also, during actual incidents, occupants may encounter toxic smoke in escape routes. While experimental data is available for effects of theatrical smoke density on walking speeds of volunteer subjects in smoke [8–11] information is limited on behavioral aspects of the probability that occupants will enter and continue through smoke in different circumstances, and how far they will be able to travel before being incapacitated, although these aspects can have a major impact on survival outcomes during incidents [12].

Limitations in predicting potential fire growth and development scenarios for large buildings arise from the application of fire growth data and models derived from limited experimental data for materials and products obtained using limited scale standard test rigs with stylized fuel installation and ignition sources. The multiple variables affecting especially early fire development and the exponential positive feedback of fires means that the forward prediction pattern, timing and scale of fire development can progress in many different ways, even for repeats of situations with identical compartment and fuel settings [13]. During

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actual incidents, reports by occupants of the smoke and heat conditions encountered at different times can be valuable to indicate the extent of fire spread and development in different enclosures [14]. Toxicity data, especially blood carboxyhemoglobin concentrations (%COHb) in survivors and fatalities can be used to calculate the integrated carbon monoxide time x concentration (Ct) exposure dose they were exposed to and, if the exposure duration is known, the average carbon monoxide (CO) concentration over that period of the fire [15,16]. Similarly, burns data provide an indication of the severity of the heat exposure and therefore an indication of the exposure heat flux and temperature history. This data can then be used to constrain and validate forward based modelling of fire development, in that Fractional Effective Dose (FED) calculations for modelled time-concentration curves for heat, smoke and toxicity must be consistent with the actual findings from the incident. Similarly, the results of any full-scale fire reconstruction experiment must be consistent with the findings for effects on occupants if the reconstruction provides a realistic representation of the fire development in the actual incident.

In relation to toxicity, since the ratios between the concentrations of smoke particulates and different toxic gases remain relatively constant as fire effluents flow away from the source fire, if the fuel composition, combustion conditions and yields of toxic products are known, then if the exposure concentrations of one component such as CO can be derived from the incident blood data, then approximate exposure concentrations of other toxic products such as smoke, hydrogen cyanide (HCN) or hydrogen chloride (HCl) can be estimated [14,15,17].

Examples of the application of these methods to fire incidents are presented that have assisted with evaluation of scenario development and effects on occupant behaviors and survivability, and with evaluation of the fire conditions they were exposed to. Although these investigations involve a wide range of parameters and data, the analysis is focused on the following topics.

- Pre-warning delays and consequences
- Effects of fire cues and warning on occupant evacuation behavior in different situations, and implications for fire awareness and pre-travel times
- Probability of entering and continuing to evacuate through irritant smoke of different densities
- Stair descent speeds of mixed occupant populations through light and dense smoke
- Exposure times to incapacitation from asphyxiant gases for effluents from mixed fuel sources as a function of smoke density
- Using smoke and carbon monoxide exposure (derived from blood and lung toxicity data) to estimate fire development and exposure history in different enclosures

The incidents considered for this review involve a range of building and transport system scenarios. The parameters evaluated and methods used are considered to be generally applicable to any occupied system. Particular occupancy types tend to present some common additional features relevant to design and scenario evaluation, but outcomes for any individual scenario may be influenced by specific characteristics. The findings for warning and behavioral responses provide some data for specific cases, but also highlight the need for designers to consider implications and mitigation features for any specific application. The smoke toxicity methods should be applicable to any occupied fire scenario.

2. Material and methods

This review draws on information from investigation of several major fire incidents with respect to witness accounts of timed fire development, the conditions encountered by occupants, effects on their condition and behavior, post-incident site investigations, toxicity, burns and other pathology or clinical information for survivors and fatalities.

For some incidents computational fire dynamics (CFD) modelling has been used to estimate the timed development of conditions occupants were exposed to in terms of fire effluents and heat. The composition of effluents in terms of smoke density and concentrations of smoke particulates, irritant and asphyxiant gases have been estimated from assessment of the fuel materials and masses involved and toxic product yields, derived mainly from bench scale ISO 19700 tube furnace data for a range of individual materials measured for flaming combustion as a function of equivalence ratio (φ) [18–21] By this means time-concentration (or time-intensity) curves for irritant smoke, CO, HCN, CO_2, oxygen depletion, temperature and radiant heat flux have been estimated in the breathing zone of occupants at their varying locations during incidents. This data has been input to FED calculations for effects of irritant smoke on escape capability, uptake of CO as blood carboxyhemoglobin and time to incapacitation or death from exposure to heat and asphyxiant gases [22,23]. For other incidents, full-scale fire reconstruction fire experiments have been used to replicate as far possible the developing fire scenario [15,16] In these cases the time-concentration curves of smoke, heat and toxic gases have been measured directly, and the data used for input to FED calculations. For both approaches witness information on occupant exposure, toxicity data on blood %COHb and cyanide levels, and records of respiratory tract injury and burns have been used to validate fire modelling or reconstruction data against fire scenario development during the actual incident by comparing the extent of agreement between the predicted effects on occupants from the forward measured and modelled heat and smoke conditions and the actual recorded outcomes.

For occupants who died at the fire scene, the extent of burns, soot deposits and blood %COHb indicate their cumulative heat and smoke exposure, but full evaluation of the exposure concentration history requires additional timing information on exposure and death. For occupants surviving immediate exposure at the fire scene, their %COHb at the time they left the fire can be back-calculated from blood concentrations measured after arrival at hospital, using CO washout expressions provided the post-exposure history of oxygen treatment is known [23]. This then gives the accumulated %COHb throughout exposure up to the time of rescue. Approximate estimates of the CO concentration x time exposure profiles can then be used for forward FED uptake calculations of %COHb. Varying the estimated CO profile using an iterative approach, the fire scenario CO time-concentration profile providing the measured outcome can be calculated. This can be used to refine the fire scenario calculation model to obtain the best fit with the measured outcome or to determine the goodness of fit of a reconstruction fire test or fire model with the outcomes of the actual incident [14].

In the absence of fire modelling or test scenario data another related approach to estimating fire scenario exposure conditions can be based on the ratios between smoke and gases in fire effluents and reported smoke visibility conditions during incidents or later measured blood %COHb concentrations [14,17]. Using the ISO 19700 tube furnace, an extensive data set has been measured of the yields of smoke particulates, optical density, CO, CO_2. HCN, oxygen depletion and acid gases for combustible materials commonly used in built structure and contents [18,21]. Data have been measured for non-flaming decomposition and for flaming combustion over a range of fuel:air equivalence ratios. For any given material the yields of both smoke and toxic gases has been found to increase considerably with increasing equivalence ratio, as combustion conditions change from well-ventilated ($\varphi < 1$) to under ventilated ($\varphi > 1$). Although the yields of these products change with combustion conditions, and the concentrations decrease as the fire effluents flow away from the combustion zone and are diluted by entrained air, the relative concentration ratios between the smoke particulates and gases remain approximately constant. For a given fuel mix, if the concentration of one component (such as smoke density), is known, the concentrations of other components can then be estimated.

3. Review results

A full assessment of design scenarios for occupied systems involves an ASET-RSET evaluation, for which the Available Safe Escape Time (ASET) analysis includes all the time-based processes involved in the developing fire scenario, including ignition, fire growth, involvement of fuel items, the production of smoke, heat and toxic products as they spread within and beyond the original fire enclosure up to or beyond the point where occupants are exposed to conditions likely to impair their ability to escape (or shelter in a refuge), or to evaluate outcomes involving incapacitation or death in higher risk scenarios. Required Safe Escape Time (RSET) analysis involves the sequence of time-based escape processes, running in parallel with the developing fire threat, including time from ignition to detection, to warnings, pre-travel and travel time. This conceptual framework for this is set out in BS7974 PD6 [1].

Historically the main component measured experimentally and calculated for evacuation time evaluations has been the travel time component. Flow patterns in multi-enclosure buildings can be resolved by computer simulation models, but simple hand calculations can give accurate results for parameters such as pre-travel times and flow times from stairs or final exits [1,24]. Work on the behavioral response of occupants to fire cues and warnings by Sime [25] Canter [26] and Proulx [27] identified the importance of pre-travel times and behaviors, for which there is now a growing set of quantified data obtained from unannounced experimental evacuations of different occupancies [3,4]. Most of these studies have been for non-residential occupancies designed for simultaneous or phased evacuation in case of fire, so incorporating automatic detection and warning systems, in most instances with 24 h security and fire safety management. Unannounced evacuation experiments and some incident investigations have shown that where warning systems are appropriate and fire safety management is of a high standard, then pre-travel times tend to be short (a few minutes) and predictable, while limited warnings with few poorly trained staff to manage an incident may lead to longer and more variable pre-travel time distributions [1,3]. Timed data for evacuation of entire residential apartment blocks is lacking because such occupancies are generally not designed for simultaneous or phased general evacuation so have no communal detection or warning systems and in most cases no onsite fire safety management for incidents [28].

3.1. Pre-warning delays affecting alarm or warning times

A parameter likely to be neglected in an experimental or design context but shown to have been of high consequence in a number of incidents is the period between the initial detection of a fire and the provision of a general evacuation warning to affected occupants (pre-warning delay) [5]. Where warnings depend on the actions of the first persons to discover a fire and the subsequent actions of others in larger or more complex occupancies this has introduced long delays before evacuations were started in some incidents, resulting in injuries and deaths or “near misses” for occupants. Examples include transport systems (London Kings Cross, Channel Tunnel, Mont Blanc Tunnel, Daegu subway, Dusseldorf airport), Bradford Football Stadium, Manchester Woolworths, World Trade Center, San Juan Du Pont Plaza Hotel, Rosepark Care Home Glasgow [29,30]. In all these incidents the fire was discovered at an early stage but there were prolonged delays before affected occupants were warned to evacuate. During these incidents fires were initially not considered a serious threat and delays were introduced during subsequent investigation and reporting up and down the management chain and among firefighters. These pre-warning delays have a large influence on overall RSET so should receive more consideration for occupancies designed for managed evacuation during incidents.

3.2. Warning times and pre-warning delays in multistory residential apartment buildings

The situation is more complicated for multi-storey residential apartment buildings. In the United Kingdom the general performance-based requirement for all buildings is for the provision of early warning of fire and means of escape to a place of safety outside, capable of being safely and effectively used at all material times. For blocks of flats this is achieved by requiring smoke or heat alarms in each individual occupancy and structural fire protection, with fire resisting construction between flats and a fire protected escape route via communal lobbies and separately protected stairs. The basic concept is that should a fire occur in any individual flat (or flats) the occupants should be alerted and able to escape via lobbies and stairs designed to remain fire and smoke free throughout an incident, while the fire and smoke remains contained within the flat of origin by the fire resisting construction and the self-closing fire and smoke resisting flat entrance doors. The guidance is based on the assumption that simultaneous evacuation of the building is unlikely to be necessary and that occupants of flats other than the flat of origin should normally be able to shelter in place (stay put strategy) but should always have a smoke-free protected escape route available should they wish or need to evacuate.

A number of recent serious fire incidents have involved rapid exterior fire spread on cladding systems of high rise buildings. Two incidents involving multiple loss of life in London high rise blocks of flats were Lakanal House (16:10 h July 3, 2009 [6]) and Grenfell Tower (00:54 h June 14, 2017 [7]). In both incidents the fires in the flats of origin were reported within minutes but there were long delays before occupants were advised or assisted to evacuate. At Lakanal House 4 deaths occurred and at Grenfell 71, involving occupants of flats remote from that of fire origin. In both cases occupants were advised to “stay put” in their flats and at Grenfell advice was not changed from “Stay put” to “evacuate” until around 02:35 h, (which was 1 h:41 min after the fire was reported at 00:54 h) [7]. This illustrates the complexity of provision of evacuation warnings for such scenarios. Initially, while the fire was confined to the flat of origin, it was arguably unnecessary to encourage all occupants to evacuate. The situation changed dramatically from ~01:15 h, from when there was rapid exterior fire spread up the entire tower to the roof crown over a 13 min period, with subsequent lateral spread in both directions around the Tower. The single 1 m protected stair remained relatively smoke free for ~40 min, so many occupants evacuated from all levels of the Tower without difficulty up to ~01:40 h, after which the lobbies on many floors and the stair were filled with dense smoke [14]. Throughout the Tower most occupants were aware from early on of the developing situation and in contact with other occupants, friends and relatives within and outside the Tower, and with the emergency services. There was also an intercom call system in the ground floor lobby available to address each flat. Despite this there was a pre-warning delay of ~1 h 41 min from when the fire was first reported or 1 h 20 min from when serious exterior fire spread up the exterior and started to break into flats from the 5th to the 23rd floor. There was an approximate 35–40 min time window when all occupants might have been encouraged to evacuate safely after the start of exterior fire spread until the stairs became smoke filled.

3.3. Pre-travel times at Grenfell [14]

Grenfell provides a case of a 23 floor multi-occupancy residential building incident for which some pre-travel time analysis is possible. Fig. 1 shows the layout with six flats on each floor numbered as shown (e.g. in the 6 position flats 16 on the 4th floor to 206 23rd floor).

The sequential timings of fire cues affecting occupants of many of the Grenfell flats are varied, but one sub-set, alerted by rapid fire development at an early stage of the incident, involved the occupants of each of the flats in the Flat 6 location directly above the flat of fire origin (Flat 16) from the 5th to the 23rd floor. They were alerted as the exterior fire

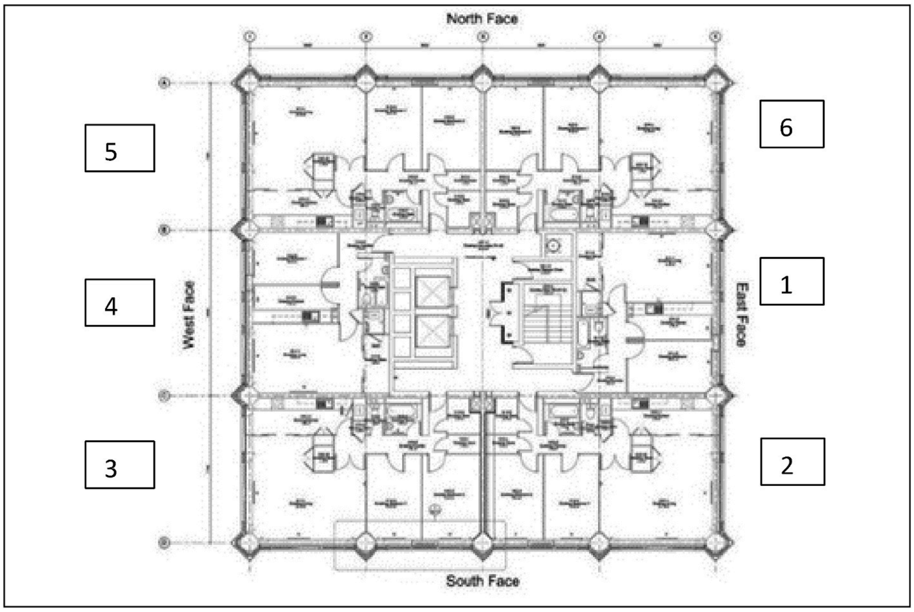

Fig. 1. Grenfell flats floor plan.

spread up outside the kitchen windows on each successive floor over a period of 13 min. As the fire reached each flat, smoke and flames penetrated the kitchen and occupants became aware of the fire by a variety of cues leading them to investigate and take rapid action in response. Those awake before the arrival of the exterior fire were generally aware earlier than those sleeping. Many were alerted by their smoke or heat alarms (Table 1), other noises (such as noises outside the Tower) or a smell of smoke before their alarms sounded, or were warned by others before the fire arrival. The arrival of smoke and flames outside and penetrating the kitchen windows prompted the occupants to make an immediate decision to escape. They then rapidly engaged in activities preparing to evacuate (waking children, alerting family members, collecting important items such as passports or mobile phones, and putting on minimal clothing). Fig. 2 shows the estimated flat exit time into the lobbies relative to fire arrival time for each floor. This was generally within 1–3 min after discovering the fire outside the windows and in some cases earlier, before the fire arrived, especially on the upper floors.

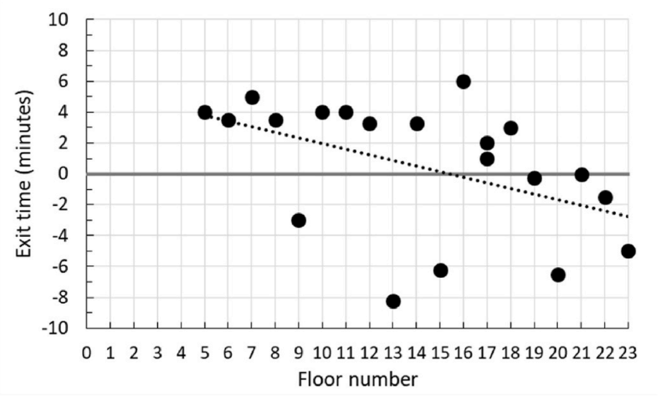

Fig. 2. Grenfell Flats 6 exit times in relation to exterior fire arrival outside kitchen windows.

3.4. *Stair descent behavior and speeds*

The Grenfell incident also provides a rare opportunity to obtain measured stair descent behavior and descent speed data for a mixed age population including children and elderly with varying abilities and disabilities, including movement through clear conditions up to dense smoke. Most Flats 6 occupants descended the stair without difficulty and exited the Tower after leaving their flats. In Fig. 3 recorded Tower exit times are shown for 40 Flat 6 occupants who descended the Tower (triangles). Occupant density in the stair was low so that descent was effectively unrestricted and those who evacuated did so by 01:31 h apart from one occupant from Floor 16 who remained in the stair assisting others. Descent rates under clear conditions were generally rapid at approximately 12 s per storey. Occupants descending the stair around this time did not report congestion. Some slower moving occupants, including one with a walking aid, reported others running past them on the stair while others reported short periods behind slower occupants (such as young children). The open squares in Fig. 3 show the calculated Tower exit time for Flat 6 occupants from each floor assuming they walked continuously down the stair at 12 s per storey immediately after leaving their flats. For most floors below the 19th the calculated times are close to the recorded exit times. Flat 6 occupants from floors 19–23 exited their flats but then sheltered in other flats and did not descend the stair. The open squares show that these occupants should have been able to descend safely and evacuate the Tower by ~01:30 h had they been

Table 1
How Flats 6 occupants first became aware of the fire.

Floor	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Smell				8	9			12											
Alarm	5	6				10				14			17	18			21		
Verbal warning			7						13										
Noise							11					16							
Saw fire outside											15								
unknown															19	20		22	23

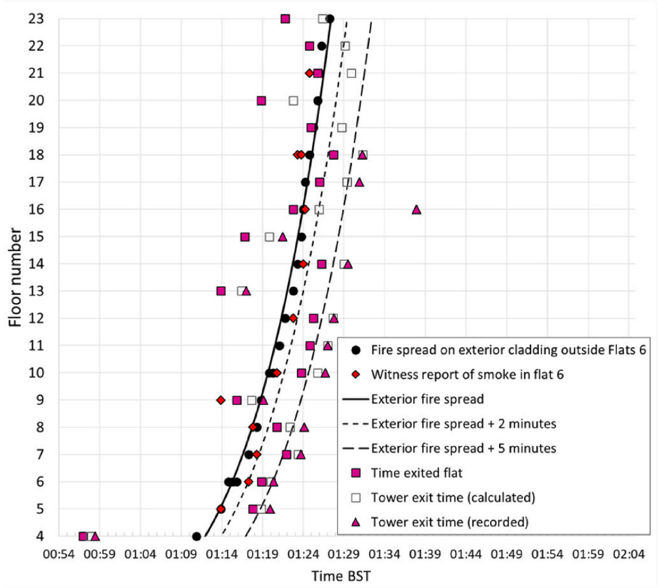

Fig. 3. Timing of fire spread up exterior cladding outside kitchens of Flats 6 on each floor with timings of witness reports of smoke in the flats and times occupants evacuated their flats. Also shown is recorded Tower exit times compared with calculated Tower exit times.

encouraged to continue down the stair after leaving their flats.

The time required to clear the building using the stair assuming simultaneous evacuation depends on three main aspects, the number of occupants, the height of the building (number of floors) and the maximum flow capacity of the stair. During a visit to the Tower I measured my descent time (73 year old male wearing protective clothing and heavy boots) at 9.3 s per floor, representing a nominal descent time over 23 floors of 3.5 min, (Table 2) which is consistent with published findings of average unrestricted descent rates under experimental conditions of 9.6 s/floor for males and 10.2 s per floor for females [31].

Some Grenfell occupants made 999 calls just before or during the period they evacuated their flats and entered the stair. For these it is possible to determine their stair entry times and descent rates [14]. Two occupants (husband and wife) descended from the 18th floor through light smoke running with a descent time of 02:30–03:30 min, exiting at 01:31:30 h, a descent rate of 8–12 s/floor (Table 2) so were unaffected by the light smoke present.

For a 1 m wide stair the calculated maximum flow at 60 persons/minute/meter effective width is 60 x (1–0.3) = 42 persons/minute [1]. For 293 occupants this gives a simultaneous evacuation flow time of ~7 min. If the entire Grenfell population had entered the stair simultaneously, this represents an average of 13 persons on the landings and stair between each floor with a low density of ~1 person/m^2 enabling unrestricted descent speeds. In practice during experimental evacuations of multi-storey buildings occupants tend to a maximum density of 2 persons/m^2. For a 1 m stair (and landings) such as at Grenfell this gives a maximum standing capacity on the stair of approximately 460 persons (~20 persons per floor) [32,33].

These findings confirm that for residential apartment buildings, occupant densities are low, so that even minimum exit and stair widths allow for stairs of sufficient standing and flow capacity for even simultaneous evacuation of all occupants without congestion on the stair, enabling unrestricted descent under smoke-free or light smoke conditions. In practice, even simultaneous warnings result in distributions of pre-travel times, thereby further reducing densities on stairs. At Grenfell, if occupants of flats on all floors could have been encouraged to evacuate around the same time as Flats 6 occupants evacuated their flats on each floor, this could have enabled almost all occupants to clear the Tower within a few minutes, before the lobbies and stair became seriously smoke filled.

Although many Flats 6 occupants and occupants of other flats did evacuate safely during this early period, occupants of some flats remained for a crucial further few minutes and were then trapped in their flats by the dense smoke filling the lobbies. Another event adversely affecting evacuation and survival during the early period was the behavior of a cluster of occupants descending the stair from the upper floors of the Tower. This group of 18 persons included 10 of the Flats 6 occupants and 8 others. After descending a few floors someone below is reported to have shouted to turn back, so the group re-ascended to take refuge in flats on the upper floors. As they passed and entered the upper floor lobbies they inhibited evacuation of occupants from those floors who were preparing to do so. At this time there was minimal smoke in the stair and many other occupants were able to evacuate safely. This behavior affected the upper six floors so the occupants then remained trapped in flats when the lobbies and stair became smoke filled.

Fig. 4 shows evacuation times from all flats at different levels of the Tower. Many occupants became aware of the developing incident at an early stage, before the lobbies filled with smoke on many floors (~01:30 h), before descending occupants started encountering thickening smoke in the stair affecting their descent (~01:45 h) and before the stair was filled with dense smoke (~02:00 h). The smaller numbers from floors 18–23 reflect the effects of the cluster turning back affecting these floors. After the lobbies filled with dense smoke there was a period of approximately 30 min during which evacuation ceased as remaining occupants sheltered.

in their flats. After this, evacuation of some occupants continued at intervals from all floors through dense smoke in both lobbies and the stair as the fire spread around the Tower and flats become untenable in sequence.

Table 2
Stair descent times.

	Floor and Flat	999 call shortly before or while leaving flat	Left flat/entered stair	Exit Tower CCTV	Approx. descent time (min:sec)	Approx. decent rate Seconds/floor
Descent in clear or almost clear conditions:						
D. Purser						9.3
Choi et al.						9.6 male 10.2 female
Adult male	18 156	01:27:36	~01:28/29	01:31:30	02:30/03:30	~8–12
Occupants descending through dense smoke:						
Adult female	22 193	03:07:00	~03:10	03:21:28	11:28	~31
Adult female	18 153	03:03:44	~03:05	03:13	08:00	~27
Female Child	21 183	03:25:45	03:28:30	03:37:06	08:36	~25
Adult male	15 124	03:31:47	03:50:39	03:54:26	03:47	~15

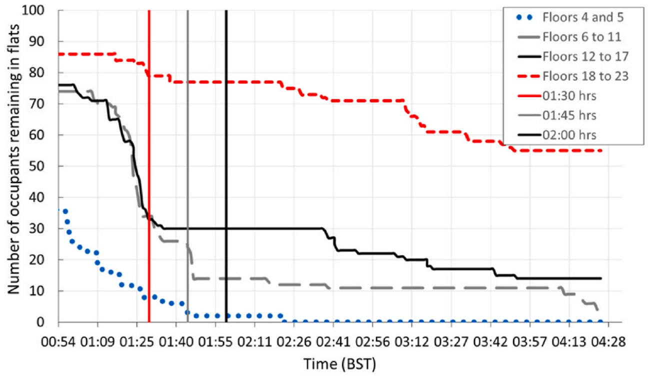

Fig. 4. Evacuation pattern from different levels in the Tower.

3.5. Effects of smoke on probability of evacuation and survival

Exposure to toxic smoke affects evacuation and survival in three main ways.

- The probability that occupants will enter and continue to move through dense irritant smoke
- The walking speed through smoke as a function of visibility and irritancy
- The time occupants can tolerate exposure to asphyxiant gases in smoke before collapse and loss of consciousness, limiting the distance they can travel through smoke filled escape routes

During incidents the willingness of occupants to enter and continue through irritant smoke can greatly affect survival. The probability that occupants will decide not to enter or turn back depends on several behaviors but mainly their assessment of the relative risks of sheltering in place compared with those involved in entering a smoke-filled escape route, in relation to the density and irritancy of the smoke. Such behavior cannot be replicated in experiments, but only evaluated from actual incidents. Data are available on the probability of entering and continuing through smoke from mixed fuel sources during incidents from the work of Wood in the UK and Bryan in the USA [12]. Fig. 5 compiled from data in Bryan [12] indicates probabilities of occupants turning back behavior during incidents. Both data sets show a similar pattern, which for the larger UK data set shows 62% of those entering smoke with <4 m visibility turned back and 77% for <2.1 m visibility. Of those turning back 91% did so in smoke with <4 m visibility compared with 9% for smoke >4 m visibility.

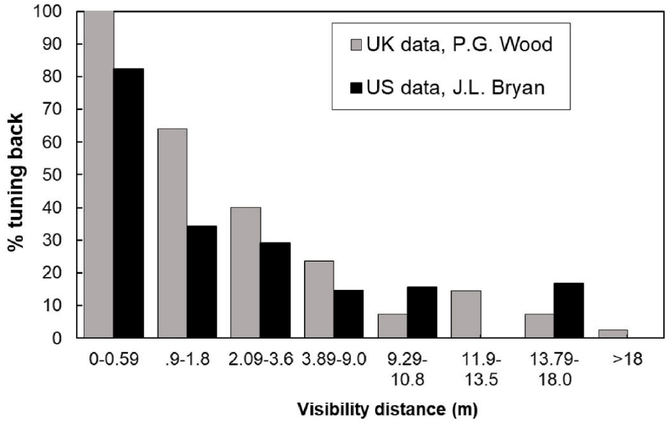

Fig. 5. Percentage of occupants entering smoke at each visibility range turning back.

Although there are some uncertainties with respect to the levels and context of these data sets, they do illustrate a strong probability for turning back or not entering smoke with a visibility less than approximately 3–4 m.

Smoke density therefore has serious effects on incident outcomes. During the Mont Blanc Tunnel fire many vehicle occupants on the French (downstream) side of the fire were strongly inhibited from leaving their vehicles to enter and attempt evacuation in the smoke-filled tunnel, while those on the relatively smoke-free Italian (upstream) side were able to do so [22,29]. The Grenfell incident, with many detailed occupant witness statements and telephone call transcripts available, shows the importance and complexity of smoke effects on evacuation behavior.

The behavior of Grenfell occupants was affected by smoke development in three locations: within flats, in the communal lobbies and in the stair. As stated, occupants of Flats 6 were highly motivated to evacuate their flats rapidly, due to fire and smoke penetration from outside, and were able to do so without significant exposure to smoke in the lobbies or stair. At the time they evacuated any smoke in the communal lobbies was mostly layered, so that they were able to evacuate in almost clear conditions under the smoke layer. On many floors, the communal lobbies then filled rapidly with dense smoke and very limited visibility within a few minutes. As shown in Fig. 4, occupants of many flats not directly affected by fire or smoke became aware of the developing fire and were motivated to evacuate during the period before the lobbies became smoke filled. Some occupants, whose flats were smoke-free at this time, decided initially to shelter in place. Within a few minutes they became aware of smoke entering their flats from the lobbies around the closed flat entrance doors, and encountered almost zero visibility when they opened their doors and attempted to enter the lobbies. Occupants of these flats often made repeated attempts to enter and cross the lobbies, but were forced to return by the dense smoke. Those from Flats in the 4 and 5 locations (Fig. 1), with a longer (10–11 m) and more complex path across the lobby to the stair door, were more likely to become disorientated. They described feeling their way around the walls, in some cases mistaking a rubbish chute and cupboard doors for the stair exit door. Occupants of Flats 1, 2 and 3 had only around 3–6 m to cross to the stair door, but in some cases considered they could not cover even this short distance, and were also unsure of the conditions in the stair. The general pattern with these occupants was that for an extended period they were able to limit their smoke exposure within their flats by sheltering in closed rooms and opening windows away from the fire. During this period they were likely to consider sheltering in place less hazardous than attempting to evacuate, but some decided to evacuate and succeeded in crossing the dense irritant lobby smoke to enter and descend the stair. Others remained trapped in their flats by the lobby smoke, but once the exterior fire spread outside rooms of their flat and began to penetrate, they became more motivated to attempt evacuation. Some succeeded in reaching the stair or moved to other flats on the same floor (in some cases assisted by fire fighters), while others were unable to leave their flats and died there. While occupants who succeeded in evacuating before smoke filling of the lobbies faced this decision only once, those who remained in their flats faced the “evacuate or stay” decision repeatedly over an extended period as the conditions deteriorated. On four floors the smoke filling of the lobbies was more gradual, so there was a period during which occupants were able to see several meters and felt able to enter and move through smoke.

3.6. Movement through smoke

During the Mont Blanc tunnel fire, while most occupants remained in their vehicles, a few left them and walked towards the French entrance through increasingly dense smoke, travelling up to 525 m before being overcome by asphyxiant gases [22,29].

During the Grenfell fire, whereas many occupants encountered very dense irritant smoke in the lobbies and in many cases turned back or remained in their flats, others crossed the lobby and entered the stair. During the early stages of the incident up to ~01:30 h the conditions in the stair were generally clear or light smoke, with good visibility, so descending occupants were unimpeded. One family, evacuating, at an early stage, encountered some smoke in the stair near the fire floor level. One family member was afraid to pass through the smoke, so they returned to their flat, but then descended again without difficulty a few minutes later when encouraged by firefighters. During the next 20 min, the stair filled with smoke penetrating from the landings at all levels. Smoke density and irritancy increased but occupants reported some visibility, such as being able to see their feet or others immediately in front of them. Some reported passing through hot conditions. 165 persons evacuated during the period up to 01:49 h before the visibility in the stair became seriously impaired. From 01:49 until 02:16 h no occupants evacuated from above the 4th floor, remaining occupants being trapped in their flats by the lobby smoke. By this time the stair was filled with dense, irritant, hot smoke with very limited if any visibility. As the spreading exterior fire broke into flats in sequence around the Tower further occupants were forced to evacuate. During the period from 02:18 to 08:07, 58 persons of varying ages succeeded in evacuating though dense, hot, irritant smoke under conditions of very limited visibility in the stair, using the handrail as a guide. Three had minor superficial burns. Only one family group turned back due to the smoke in the stair and returned to their flat.

3.7. *Descent speeds in smoke*

While the upper part of Table 2 shows descent speeds under clear and light smoke conditions of 9.3–10.2 s/floor, the lower part shows that later evacuees encountered dense smoke in the stair and made slower progress. Two adult females descended from the 22nd floor through almost zero visibility, but could just see the stair lights and used the hand rail as a guide. Their descent speed of ~31 s/floor was a third of that under clear conditions. Similar speeds (~27 s/floor) were measured for a family group including children descending from the 18th floor assisted by firefighters. A family party of six including children evacuated from the 21st floor through zero visibility smoke using the handrail as a guide (descent rate 25 s/floor). A single adult male ran and jumped down the stair through zero visibility, using one hand against the wall as a guide, achieving ~15 s/floor.

These few examples show descent rates for mixed family groups under almost zero visibility conditions during an incident. They confirm that some occupants were able to evacuate effectively under dense irritant smoke conditions, and that their descent rates slowed to a similar extent as during experimental studies by Refs. [8–10] (to a third of the speed under clear conditions). They also confirm that in corridors or stairs the hand rail and walls are important aids to progress under these conditions. Three occupants with physical disabilities descended the stair. An adult female was carried down by a firefighter, while two aged adult males (one using a crutch) were assisted to walk down slowly by accompanying young adults, as more rapidly descending occupants were able to run past (despite the 1 m stair width) [14].

3.8. *Assessing effects of exposure to asphyxiant gases on sheltering and escaping occupants*

Incapacitation (loss of consciousness) followed by death during fires results from inhalation of asphyxiant gases (mainly CO but also HCN, CO_2 and low O_2), [23]. If the time concentration curves for these gases at head level for occupants are known, then the uptake fractional effective doses (FED) and times to predicted incapacitation and death can be calculated. For CO, incapacitation occurs when the blood level reaches ~40%COHb (at rest) and 30%COHb (light to moderate exercise, such as walking rapidly along a tunnel or down stairs). There is a low probability of survival, even with treatment, after inhaled doses exceed ~50% COHb as shown in Purser [16] for survival incidence for blood %COHb at the time of exposure from a 260 survivor set compared with outcomes for Rosepark care home occupants. During this incident, in which occupants were exposed for up to an hour to toxic smoke, two persons with levels below 35%COHb were rescued conscious from the scene and recovered rapidly. Four with 40–50%COHB were comatose or semi-conscious at the scene and died in hospital, while eight fatalities from the scene had no burns but %COHb in the 48–85% range [16].

During incidents, evacuating occupants are likely to have ~30% COHb at the time they reported collapsing of feeling close to collapse. Also, since blood %COHb levels are measured in fire survivors after rescue, it is possible to back-calculate the blood %COHb at the time exposure ceased. These accumulated blood levels of survivors and fatalities can then be used to estimate the total Ct dose of CO inhaled and therefore the average CO concentrations they were exposed to, if the exposure duration is known. The effects of exposure and uptake for HCN are more complex than for CO, but the contribution to incapacitation FED from cyanide inhalation can be calculated if the exposure concentrations and exposure times are known and also to some extent from blood cyanide measurements after exposure. For fire incidents, depending on the information available, it is therefore possible to combine estimates of fire conditions derived from CFD calculations or full-scale reconstruction tests with information from occupant witness statements on the smoke, heat and toxicity conditions they encountered at different times and effects on them, and the subsequent measured blood carboxyhemoglobin, blood cyanide, soot deposition in airways and extent of burns, to arrive at an overall understanding of the developing conditions during an incident and effects on occupant escape and survival. In the following section three examples are presented of the use of data from occupants to evaluate causes of incapacitation and death and for evaluation and validation of the fire development history.

3.8.1. *Estimation of developing conditions during fire incidents*

Full-scale incident reconstruction experiments can provide direct measurements of time concentration and intensity curves for smoke, heat and toxic gases for input to FED calculations for estimation of time to escape impairment from dense smoke, incapacitation and death from asphyxiants or from heat and burns. Fire dynamics modelling can also be used to estimate fire growth and effluent dispersal volume, and toxic product yields, to obtain time concentration curves. Toxic product yields depend on the fuel load mix (mainly the overall elemental composition [especially the carbon, nitrogen and halogen content]) and the combustion conditions [especially the fuel-air equivalence ratio (φ)] [21].

Toxic combustion products result mainly from inefficient combustion of fuel carbon (smoke particulates, organic irritants, CO) and fuel nitrogen (HCN). Yields tend to be low under well-ventilated flaming conditions ($\varphi < 1$) but increase considerably for under-ventilated flaming ($\varphi > 1$). Halogen acid gases (HCl, HBr, HF) tend to be released at high normalized yields under all conditions, and their presence decreases the combustion efficiency of fuel carbon and nitrogen under well-ventilated combustion conditions. Yield data for fuel materials commonly used in structure and contents have been measured as a function of defined combustion conditions and fuel air ratios for input to fire dynamics calculations [18–21,34].

3.8.2. *Use of smoke particulate and toxic gas yield and concentration ratios to estimate time to incapacitation and time available for escape*

Although fire dynamics calculations or incident recreation experiments can be applied to some scenarios, there are often considerable uncertainties with forward estimates of fire development and conditions, and of the extent of dilution as air is entrained into smoke effluent flowing away from the seat of the fire through complex building enclosures. The varying fuel/air equivalence ratios can also introduce uncertainties in modelling developing conditions. Where witness or other information is available on smoke density (or visibility) conditions, an alternative approach to hazard assessment is to calculate time to incapacitation from asphyxiant exposure by estimating asphyxiant gas concentrations from smoke density and gas concentration ratios.

For occupants attempting to move through smoke, tenability ultimately depends on the concentrations of asphyxiant gases, especially CO, HCN and CO_2 in the smoke or on heat and burns. The absolute concentrations depend on the mass and composition of the fuels, the combustion conditions and plume dilution by entrained air. As the effluent plume flows away from the combustion zone and is diluted by entrained air the temperature decreases and combustion reactions cease, so that the concentration ratios between smoke particulate concentrations (and hence smoke density and visibility) and the concentrations of asphyxiant gases, remain approximately constant. Also, since the yields of both smoke particulates and asphyxiant gases increase with increasing equivalence ratio, the ratios between smoke and gas concentrations remain similar.

From data on these ratios measured for different fuels in bench-scale or large-scale fire tests [18–21] it is possible to determine gas concentrations for different smoke densities and calculate times to incapacitation (collapse) from exposure to aphyxiant gases using FED analysis. As a simple limiting value, for smoke from any flaming fire involving any fuel mix, for 10 m visibility, the concentrations of asphyxiant and other toxic gases will be too low to have significant effects on escape or survival for exposure periods of up to ~60 min. At higher smoke concentrations estimated exposure time before a person walking through an escape route would collapse from asphyxiant intoxication depends mainly on the CO and HCN concentration.

Fig. 6 [17,35] shows plots for a mixed fuel package consisting of equal masses of four materials including common cellulosic and polymeric fuels with elemental compositions typical of fuels in fully involved compartment fires (polymethyl methacrylate [PMMA] medium density fiber board [MDF], polyurethane foam [PU] and Polyisocyanurate foam [PIR] for two combustion conditions: reasonably well-ventilated combustion (φ~1) and under-ventilated combustion conditions (φ ~1.5). Fig. 7 shows the calculated time to collapse for occupants walking though smoke and asphyxiant gases at these concentrations.

Fig. 6 shows that for this mixed fuel package, under both well ventilated and under ventilated conditions, the concentrations of CO and HCN are very low at smoke densities exceeding approximately 4 m visibility (the visibility above which most occupants will evacuate through smoke). Fig. 7 shows this exposure is tolerable for approximately 1 h or more, but once visibility decreases to ~1 m, the time to calculated collapse for average susceptibly occupants decreases to ~18–24 min (~5–7 min for most vulnerable 1% of the population). Since the yields of both smoke particulates and asphyxiant gases increase with equivalence ratio, the ratios between them remain relatively similar, so that CO and HCN concentrations at specific smoke densities are quite similar across the equivalence ratio range.

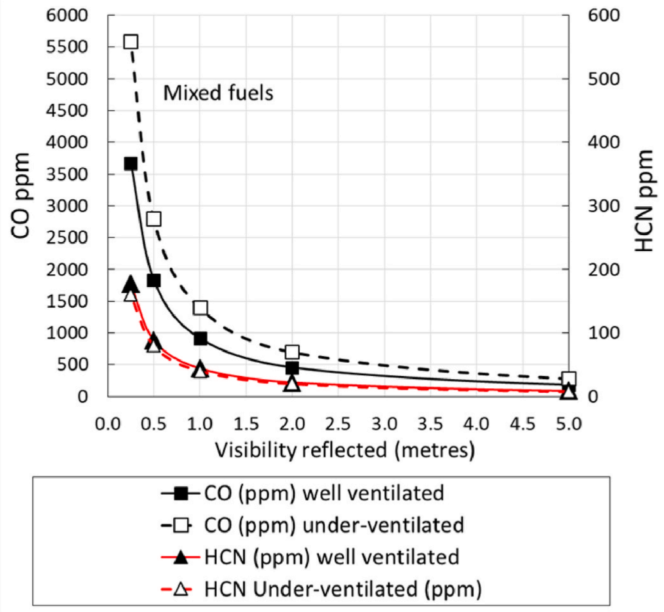

Fig. 6. Concentrations of carbon monoxide (CO) and hydrogen cyanide (HCN) at different smoke visibilities for a mixed fuel set.

For any particular fuel mixture, the main determinants of time to collapse are the CO and HCN concentrations, which depend mainly on the organic carbon and nitrogen content of the fuel. All fuels have a high carbon content so CO is always a major asphyxiant. Where the organic nitrogen content is <~1% by mass the contribution from HCN is negligible. For fuels with a 6–10% nitrogen content (such as upholstered furniture and some insulation materials) HCN is a major determinant of incapacitation. The fuel mix used for Figs. 6 and 7 has a 57% carbon and 4.5% nitrogen content, which is close to typical mixed fuel content of fully involved compartment fires. For this mixture the main determinant of asphyxia is CO with some additive contribution from HCN.

3.8.3. *Application to three case examples*

Three examples of the application of these methods to the evaluation of exposure conditions and effects on occupants during major fire incidents are.

- Mont Blanc tunnel fire: CFD and FED modelling related to data on fatalities
- Rosepark Care home fire: Full scale fire reconstruction test and FED modelling related to survivor and fatalities data
- Grenfell Tower fire: Smoke and asphyxiant gas yield and concentration ratios with FED modelling related to survivor and fatalities data

3.8.4. *Mont Blanc Tunnel fire – CFD and FED modelling related to data on fatalities [22,29]*

As described in detail in Purser [22,29], the developing conditions in the Tunnel were estimated using CFD analysis for a set of scenarios for source fire data from a heavy goods vehicle tunnel fire test, correlated with data from the Tunnel ventilation and smoke opacimeters to establish the rate of spread of the smoke plume, mainly towards the French tunnel portal, with incapacitating effects on vehicle occupants estimated by FED analysis. The CFD analysis predicted relatively clear

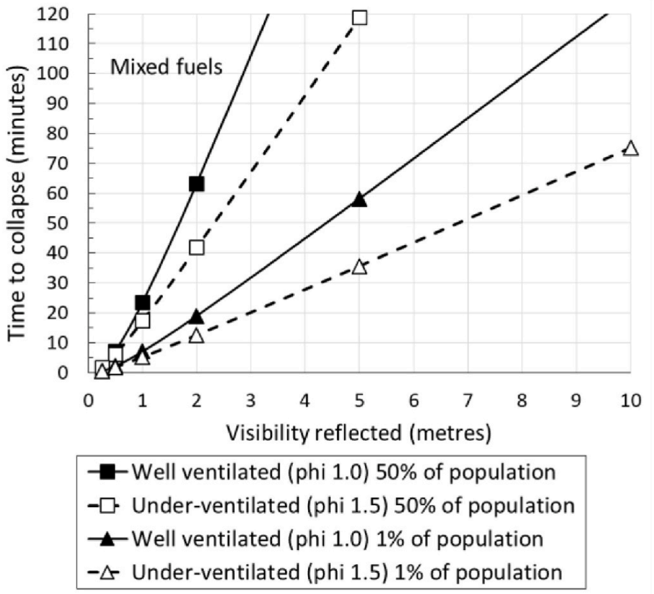

Fig. 7. Calculated time to collapse from asphyxia at different smoke visibilities.

conditions close to the original burning vehicle so that occupants of vehicles 1,2 and 8 (12–166 m from the fire) could see the fire and were highly motivated to exit their vehicles. They attempted to evacuate back along the tunnel until they collapsed and died ~220 m from the fire. Other vehicles further from the fire were enveloped in dense smoke as the smoke plume was diluted and mixed from floor to ceiling. The majority were unwilling to leave their vehicles to enter the dense smoke and sheltered until they were overcome by the spreading fire. A small group of occupants left a vehicle in smoke 407 m from the fire and walked back a further 525 m before collapsing and dying in the tunnel.

From the known times of vehicles arrival, and estimated walking speeds as function of smoke density and distances to the point of collapse, it was possible to estimate the times of collapse of these two groups. Comparing the times of collapse calculated from the vehicle timing and occupant final location data with the times of collapse calculated from CFD/FED, the effects predicted from the modelling calculations were shown to be consistent with the actual outcomes, giving a reasonable estimate of the conditions encountered and effects on the persons involved.

3.8.5. Rosepark Nursing Home fire, Uddingston, Scotland 04:27 h January 31, 2004–14 deaths [15,30]

A combination of a full-scale incident fire reconstruction test with FED analysis of timing and effects on the occupants was used in combination with occupant toxicology and pathology data to establish the exposure conditions, and effects on occupants. Forensic data (%COHb), burns and smoke inhalation injury) were examined for fatalities and survivors. The uptake of CO as blood %COHb was calculated from the test data. For those surviving exposure at the scene blood %COHb levels were measured on arrival at hospital, enabling the levels at the time of rescue to be back-calculated. By comparing the forward-calculated %COHb levels from the test data at the time of rescue with the %COHb levels at rescue back-calculated from the hospital blood levels it was possible to determine the extent to which the reconstruction test results in terms of the integrated time-concentration CO conditions represented the conditions during the actual incident. Other parameters such as the condition of occupants at rescue and extent of any burns also provided information on the conditions at different occupied locations during the fire.

The Rosepark fire started in a cupboard with the doors partly open to Corridor 4a (Fig. 8) A short violent fire then spread along the corridor (Fig. 9), with some damage to surfaces and two upholstered chairs, and effluents filling the corridor and open bedrooms off it. The fire doors between corridors 4a and 3 closed, but exploding aerosol cans in the cupboard resulted in overpressure pulses causing the fire doors to blow open briefly, with smoke spread into corridor 3 and open rooms off it.

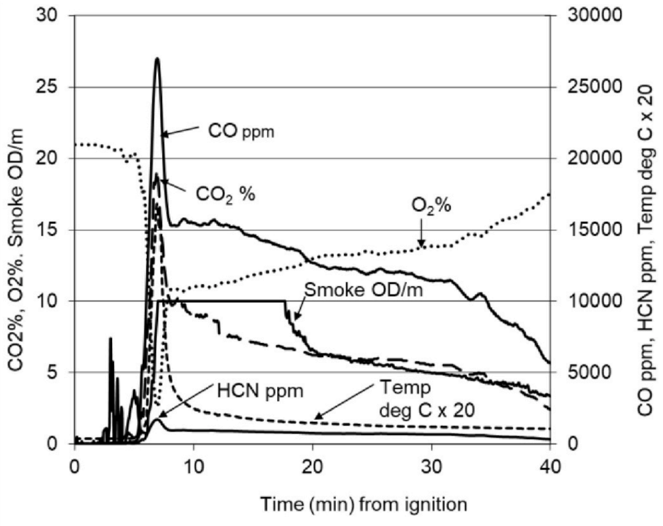

Fig. 9. Toxic gases, smoke and temperature corridor C4 Rosepark reconstruction fire.

The fire self-extinguished after ~4 min as the oxygen in the compartment decreased. After this, corridor 4 and open rooms off it contained high levels of smoke, CO (~13,000 ppm) and HCN (~1000 ppm), declining slowly over the next hour.

Fig. 10 shows the FED analysis for conditions in the corridor, predicting loss of consciousness from asphyxiant gases after 5.5 min and death a few minutes later, with pain from heat exposure by 6.5 min. Conditions in open bedrooms were similar to those in the corridor except that the temperature at bed height was much lower, so that no burns were predicted. Occupants of the open bedrooms were all fatalities at the scene. The pathology and toxicology supported the test results: bodies unburned but with very high blood %COHb concentrations.

During the reconstruction test, smoke and gases in closed rooms off corridor 4 showed a slow gradual smoke and CO penetration from the corridor over 70 min increasing to ~2000 ppm CO. Two occupants were rescued alive, after 41 and 72 min. Their forward calculated %COHb levels from the test data were similar to their back-calculated levels from hospital blood data (Table 3), confirming that the conditions doing the reconstruction test were similar to those during the actual incident. The blood levels for the occupant of Room 11 were slightly higher than predicted, but the fire scene showed this closed room door had been partly burned through during the fire, somewhat increasing smoke penetration compared to the closed test room.

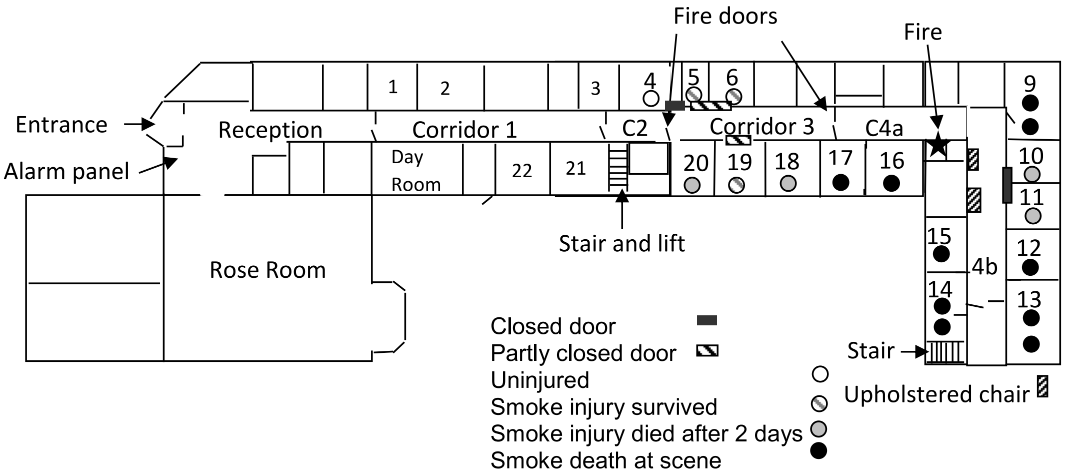

Fig. 8. Rosepark Nursing Home ground floor showing locations of exposed residents.

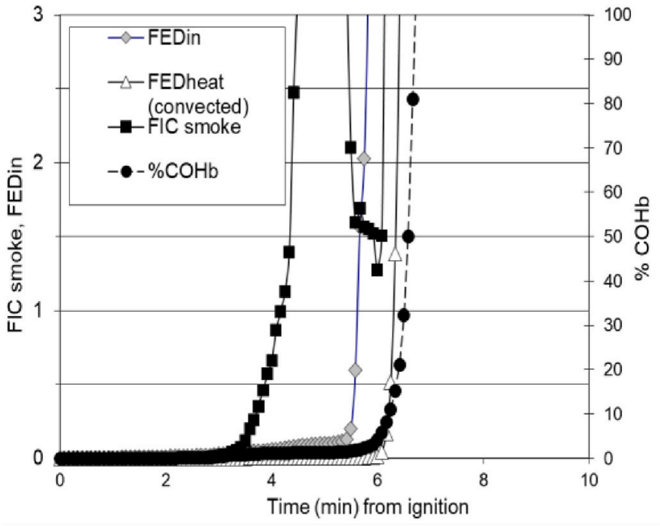

Fig. 10. FEDs to incapacitation Corridor C4.

In corridor 3 and the open rooms off it, the CO concentration over 40 min averaged ~2000 ppm (~70 ppm HCN). Occupants were exposed for ~30 min before rescue, giving calculated levels of 20–29%COHb (Table 3) in two open rooms, and somewhat lower exposures in three rooms with doors ajar or closed at some time during the fire (~12-27% COHb depending on time open). The actual blood levels for all these occupants back-calculated from hospital blood data were higher than predicted from the test. Further examination of the incident and full-scale testing revealed that an air circulation extract duct system, not included in the original reconstruction test, had extracted air from corridor 4 and partially released it into corridor 3, thereby increasing the smoke and CO concentrations in this area as confirmed by the data derived from the blood toxicology.

3.8.6. Grenfell Tower: 00:54 h June 14, 2017. Using smoke and toxic gas yields and concentration ratios with witness reports and occupants pathology and blood toxicology data [7,14,35]

Establishing exposure conditions and effects on occupants throughout the Grenfell fire incident presents particular challenges due to the size, complexity and long duration of the fire. Due to the size of the incident, involving exterior fire spread and penetration of many flats, communal lobbies and stairs, it was not possible to carry out a full-scale reconstruction to measure the conditions, although limited testing has provided some relevant information. Due to the size and complexity of the structure and developing fire it is also challenging to carry out CFD modelling, since this can result in a wide variety of possible outcomes depending on assumptions for key parameters affecting fire performance. Videos from the incident provide a detailed record of the real-time fire spread up and around the Tower from origin on the 4th floor in Flat 16. Post-fire investigation showed that many flats, especially in the upper floors of the Tower, were almost completely burned out, but not when this occurred. Some flat entrance doors were burned, with fire spread to communal lobbies, but there was only local and very limited flame penetration (but extensive smoke penetration) into the stair.

Exterior views showed the timing and extent of fire spread across the outside of each room of each flat but there was limited direct information on the timing of interior fire development or smoke and flame spread within each flat during the critical periods when occupants were exposed. Similarly, the timing of fire and smoke penetration into the lobbies and stair could not be determined directly from the site post-fire investigation. The large exterior flaming fires involving the cladding and insulation passed across each room over a period of a few minutes. The local exterior fire then extinguished and the window openings were dark, with no immediate indication of the presence of interior fires. After a variable periods of ~0.5–1 h, some window openings then became illuminated by a bright orange glow, indicating the presence of large interior compartment fires in some flats.

Considerable information on the developing fire conditions, extent and effects of exposure experienced by occupants is available from the many telephone calls made throughout the incident, witness accounts of survivors, medical and toxicology information for survivors and pathology and toxicology data for fatalities. From this it has been possible to establish the extent of exposure and effects on surviving occupants who evacuated while in different flats, while crossing the lobbies and while descending the stair, and for fatalities, their exposure and effects on them up to the time of their deaths in different locations.

With regard to their exposure to asphyxiant gases or heat and the estimated exposure times to incapacitation and death. The main considerations were.

- For occupants trapped in their flats for up to several hours after the lobbies became smoke filled (after ~01:30 h): the extent of exposure and uptake doses of smoke and gases penetrating their flats, mainly from the lobbies, before exterior fire spread outside their flats.
- Once the exterior fire spread across the outside of the first room of a flat: the extent of fire penetration and interior fire development in that room, and the extent of spread to other rooms where occupants were sheltering.
- Once the exterior fire spread outside the room in which occupants were sheltering: the timing and extent of smoke and heat penetration and the development of lethal conditions
- For occupants who evacuated their flats before or within a few minutes after the arrival of the exterior fire: the extent of their cumulative exposure and uptake of CO (and HCN) up to times they evacuated the flat, as they crossed the smoke-filled lobbies and as they descended the smoke-filled stair.

The conditions were evaluated from witness evidence, in relation to observed patterns of exterior fire spread, occupant toxicity and pathology data, and FED calculations using estimated exposure concentrations with time in different locations. The approximate exposure concentrations were estimated in terms of three main components, the smoke particulates (in terms of reported visibility and optical density), and the main asphyxiant gases (CO and HCN), using the estimated ratios between these components derived from the composition of the burning mixed fuel load as illustrated in Figs. 6 and 7. In order to estimate the yields and concentration ratios for effluents from the burning contents of a fully involved flat fire, the material masses and approximate elemental compositions of the combustible contents of a typical one and two-bedroom flat were estimated. The masses of contents items consisting of typical furniture, floor covering and contents in the lounge, bedrooms, kitchen and bathroom of a flat were estimated from average weights of furniture items and appliances as a total approximate combustible mass of approximately 660 kg in a two-bedroom flat and approximately 470 kg in a one bedroom flat. For each item the elemental composition in terms of carbon, nitrogen and chlorine was estimated from the main material components and their elemental composition. In addition to estimating the total masses and major component materials for a flat, the total masses and percentages of carbon, nitrogen and chlorine were estimated, to determine the potential of these materials and fuels to produce the toxic smoke and gases, as sources of soot particulates, carbon oxides (CO and CO_2) hydrogen cyanide (HCN) and hydrogen chloride (HCl).

The main combustible contents in a flat consist of "soft furnishing" items including upholstered furniture (upholstered chairs and bedding) fabrics, curtains, and carpets and "rigid" items composed mainly of cellulosic (wood-based) materials including chairs, tables, cupboards, wardrobes, sideboards, doors and similar items. Fabrics and furniture foams typically have a carbon content of ~60% by mass plus a significant nitrogen content of ~8–13% and a few percent of chlorine or bromine additives as flame retardants. All these items produce high yields of carbon monoxide (CO) and of smoke particulates, high yields of HCN from their nitrogen content, and a highly irritant smoke due to the halogen additives and their organic composition.

The "rigid" wood-based items (including paper and cardboard) generally have a carbon content of approximately 45–50%. While wood and plywood have a very low nitrogen content of 0.1–0.3% and a negligible chlorine content, many cellulosic items are made from composite materials such as medium density fibreboard or similar materials, with a similar carbon content to wood, but a significant nitrogen content of up to approximately 4% in the adhesives and resins they contain, and also a significant chlorine or bromine content (around 1% depending on the material). Overall the combustible contents of a flat (including fitted internal doors and cupboards) are dominated by cellulosic materials, with the estimated overall mass-weighted elemental averages shown in Table 4.

The materials mass weighted mean elemental composition is similar to that for the equal mass fuel load used for Figs. 6 and 7, with a high carbon content (~50–60%) and a relatively low nitrogen content (~3–4.5%). For these ratios CO is predicted to be the dominant asphyxiant gas, with a minor additional contribution from HCN. The measured smoke and asphyxiant gas yields from each material in a flat summed on a mass weighted basis and expressed as equivalent volume concentrations for a 20 g/m^3 fuel mass loss concentration, are shown in Table 5 for moderately under-ventilated combustion conditions. While the yields vary with the combustion conditions, and the actual concentrations depend on both the combustion conditions and the smoke dilution, the relative concentrations (concentration ratios) remain relatively similar. This case allowed for a contribution from the exterior cladding, insulation and uPVC window surround materials.

Table 6 shows the calculated concentration ratios (molar ratios) between CO_2,CO, HCN and smoke (expressed as optical density per meter [D] and soot concentration), for two equivalence ratios, a somewhat under ventilated set (φ~1.3) and a more under ventilated set (φ ~1.7). The relative concentrations of HCN and smoke to CO are similar, but the CO_2/CO ratio somewhat higher for the lower equivalence ratio. Similar ratios were obtained for the structural materials (window surrounds, exterior cladding and insulation).

The similar ratios enable the relationship between visibility and the asphyxiant gas concentrations to be compared at any time and location during the incident. Where the concentration of one component was known it was possible to estimate the concentrations of the other components. Information available was the approximate smoke density, as reported by witnesses, and the overall CO exposure estimated from the intoxicating effects on the occupants or from measured accumulated blood %COHb in survivors and fatalities.

Table 4
Approximate elemental composition of the mixed combustible contents of a flat.

Element	Elemental mass %
% carbon	47.1
% nitrogen	3.7
% chlorine	2.0

Table 5
Estimated yields and volume concentrations of smoke and gases from mixed flat contents.

	Flat contents including window frames plus cladding and insulation component Yield mg/g φ ~1.3	Volume concentrations for fuel mass loss of 20 g/m^3 Weighted to C 54% N 2.7%
CO_2	1225 mg/g	1.34%
CO	106 mg/g	1822 ppm
HCN	4 mg/g	70 ppm
Smoke SEA	221 m^2/kg	1.99 D/m
Soot	34 mg/g	0.68 g/m3

Table 6
Estimated volume concentration ratios for mixed flat contents.

Toxic gas and smoke volume concentration ratios	Flat contents including window frames plus cladding and insulation component Yield mg/g	
	φ ~1.3	φ ~1.7
CO_2 ppm/COppm	7.3	4.0
HCNppm/COppm	0.0382	0.0388
D/COppm	0.0011	0.0010
Soot mg/l/COppm	0.00037	0.00032

3.8.7. First approximation from witness evidence of smoke

A first approximation of the conditions encountered by occupants was derived from their description of smoke visibility, their level of alertness, the estimated smoke, CO and HCN ratios and data from large-scale fire experiments in domestic dwellings. From witness accounts, although smoke penetrated into the flat hallways from the communal lobbies, occupants trapped in their flats for up to several hours were able to shelter in closed rooms, often opening windows facing away from the fire. Although irritant smoke penetrated, visibility was generally several meters so that CO concentrations varied from approximately 0 to <500 ppm and HCN 0 to <20 ppm, occupants remaining alert. After the fire spread outside the first room of a flat, smoke and gas concentrations increased more rapidly, but remained tolerable for a further 15 min or

Table 3
Occupants alive and rescued at the fire scene: outcomes and comparison between actual and calculated %COHb.

Closed rooms off fire corridor (Corridor 4)						
Subject and location	Room	Time exposed in room (minutes)	Time on oxygen (min)	COHb at scene		
				from fire test data	fro m blood data At	
					Scene	Hospital
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		

so. Once the exterior fire spread outside and breached the windows of the room they were sheltering in, conditions deteriorated rapidly so that occupants were overcome and collapsed within a few minutes, then died from asphyxia. The flats and bodies were then burned, but tissue remains showed very high blood %COHb (Fig. 11), well above lethal threshold, indicating death from asphyxia due mainly to CO before their bodies were burned, with a likely minor contribution from cyanide (although blood cyanide levels measured in some survivors and fatalities were close to background levels). In three cases flat occupants fell from the Tower soon after the exterior fire spread outside the room they were sheltering in. None had burns. Two had sub-incapacitating blood levels of 20%COHb, while one had a close to fatal level (50% COHb). The % COHb measured in the blood of fatalities is shown in Fig. 11 From the timings when occupants fell from the Tower or became unresponsive during telephone calls as they became comatose (~40%COHb), FED uptake calculations have been made for CO time-concentration exposure profiles over the period of exposure within flats. Using iterative variations of profiles it has been possible to estimate the exposure concentration conditions for smoke, CO and HCN, constrained by the requirement to reach the measured blood levels at the time of incapacitation of death.

For occupants who evacuated their flats before or soon after the arrival of the exterior fire, their total exposure at the time they exited the Tower represents the sum of the accumulated doses inhaled while in their flats, crossing the communal lobby and descending the stair. From the descriptions of dense irritant smoke in the lobbies, and based on the general fire conditions, with almost zero visibility in the lobbies, the concentrations of CO are likely to have been high, in the ~5000–10,000 ppm CO range with HCN in the ~190–380 ppm range based on the ratios between smoke density and gas concentrations. These conditions are sufficient to cause collapse within <~3–5 min. Due to the short travel distances in the lobbies from the flats to the stair door, and the familiarity of the occupants with the layout, most who evacuated were able to cross the lobby rapidly, with minimal if any inhalation of asphyxiant gases. For a few cases there is evidence that occupants became disorientated by the dense irritant smoke and may have remained for several minutes, then collapsed either in the lobby or almost immediately after entering the stair. The main exposure for most occupants therefore occurred while descending the stair over periods of approximately 5–12 min depending on entry floor and descent speed. Of those who evacuated after 02:00 h, some could see nothing in the stair but others reported being able to see lights in the stair or their knees, or a person in front of them. Others described visibility improving at lower floor levels. From these descriptions of the smoke conditions, reporting some limited visibility in the ~0.4–1 m range, and occupants walking down without collapsing, the average CO concentrations over the stair column during sxposure were at moderate levels (in the range ~1000–2000 ppm CO and ~35–75 ppm HCN).

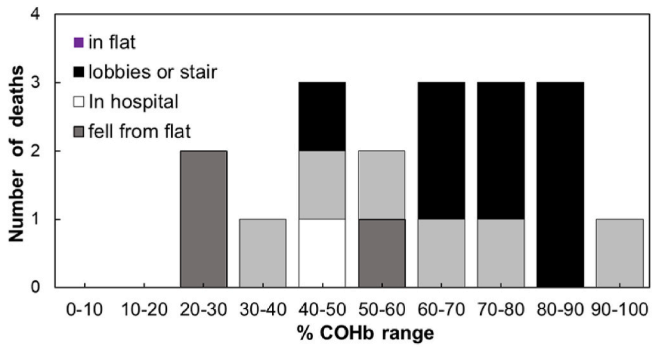

Fig. 11. Distribution of percentage COHb in individual Grenfell fatalities.

3.8.8. *More accurate estimates of asphyxiant gas concentrations derived from effects of CO exposure and measured blood carboxyhemoglobin concentrations*

More accurate estimates of asphyxiant gas exposure were made from estimates of CO uptake doses calculated from known descent times, signs of intoxication reported by escaping occupants and hospital blood %COHb levels. Some reported being near collapse, feeling dizzy, or collapsed and were assisted to evacuate by firefighters near the base of the Tower, so were at the threshold of incapacitation (~30%COHb) by the time they exited the Tower. Back-calculation from hospital blood data confirmed levels of ~30% COHb when they exited.

CO uptake and FED calculations were made initially using CO exposure estimated from the smoke exposure history, providing forward calculated estimates of their %COHb blood levels at the time of Tower exit. From witness reports, flat occupants were exposed to CO increasing from zero to a low concentrations for those leaving their flats before or within a few minutes after the arrival of the exterior fire, then a few seconds of high concentration exposure while crossing the lobby with negligible uptake, followed by exposure to an average concentration of ~1800–2000 ppm CO while descending the stair. The results of the calculation showed the time during descent when COHb approaches 30% (and FED ~1 for the combined effects of all asphyxiant gases). The calculation was then repeated with adjusted exposure profile estimates to obtain the observed outcome. When ~30% COHb and FED~1 occurred as the subject reached ground level the results confirmed that the estimated CO concentrations in the flat, lobby and stair, and therefore the accumulated dose of COHb were close to actual levels.

Occupants from upper floors evacuated through dense smoke in the stair over ~90 min between 02:26 and 03:55 h. They reported similar smoke levels during this period, some descending within minutes of each other, so were generally exposed to similar conditions and similar CO concentrations while in the stair. Some occupants reported no exposure in their flats, so were only exposed in the stair. Where occupants were exposed in their flats, differences between calculated uptake in the stair and actual total uptakes represent the extent of exposure in their different flats before entering the stair. The results are also correlated with the smoke density and fire conditions described by occupants in different flats. One purpose in carrying out these analyses is to try to arrive at a better estimate of the accumulated dose while in the Flats. By carrying out these uptake calculations for the set of occupants evacuating from different floors around this time, in some cases with no exposure in their flats and therefore only in the stair, the best fit for the average stair concentration giving the best predictions for observed outcomes is ~1800 ppm CO (±20%). This level is therefore an emergent value derived from the evacuation and uptake calculations for the set of occupants from different flats on different upper floors (evacuating in

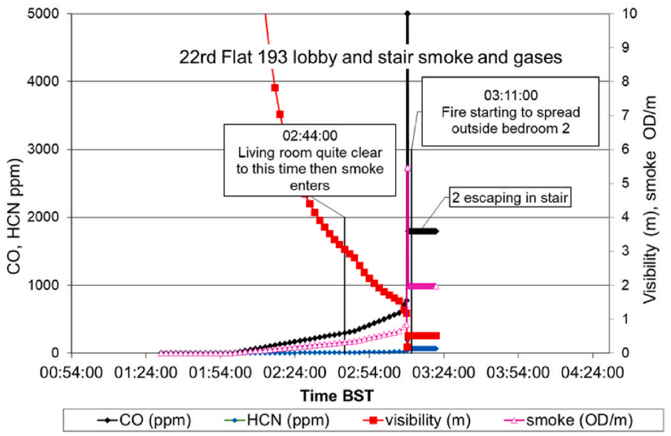

Fig. 12. Flat 193 lobby and stair smoke and gases.

clusters between approximately 2:32 and 3:55).

As a case example Figs. 12–14 show the estimated exposure profile, and CO uptake for 2 22nd floor occupants who evacuated Flat 193 at 03:10 h and exited the Tower after an 11.5 min decent time. Around first floor level both were affected by CO intoxication, one felt able to walk out while the other collapsed and was carried out by a firefighter, recovering once outside the Tower. They were therefore at the threshold for incapacitation (~30% COHb), confirmed by the hospital blood level back-calculated to 32% COHb for the person who collapsed. They sheltered in Flat 193 for ~1 h 40 min before evacuating and entering the stair. There was some slow infiltration of smoke from the lobby. Sheltering in the living room, with windows open for some of the time, they were able to maintain relatively clear conditions until ~02:44 after which smoke in the flat started to increase, especially as the flat entrance door was opened several times. As the exterior fire spread closer, they reported a brief exposure to dense smoke, in the flat kitchen and hallway, for a minute or so before they evacuated.

Smoke and CO concentrations were therefore low up to 02:44, then gradually increased. Fig. 12 shows an estimated time-concentration profile for carbon monoxide and smoke during this period in the flat using the derived ratios of CO to visibility, and gradually increasing concentrations with decreasing visibility The main constraint is that the final calculated %COHb as the occupants reach the base of the Tower must be ~30%COHb.

For this individual worked case there are therefore three unknowns to estimate for the final value of ~30%COHb, including the accumulated doses in the Flat, while crossing the lobby and while descending the stair. For this case an estimated 30 s exposure a high concentration of 5000 ppm CO in the lobby was used (based on 3 m distance crossed from flat to stair). This brief exposure to a high concentration adds only 1% COHb so has very little influence on the total dose. In practice it is likely that the escaping occupants crossed the lobby within a few seconds and held their breath while doing so. The average CO concentration in the stair column is set at 1800 ppm CO derived from the best fit with the set of stair descent cases. The CO uptake curve for this exposure sequence is shown in Fig. 13. Respiration levels used are 10 L/min while in the flat and 20 L/min while descending the stair, adjusted for VCO_2 depending on the CO_2 concentration calculated from the ratio factor in Table 6 (for φ 1.3).

The estimated CO time-concentration profile provides the determined percentage COHb level by the time of exiting the Tower at 34% COHb which is close to the back-calculated level from hospital data of approximately 32%COHb for the subject who collapsed on the stair. For an estimated average CO concentration in the stair of 1800 ppm this analysis constrains the dose accumulated due to smoke exposure while in the flat to a low level of ~8%COHb. So the occupants' exposure while in the flat was only a quarter of the level causing incapacitation at this time (03:10). The accumulated dose while crossing the lobby is very small (0–1%COHb). The main exposure then occurred descending the stair, resulting in an incapacitating dose by the time they reached the base of the Tower.

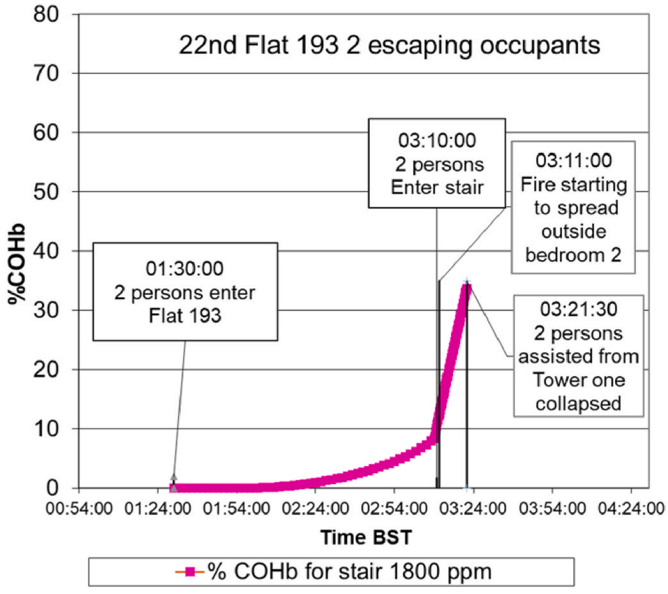

Fig. 13. Calculated (%COHb) uptake.

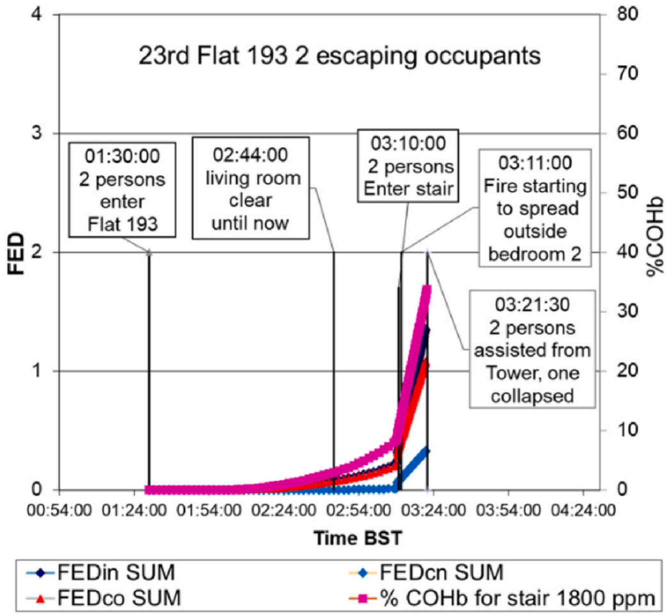

Fig. 14. Full FED analysis for Flat 193 case.

Although CO asphyxia dominates, the overall extent of asphyxia results from the combined effects including HCN and reduced levels of oxygen. The rate of uptake of these gases is also affected by the presence of carbon dioxide (CO_2) since this stimulates breathing [18]. The full analysis shown in Fig. 14 fixes the carbon monoxide concentration profile as described to provide the known COHb concentration outcome. Using the concentration ratio factors to CO shown in Table 6 (φ1.3 case for mixed flat contents), the concentrations of HCN, visibility and smoke density are shown in Fig. 12, plus the concentration of CO_2 and oxygen. These were used as input to the FED calculations for asphyxia from the mixed gases (FEDin SUM). Of particular concern was the extent to which HCN may have contributed to the overall level of asphyxia (FEDcn SUM). The calculated smoke density and visibly can also be compared with that reported by the occupants. Another derived value is the concentration and dose of soot (smoke particulates) inhaled by those exposed.

For this exposure case, CO was the dominant asphyxiant gas, which alone provided a dose capable of causing incapacitation (FED = 1 or 30%COHb). The blue curve (FEDcnSUM) shows an accumulated HCN dose of FED = 0.3, a third of an incapacitating dose, sufficient to make a minor but significant contribution to the overall incapacitating effects on occupants in the stair. There was ~1% CO_2 in the stair, sufficient to produce a small increase in breathing, but a negligible decrease in oxygen concentration. The analysis also shows a calculated low visibility in the flat of ~1 m just before the occupants left and approximately 0.5 m in the stair, consistent with the conditions described. Another effect of inhaled irritant smoke particulates is that the accumulated dose of (soot) particulates can lead to lung inhalation injury in the form of inflammation and edema developing several hours after exposure. The pooled anonymized hospital data have been used to estimate lung injury. For the case example shown in Fig. 13 the smoke particulate concentrations curve (soot mg/l) was calculated using the soot mg/l/COppm ratio in

Table 6 for the mixed fuel (φ 1.3) case. Using the smoke particulate concentration (mg/L) and the volume of air breathed per minute (L/minute), the cumulative dose of smoke particulates inhaled (mg) was calculated as approximately 300 mg for the periods of exposure in the flat lobby and star until exiting the Tower.

3.8.9. Using carbon monoxide washout curves to back-calculate percentage carboxyhemoglobin concentrations at times of tower exit from survivor hospital blood data

CO is excreted (washed out) via the lungs with an exponential decay curve, the rate depending of the partial pressure of oxygen inhaled, with a half-life in air (20.95% O_2) of 4–5 h [36]. A study of 93 adult CO-poisoned patients breathing 100% oxygen showed an average half-life (t1/2) of 74 min (k = -0.00937 sd ± 25 min). As with CO uptake, the CO washout time varies with bodyweight and activity, and is somewhat more rapid for children [23,37].

Evacuating Grenfell occupants received oxygen at the scene and on arrival at hospital. Hospital blood % COHb data for 21 Grenfell survivors enabled fitted decay curves to be back-calculated to the Tower evacuation time. Fig. 15 shows curves fitted to pooled data for upper floors (14 and 19–23) and lower floors (10–12). For the upper floors the back-calculated level at Tower exit time is 32% COHb (or 30%COHb if oxygen was delayed for 10 min). The t1/2 for the upper floors set is 66 min (close to the published 74 min average, plotted as the dotted line for 30%COHb starting value and confirming that all these persons were receiving continuous oxygen treatment after arrival at hospital). For the lower floors the back-extrapolated curve gives 17%COHb at Tower exit (16%COHb for a 10 min delay), t1/2 87 min. This is below an incapacitating level so occupants were conscious and active as they walked from the Tower.

Fig. 16 shows %COHb levels at Tower exit for those from upper floors against Tower exit time, with no obvious trend in %COHb, so indicating approximately constant average CO concentrations in the stair during this period (with slightly higher levels for a heavy smoker, a child and a person remaining 26 min in the stair). The main exposure was in the stair so there is a relationship between evacuation floor and total blood %COHb at exit (Fig. 17). Since CO dose and irritant particulates dose are correlated a relationship between %COHb and severity of inhalation injury is predicted. For surviving occupants the severity was scored from the clinical records (Table 7). From previous work [38], there tends to be a threshold dose of inhaled irritant smoke below which effects are minor but above which there is a significant increase in severity. There was negligible or mild injury for individuals with <~20%COHb (inhaling <~200 mg particulates), but injuries ranging from mild to severe in individuals from ~22%COHb (see Fig. 18).

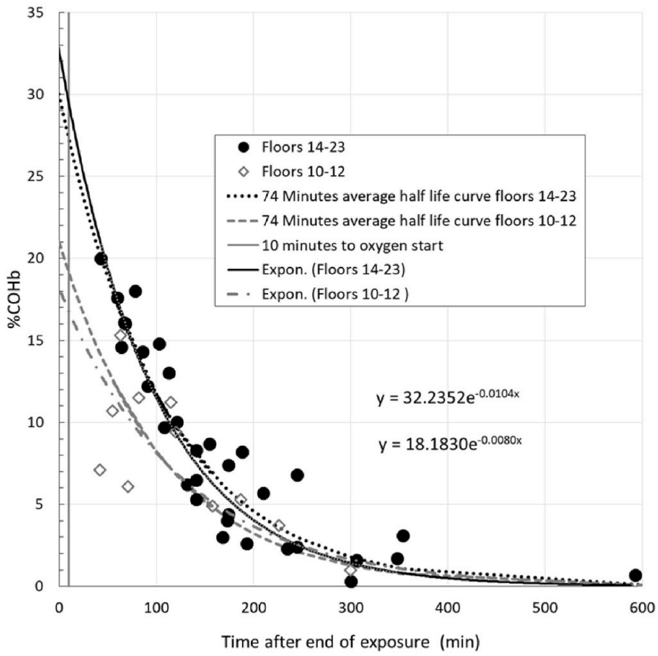

Fig. 15. Blood %COHb from 21 Grenfell survivors with fitted washout curves back-calculated to time of Tower exit [14].

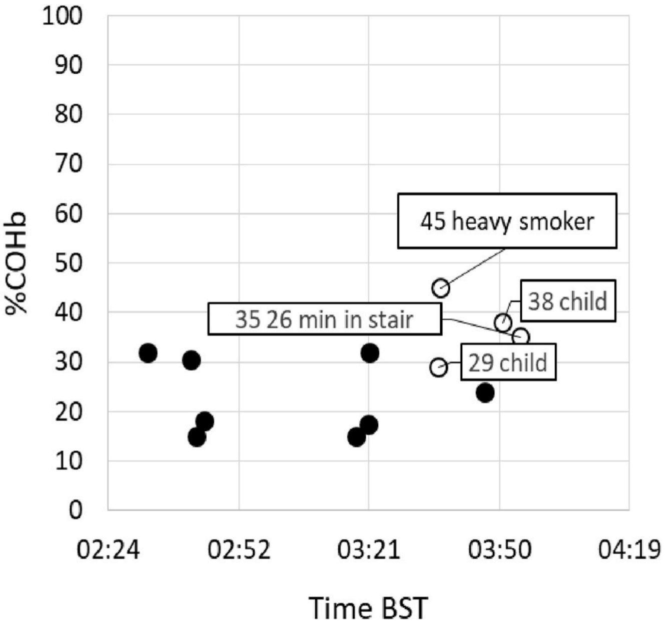

Fig. 16. Relationship between %COHb and exit time (upper floors) [14].

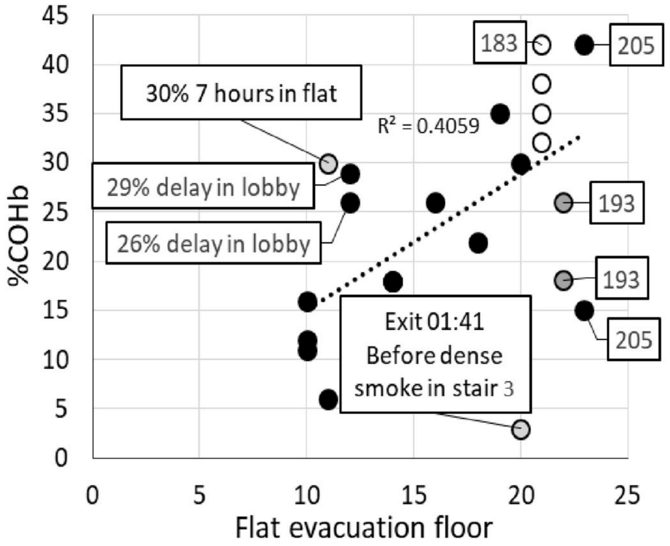

Fig. 17. Evacuation floor number and percentage COHb at Tower exit [14].

The person who evacuated at 01:41 had a very low smoke and CO exposure and no inhalation injury. The person who waited for 7 h before being assisted to evacuate from a smoke-filled flat, containing a flaming interior fire, had the most severe inhalation injury score.

4. Conclusions

Integrating behavioral, fire dynamics and fractional effective dose calculations with incident investigation, witness, pathology and toxicology data can provide an effective method for evaluating developing exposure scenarios, enabling key parameters to be identified and

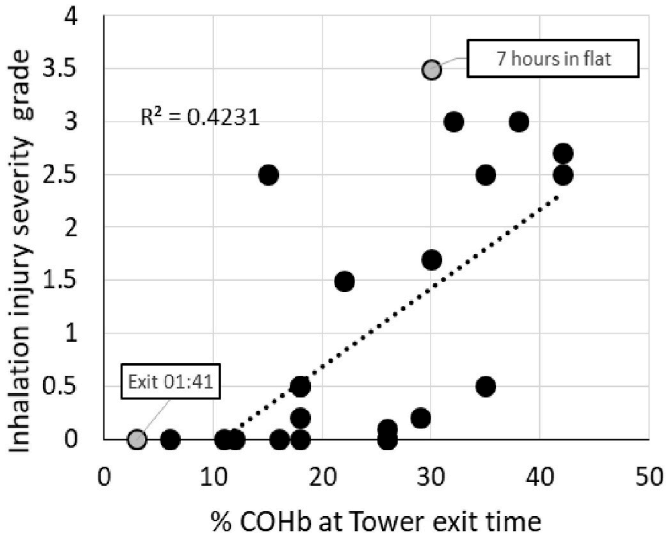

Fig. 18. %COHb at time of Tower exit and inhalation injury severity grade [14].

Table 7
Inhalation injury score [39].

Grade	Class	Description
0	No injury	Absence of carbonaceous deposits, erythema, edema, bronchorrhea, or obstruction
1	Mild injury	Minor or patchy areas of erythema, carbonaceous deposits, bronchorrhea, or bronchial obstruction
2	Moderate injury	Moderate degree or erythema, carbonaceous deposits, bronchorrhea, or bronchial obstruction
3	Severe injury	Severe inflammation with friability, copious carbonaceous deposits, bronchorrhea, or obstruction
4	Massive injury	Evidence of mucosal sloughing, necrosis, endoluminal obstruction

methodology to be validated against known outcomes. For behavioral parameters, the cases described demonstrate the importance of including control and quantification of pre-warning delays for design scenarios and incident management, with early recognition of the need for effective warnings to instigate evacuation. Current methods for assessing pre-travel and movement (travel) behaviors, including walking speeds in smoke, were generally validated for these incidents. For residential buildings, the low occupant densities facilitate unrestricted stair flow. The willingness and ability of occupants to enter and evacuate through irritant smoke was identified as a high consequence behavioral parameter affecting survival outcomes, requiring more serious consideration in design and further research evaluation. Smoke density and asphyxiant gas concentration ratios derived from fuel composition and combustion yield data, combined with carbon monoxide toxicology and FED calculations provides a scenario assessment and validation method for fire tests or dynamics modelling.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Most data cited is in the public domain

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