Effects of exposure of Grenfell occupants to toxic fire products
– Causes of incapacitation and death

Phase 1 Report: General description of hazards excluding
comprehensive references to individual occupants

Prof. David A. Purser
Causes of incapacitation and death at Grenfell fire from exposure to toxic fire products

Name
Prof. David Purser

5th November 2018

Signature

Hartford Environmental Research,

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Causes of incapacitation and death at Grenfell fire from exposure to toxic fire products

STATEMENT

My qualifications are:
BSc (Hons) first class: Zoology and comparative physiology University of Birmingham
PhD Neurophysiology (Neurocommunications) University of Birmingham
Dip RCPath (Toxicology) Royal College of Pathologists

I am a diplomate member of the Royal College of Pathologists

I have worked for over 40 years as an inhalation toxicologist and fire scientist specialising in research into the fire hazards and effects on the behaviour and survival of people involved in fires, on the toxicity of combustion products and health hazards from fires, fire chemistry and the mechanisms of fire development. I have authored in excess of 100 scientific publications on topics related to this subject area. I have appeared as an expert witness in cases on this subject area in the United Kingdom, France and a Federal Court in the United States, and am recognised as an international expert, representing the United Kingdom on International Standards Organisation committees. I have also served as an expert on Department of Health committees advising the Chief Medical Officer on the medical effects of air pollutants, environmental hazards from smoke toxins, and the effects of smoking on health.

Signature:

David Purser  Dated: 5th November 2018
Causes of incapacitation and death at Grenfell fire from exposure to toxic fire products

SUMMARY

1. I have been instructed to prepare an expert report for Phases 1 and 2 of the Grenfell Inquiry addressing the following:

   (1) The production of toxic gases in fires and consequences to occupants of inhaling toxic gases, both physiological and behavioural, for different generic fire scenarios and conditions occurring in domestic fires similar to those likely to have occurred at different stages and locations during the Grenfell Tower fire;

   (2) The likely causes of incapacitation and death at Grenfell Tower, including those whose bodies were consumed by the fire;

   (3) The possible toxicity performance of materials present at Grenfell Tower.

   (4) Any recommendations arising from points (1) to (3) above, including as to any further testing which ought to be carried out which is relevant to these issues.

   The phase 1 report is a preliminary report based on information currently available. For phase 2 the report will be updated and expanded as necessary in relation to the results of ongoing and any future investigations.

2. This Phase 1 report is intended as a preliminary report. Its content is for the most part based on general information available to me. For Phase 2 the report will be updated and expanded as necessary to take account of all relevant evidence before the inquiry and the results of ongoing and any future scientific investigations. While the present report makes reference to preliminary observations derived from my consideration of for example written statements, it does not address such evidence with the same degree of detail as envisaged for my Phase 2 report.

3. My Phase 2 report will include the results of an examination of witness statements from, and oral evidence of, occupants of Grenfell Tower together with the transcripts of calls made by Grenfell occupants to the emergency services so as to obtain a detailed understanding of the conditions to which those inside the Tower were exposed and how their behaviour, escape capabilities and survival were affected. I will also have regard to the evidence of firefighters where relevant. My Phase 2 report will also include findings from examination of toxicology data with blood carboxyhaemoglobin concentrations for persons who died during the fire and from photographs of decedents where their remains were recovered in the Tower or outside. For Phase 2 further tests and investigations are in progress or under consideration relating to the fire development and contributions of different materials present at Grenfell to the generation and spread of toxic smoke within the Tower.

4. No measured data for toxic smoke and gases are available for the actual Grenfell incident. The scale and complexity of the incident are also too great for the conditions throughout the Tower to be replicated comprehensively by any experimental tests or computational modelling methodology, although such tests and method can and are being applied to specific aspects of the incident. Also, the conditions directly affecting Grenfell occupants changed rapidly during the course of the fire, so that although useful information has been obtained by examination of the Tower since the incident, this is limited with respect to understanding the conditions at the time of exposure.

5. In order to estimate the conditions to which the Grenfell occupants were exposed, and the likely effects on their escape and survival I have therefore relied in the first instance mainly on my knowledge derived from previous experiments involving different fire scenarios commonly occurring in domestic dwellings, on studies of the physiological effects of exposure to heat, smoke and toxic fire gases, and from detailed studies of fire survivors and fatalities from previous incidents.

6. In order to estimate the likely contribution to the smoke toxicity of different burning materials present at Grenfell I have relied in this Phase 1 report on previous experimental studies of the toxic
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gases produced by a wide range of materials commonly occurring in building structures and their
contents, generic versions of many of which were present at Grenfell, under a range of different
fire conditions likely to have occurred at Grenfell.

7. To relate these generic studies to the actual Grenfell incident I have relied on:

a) The Phase 1 reports from other experts instructed by the Grenfell Inquiry on the
construction and fire damage to the Tower, the fire development and spread outside and
within the Tower during the incident and the timing of escape for those who survived.
b) The observations I made during two visits to the Tower to examine the extent of fire and
smoke damage, the remains of the exterior cladding and insulation, the materials
surrounding the windows, the flat interiors (including those in which occupants died) and
the condition of the lobbies and the stair.
c) Statements of Grenfell occupants present during the fire.
d) Transcripts of emergency (999) calls from Grenfell occupants during the fire.
e) Toxicology data with blood carboxyhaemoglobin concentrations for 20 persons who died
during the fire.
f) Photographs of decedents where their remains were recovered in the Tower or outside.

Approach and methodology

8. The major hazards causing injury and death in fires are toxic smoke and heat. Of these the cause
of the majority of cases of incapacitation and death is toxic smoke, while burns mostly occur when
people are close to a fire (for example when they ignite their clothing).

9. Fire hazards in domestic dwellings fires (fires in houses and flats) typically occur in a sequence as
follows:

a) Exposure to smoke. This immediately impairs escape by directly reducing visibility, so
that persons may be unwilling to enter smoke filled escape routes (typically when visibility
is < 3 metres) and if they do they may become disorientated and their walking speed is
reduced.
b) Smoke also contains irritant organic chemicals and acid gases. These immediately further
impair visibility by stinging the eyes, causing tears and reflex eye closure, and cause
breathing difficulties, pain to the nose, throat and chest, coughing and wheezing. The
combination of poor visibility and smoke irritancy causes some persons to turn back rather
than continue to walk through the smoke. Prolonged exposure to irritant smoke may result
in lung inflammation a few hours after exposure in fire survivors, which can be fatal.
c) Exposure to a mixture of asphyxiant gases also in the smoke. These include carbon
monoxide (CO), hydrogen cyanide (HCN), carbon dioxide (CO2) and depleted oxygen (low
O2). The effects of inhaling these gases depend on an inhaled dose increasing over a
period of time. The dose depends on the concentrations of these gases present and the
duration of the exposure. There is no immediate effect and subjects may be unaware that
they are inhaling them. When the combined inhaled dose reaches a critical level, there is
a brief period of intoxication, with symptoms of weakness, dizziness, or euphoria, followed
by collapse and loss of consciousness. Once unconscious, the inhaled dose continues to
increase until the circulation and breathing cease and the person dies.
d) Exposure to radiant and convected heat from flames or from immersion in hot
smoke. This first causes pain then burns to exposed skin and to the mouth and nose if
hot air is inhaled. As with asphyxiant gases, the effects of heat exposure are dose-related,
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depending on the heat radiation or smoke temperature and the exposure time. The heat “dose” causing minor (first degree) burns is several times that causing pain, and that causing full-thickness and fatal burns is several times that causing minor burns.

10. The exact sequence and extent of exposure to these hazards depends on the developing fire and exposure conditions (the fire “scenario”). Typical fire exposure scenarios in dwellings (including those at Grenfell) include the following:

a) The occupants are in the same room or open plan flat as a developing flaming fire but away from the area where the flames start. As the fire grows a smoke layer forms under the ceiling and fills the room from the ceiling down over a period of around 10 minutes. If the occupants remain in the room or flat they become exposed to the smoke, which is irritant and starts to get hot. This may affect their ability to escape from the flats. As they inhale the smoke their dose of asphyxiating gases increases. After a few minutes the flames are around a metre or so high but still confined to a small area of the flat. The occupants then become dizzy and collapse unconscious. If they are close to the fire they may also start to feel pain from the heat, but if they take refuge (for example in another room or under covers of furniture) they may avoid significant heat exposure, until after they are comatose or dead due to continued smoke inhalation. If the occupants are rescued soon after they collapse and are given oxygen they may make a good recovery. If they remain in the fire and the fire continues to spread within the flat then their bodies may be burned after they are comatose or after they are dead.

b) The occupants are in a different room within a house or in a different flat from that containing the fire (for example a situation where the occupants are in a closed upstairs bedroom when the fire is in the lounge downstairs). In this scenario the fire burns for some time and fills the open areas of the house (or the common lobby outside adjoining flats) with dense toxic smoke. The bedroom or flat occupants “stay put” and await rescue. Over a period of up to an hour the concentration of smoke in the room or flat slowly increases. The occupants can still see across the room but visibility becomes reduced to about two metres and the smoke is irritant. The room never becomes hot. Over a prolonged period there is a gradual slow increase in the inhaled dose of asphyxiating gases. The occupants start to feel dizzy and have breathing difficulties, then one by one they lose consciousness. If they get up and try to walk, the increased activity rapidly results in collapse.

c) As above but the occupants only wait a few minutes before opening the door and attempting to escape through the dense smoke on the stair outside the bedroom or the lobby outside the flat. At the time they decide to leave the occupants have inhaled only a very small dose of smoke so are unaffected. As soon as they step out they cannot see anything and are immediately affected by the irritant smoke stinging their eyes and affecting their breathing. They may decide to shut the door and stay put at this point. If they continue to walk through the smoke, as soon as they take a few breaths they inhale high concentrations of asphyxiating gases, especially carbon monoxide and hydrogen cyanide. For a typical domestic lounge fire consuming an armchair, the concentrations on the stairs of a house may be sufficient to cause collapse and loss of consciousness within a few seconds. If the smoke is more diluted (for example by flowing up the stair of a block of flats), then the occupants may be able to walk through it for a few minutes before they collapse. They cannot see so have to feel their way along walls or by holding the bannister rail in a stair.

11. As a general guide, during fire incidents occupants tend to turn back rather than enter smoke when the visibility is less than ~3 three metres, but some people in some situations will attempt to escape through zero visibility smoke. Smoke with a visibility of greater than approximately two metres can be tolerated for 40-60 minutes before an exposed person is likely to collapse due to inhalation...
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of asphyxiant gases (CO and HCN) in the smoke. Exposure to smoke with a visibility of less than a metre is likely result in collapse within 1-15 minutes, depending on the exact concentration.

12. For all these scenarios, where people collapse or die from smoke inhalation they always have soot in their lungs and high concentrations of carbon monoxide in their blood (as carboxyhaemoglobin). If the smoke also contained hydrogen cyanide this also accumulates in the blood and tissues, and can be measured in fresh blood taken soon after exposure in survivors or in fatalities at autopsy, but decreases rapidly in bodies before autopsy and gradually in stored blood. Where bodies have burns, the presence of high concentrations of carboxyhaemoglobin in the blood is indicative that the deceased were exposed to toxic smoke for some time before they collapsed and died, so that the burns occurred after death or after they were comatose during the fire.

Toxic products from burning materials

13. The yields of toxic gases (kg of each gas released per kg burned) produced by burning materials depend mainly on the elemental composition and the combustion conditions. All common combustible materials have a high carbon content. Under well-ventilated combustion conditions (for example in open air flaming outside) the main products of efficient combustion are carbon dioxide, some carbon smoke particles (soot) and water. For under-ventilated combustion conditions (for example during fires in closed rooms or in enclosed voids (such as between the outer cladding and the insulation at Grenfell), combustion becomes inefficient so that high yields of toxic carbon monoxide, irritant organic products and smoke particulates are produced. Materials with a high nitrogen content (including the polyurethane foam (PUR) and acrylic covers of upholstered furniture, and the polyisocyanurate (PIR) foam in the Grenfell insulation) produce toxic nitrogen oxides when during well-ventilated combustion and high yields of hydrogen cyanide during under-ventilated combustion. Where materials have a significant content of halogen flame retardants (such as the polyvinylchloride (PVC) window surrounds at Grenfell and the additives in the PIR) these cause inefficient combustion, increasing the yields of CO, HCN, organic irritants and smoke, as well as producing irritant acid gases.

Development of toxic smoke exposure conditions and effects on Grenfell occupants

14. The requirements of the Building Regulations are for early warning in case of fire and for means of escape that can be safely and effectively used at all material times. Also required is fire resisting construction and that the building exterior should resist exterior fire spread.

15. For blocks of flats such as Grenfell these requirements are met by fire resisting construction of each flat so that a fire in any flat (including flames and smoke) should be confined to the flat of origin and should not spread into the common lobby or via the exterior to other flats. Early warning for fire in a flat is provided by smoke alarms in each flat and a safe means of escape is provided by the fire resisting common lobbies, which are separated by further fire resisting construction from the escape stair. This should prevent smoke from entering the lobbies or stair should fire occur in one or more of the flats, or on the building exterior, enabling occupants to evacuate in safety should they need to do so without exposure to toxic smoke.

16. Clearly there were failures of all these requirements during the Grenfell fire. For my analysis I have investigated the timing and extent of penetration of flames and smoke into the flats, lobbies and the stair and effects of exposure on the escape capability and survival of the occupants.

17. I consider that the 1 metre wide stair at Grenfell had more than sufficient capacity to accommodate the entire building population of 293 persons even if they had all entered it at the same time. I have calculated that the time required for an able bodied person to descend the stair from the 23rd floor is ~4 minutes, while the time required for the entire population to flow down the stair and out of the building is ~7 minutes if they all entered the stair and descended at the same time. In practice some persons descend more slowly, although there was overtaking on the stair at Grenfell. During the incident occupants did not all leave at once, but over an extended period of several hours.
18. Throughout the incident those in all occupied flats were faced with the difficult decision of whether to remain in a flat ("stay put") or to attempt evacuation through the lobbies and down the stair (or in some cases a lift). Occupants were faced with conflicting considerations and advice. On the one hand the basic policy was that it should be safer to stay put unless the flat was threatened by fire, and this was the advice generally given to flat occupants when they made emergency calls up to the time when a decision was made to change that advice. On the other hand a significant number of occupants decided it would be advisable to evacuate or at least descend the Tower to investigate the situation, and many occupants were receiving calls from friends and relatives outside the Tower urging them to evacuate. The appearance of flames outside, and smoke in the flats, lobbies and stair also had an influence on the decision to stay put or evacuate, and the ability to do so.

19. The first stage of major fire development was the exterior fire spread up the east side of the Tower between ~01:15-01:25 hrs. This resulted in extensive smoke and flame penetration into all flats in the Flat 6 position on all floors of the Tower above the flat where the fire originated (4th floor flat 16). Fire penetration into these flats occurred around and through the kitchen window on most floors.

20. The Flat 6 occupants on all floors appear to have become aware of the fire at an early stage, alerted by a variety of cues including noise from people and emergency vehicles outside, smell of toxic smoke and the internal smoke alarms. They then rapidly evacuated their flats and in some cases alerted their neighbours or met them in the common lobbies. At this time (~01:20-01:30 hrs) there was little or no toxic smoke in the lobbies or stair. All Flat 6 occupants on all floor succeeded in evacuating their flats and there were no deaths in any "Flat 6". The majority then evacuated the Tower safely although some took refuge in other flats on the same floor or went up to the 23rd floor.

21. The development of toxic smoke in the flats, lobbies and stair had a major effect on the escape behaviour and capabilities of Tower occupants. This occurred in three stages as follows:

   a) Stage one was the period after the fire started (00:54 hrs) up to that when the lobbies on each floor filled almost simultaneously with dense smoke (~01:30/01:35 hrs). During this period the lobbies and stair were essentially smoke free. Tower occupants became aware of the fire and entered the lobbies, then many evacuated immediately using the stair (so that approximately half the Tower occupants entered the stair by 01:30 hrs and evacuated the Tower safely without significant, or any, exposure to toxic smoke (other than a minor haze or smell)).

   b) Flat 6 occupants were forced to evacuate their flats by fire penetration towards the end of this period, but almost all other flats were smoke free, other than in some flats a minor haze or smell.

   c) Although many occupants evacuated the Tower during this period, a group of occupants from Floor 18 and above first started to evacuate down the stair, but for some reason, after descending several floors, turned around and climbed back up away from the fire, taking refuge in flats on the 23rd floor. The behaviour of this group and their physical presence filling the stair and moving upwards acted as a temporary barrier to others descending. In practice, had there been a method of encouraging them to do so, it would have been physically possible for these occupants, like many others from all floors to have descended the stair and evacuated the Tower safely and without significant difficulty at this time.

   d) If these and other occupants who remained in their flats had been encouraged to evacuate at this stage they could have done so in safety.

   e) Stage two was the period from ~01:27/01:30 hrs up to ~ 01:45-02:00 hrs when the lobbies on all floors became filled with dense black irritant smoke. Although there are several possible routes of fire spread between the lobbies on different floors, the main source of smoke entering the lobbies at this time was from Flat 6 on each floor. Flat 6 occupants
were forced to evacuate in a hurry from their flats, which were filling with smoke and had flames penetrating around the kitchen and lounge windows. When they opened their flat door to escape into the lobby, the smoke flowed out of their flat entrance doorway, forming a rapidly deepening black smoke layer under the lobby ceiling. On many floors the occupants left their flat door open when they left, so that the entire lobby filled with dense, irritant smoke rapidly. Some Flat 6 occupants have stated that the self-closing mechanisms on their flat doors did not work, so that the doors remained open unless deliberately closed. Several Flat 6 occupants stated that they closed their flat doors before they left. These lobbies still filled quite quickly with dense smoke over a period of minutes. This smoke is likely to have also originated mainly from Flat 6 on each floor, leaking into the lobby around the flat entrance doors and any other leakage paths (as reported by several occupants).

f) The main source of the smoke and toxic gases flowing through Flat 6 on each level and entering the lobbies during this period was smoke originating from outside the Tower, derived from burning cladding and insulation, and smoke generated from burning insulation and other materials in the window surround. As the fire spread into the flat and involved increasingly more of the flat contents over the following hours, an increasing proportion of the smoke entering the lobbies was derived from the burning flat contents.

g) Occupants who attempted to leave their flats during this period were confronted by increasingly difficult conditions in the lobbies, reporting zero visibility, irritancy and difficulty breathing. At this time the flats (other than Flat 6 and some in the Flat 1 location on upper floors) were generally smoke free, so that many of these occupants shut the door and decided to stay put during this time. Others decided to evacuate and with some difficulty felt their way along the walls to the stair entrance door, then entered the stair. During this time the stair was relatively clear of smoke and occupants were able to descend the stair safely. At the start of this period the smoke in the stair was mostly described as a haze, but gradually increased as occupants on different floors opened their lobby doors to enter the stair. Each time as they did this more smoke flowed in from the smoke-filled lobbies until the stair door shut automatically after they passed through. Escaping occupants also described denser smoke at lower floor levels, and there are some descriptions of smoke entering the stair from the lobbies on the 4th and 5th floor, when the stair doors were held open by firefighter hoses laid through them. 51 persons from Floor 4 and above entered the stair and then evacuated safely during the period from 01:30 to 01:50 hrs without suffering from serious smoke exposure or toxicity sufficient to cause collapse.

h) Stage three was the period from ~02:00 to ~06:00 hrs. During this period the flats that were still occupied gradually filled with toxic smoke over a period of 1-2 hours. The lobbies and stair were filled with hazardous concentrations of toxic smoke, with zero visibility in the lobbies and zero or near zero visibility in the stair. Under these conditions the concentrations of asphyxiant gases (CO and HCN) in the flats gradually increased. The occupants suffered from increasing loss of visibility, increasing irritancy and breathing difficulties. They also gradually inhaled an increasing dose of asphyxiant gases over a period of an hour or so. This had no significant effects initially, but eventually increased to incapacitating levels. During this period many occupants made 999 calls, and were able to discuss the situation, so were unimpaired in terms of mental ability, although suffering from increasing distress. Flats 4 and 3 on each floor were affected mainly by gradual smoke infiltration over this period, from the exterior smoke plume and from smoke leaking in from the lobby around the flat entrance door. Flat 1 was penetrated by smoke and flame not long after Flat 6 (especially on the upper floors), so that smoke from the burning window surround and some room contents was added to that leaking in from the lobby. Flats 2 and 5 were also more exposed to smoke penetration and then flame penetration from outside. Flame penetration eventually also spread to Flats 3 and 4.

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1 CCTV exit time spreadsheet, MET00016072; MET00012529
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i) The occupants of these affected flats were once again faced by an even more difficult decision on whether to attempt escape or stay put. They made frequent 999 calls and some made several attempts to leave the flat and enter the lobby, but turned back and shut the door due to the dense irritant smoke in the lobby.

j) Some flat occupants decided they had to leave as the smoke got worse and as flames appeared outside or started to penetrate the flats. Their survival then depended mainly on the extent of their asphyxiant gas exposure in the flat before they left it. All were faced with dangerously high concentrations of asphyxiant gases in the lobbies and stair. Some occupants, although they had inhaled a significant dose while in the flat, were able to function well and descend from as high as the 22nd floor to near the ground floor without collapsing.

k) Others were able to descend a number of floors, but then became dizzy and collapsed due to the exertion and increased uptake of gases, and were assisted out by other occupants or by firefighters.

l) Others were reasonably alert when they left the flat, but must have inhaled a high dose of asphyxiants while in the flat, so that they collapsed almost immediately after leaving the flat in the lobby or in the stairs. Once they had collapsed, they continued to inhale the toxic gases for some minutes until they died.

m) Although the conditions in the stair were hazardous during this period, there was no time up to 06:00 hrs when it was impossible to descend the stairs itself and escape, since occupants descended successfully at intervals throughout this period.

Toxicology and causes of death of fatalities

22. The long period for which the Grenfell fire burned resulted in almost complete burnout of many flats in which occupants died, and reduced many of the bodies of the deceased to ashes. Blood samples were obtained from only 20 decedents, for whom toxicology measurements of blood carboxyhaemoglobin (%COHb) were possible in only 15 cases. Sufficient samples were obtained from the badly burned remains of five persons who died in burned-out flats. These showed high %COHb concentrations consistent with death due to smoke inhalation, with carbon monoxide poisoning as the main cause of death. These results support the indications from the 999 call transcripts that people who died in their flats were overcome by the inhalation of asphyxiants gases (CO and HCN) and died before their bodies were burned.

Contribution from different materials to toxic smoke at Grenfell

23. Toxic smoke was produced by all the combustible materials at Grenfell in the sequence over which they became involved in the fire. The contribution from different materials at any time depended on the mass of material involved and how the smoke was dispersed.

24. During approximately the first 30-45 minutes of the fire the main large masses of burning fuels were the PIR insulation and the PE cladding core outside each flat penetrated by smoke and flames. The early fire involving each flat also involved significant masses of combustible structural materials surrounding the windows, including items of rigid and flexible foams, rubberised material, the polystyrene panels between the windows and the polyvinylchloride (PVC) window surrounds.

25. The mixed toxic smoke products from approximately five kilograms of these materials was sufficient to produce dense, lethal smoke conditions in a flat (initially Flat 6 on each floor), and the adjoining lobby, which inhibited occupants from escaping after ~01:30 hrs. As the flames continued to penetrate the flats, the flat contents started to become involved, considerably adding to the smoke flowing into the lobbies and out of the flat windows. From ~02:00 hrs the mixed smoke from all these sources gradually infiltrated other occupied flats from both outside the Tower and around the flat doors from the lobbies. Once fire penetrated into any flat the burning structural and contents materials caused a rapid development of lethal smoke conditions.
26. During the early exterior fire, the main source of smoke particulates, carbon monoxide and hydrogen cyanide is likely to have been under-ventilated burning of the PIR insulation in the cavities outside each flat, especially that on the columns, together with other PIR and PUR items in the window surrounds. The PIR also releases organic irritants and acid gases, which combined with HCl from the PVC window surrounds to produce a highly irritant smoke. PVC also produces high yields of CO. Although the PE in the cladding is likely to have contributed somewhat to the smoke, it is likely to have produced low yields of CO due to the open burning conditions.

27. Once the flat contents became involved the combustion conditions in a flat were under-ventilated. Cellulosic materials (wood, paper, chipboard) produced high yields and large masses of CO, while upholstered materials such as furniture and bedding produced both CO and HCN.

28. The combination of toxic smoke products from these sources continued to penetrate the flats, lobbies and stair for the remainder of the fire, affecting those remaining in the flats or attempting to escape.
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- Scientific references cited in footnote throughout this report

**Appendix A: Basis of hazard assessment methodology**

**Appendix B: Developing fire conditions in BRE house fire tests CDT16 and CDT18**

**Appendix C: Curriculum Vitae for David Purser**
INTRODUCTION

29. I have been asked to provide reports, for the purposes of Phases 1 & 2 of the Inquiry, which address the following issues:

(1) The production of toxic gases in domestic fires and the consequences of inhaling toxic gases in such circumstances, both physiological and behavioural;

(2) The toxicity when exposed to fire of certain materials which were present at Grenfell Tower;

(3) Any recommendations arising from points (1) to (2) above, including as to any further testing which ought to be carried out which is relevant to these issues.

Phase 1

30. I have been asked to provide a report for Phase 1 of the Inquiry addressing items (1) to (3) above and setting out my preliminary conclusions in respect of:

(a) The production of toxic gases and consequences to occupants of different generic fire scenarios and conditions occurring in fires similar to those likely to have occurred at different stages and locations during the Grenfell Tower fire;

(b) The likely causes of incapacitation and death at Grenfell Tower, including those whose bodies were consumed by the fire;

(c) The possible toxicity performance of materials present at Grenfell Tower.

Phase 2

31. I have also been asked to provide a report for Phase 2 of the Inquiry on the subject matter at points (1) to (3) above and updating and expanding my Phase 1 report as necessary.

Investigation and evidence to be considered in Phase 1 and Phase 2 reports

32. This Phase 1 report is a preliminary report based, in greater part, on general information currently available to me.

33. In this report, I have attempted to determine insofar as possible how those in Grenfell Tower may have been affected by exposure to fire effluents (heat and toxic smoke), how their ability to escape may have been affected, how some could have been incapacitated as they attempted to escape and how others were overcome and died. I have then considered the possible contribution of different materials present to the development of life threatening toxic conditions.

34. In this report, I have made general observations which draw on the evidence available from those who were in the Tower on 14 June 2017. Given the size and complexity of this incident, that evidence is still being obtained and the need for further investigations to be completed, the information and opinions presented here must be seen as preliminary and subject to further analysis and confirmation.

35. For Phase 2 the report will be updated and expanded as necessary by reference to the evidence available, including the oral evidence of survivors given to the Inquiry, and the results of ongoing and any future investigations.

36. In order to relate the generic Phase 1 investigation to the actual Grenfell incident in a Phase 2 report, I am in the process of examining witness statements, oral evidence and emergency 999 calls from Grenfell occupants present during the fire to obtain a detailed understanding of the conditions to which they were exposed and how their behaviour, escape capabilities and survival
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were affected. My Phase 2 report will therefore involve a more detailed analysis with specific reference to individual accounts and supporting documentation.

37. For Phase 2 I am also examining toxicology data with blood carboxyhaemoglobin concentrations for persons who died during the fire and photographs of decedents where their remains were recovered in the Tower or outside. I also plan to examine any further relevant evidence on decedents and survivors as becomes available in relation to causes of death, and effects on the health of survivors.

38. For Phase 2 further tests and investigations are in progress or under consideration relating to the fire development and contributions of different materials present at Grenfell to the generation and spread of toxic smoke within the Tower.

General effects of exposure to fire effluents and causes of escape impairment, incapacitation and death during and immediately after fires

39. Fires generate the following hazardous products affecting exposed persons to a different extent depending upon their intensity (for heat) and concentration (for toxic smoke) and the time over which they are exposed\(^2,3\). These hazards are generally encountered in sequence as follows:

a) Optical obscuration (affecting visibility), eye and respiratory irritancy, from exposure to smoke particulates and irritants, resulting in immediate impairment of escape capability depending on the exposure concentration.

b) Confusion, collapse and loss of consciousness followed by death, resulting from exposure to asphyxiant gases, occurring after a critical dose has been inhaled over a period of minutes, depending on the exposure concentration and duration of the exposure.

c) Pain followed by burns resulting from exposure to radiant and convected heat. This also occurs after a critical exposure “dose” of heat has been acquired over a period of time depending on the radiant heat flux and the air temperature to which a person is exposed. Exposure to heat initially impairs escape capability, while prolonged exposure may result in incapacitation due to burns and death from prolonged or extreme exposure.

40. Effects of exposure to smoke:

a) The first hazard generally encountered is visual obscuration by smoke. The main component of smoke is fine carbon soot particles, which are not in themselves very toxic, but those generated by fires involving mixed building materials (such as cladding and insulation materials) and contents (such as furniture in the flats), as at Grenfell, contain a range of irritant organic substances (such as aldehydes) and acid gases (including hydrogen chloride, hydrogen bromide, nitrogen oxides, and sulphur dioxide).

b) The first effect of smoke on occupants is likely to be the behavioural response to seeing or smelling smoke before significant exposure to it. When smoke became visible, either outside Grenfell during the early stages of the fire, or when it first started to penetrate individual flats, the occupants were faced with a difficult decision on whether to remain in place (stay put), or whether to attempt escape. If they decided to attempt escape and opened their flat door, then their behaviour was affected by the density of the smoke in the common landings and stair.


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c) Once occupants are directly exposed to smoke then they are further affected by the smoke irritancy. Smoke irritants cause stinging pain to the eyes and tear formation, which further impairs visibility through smoke, and also causes pain and irritation of the nose, throat and lungs, resulting in breathing difficulties. The severity of these effects depend upon the concentration of the smoke, they occur immediately on exposure and reduce quickly if the smoke clears.

d) The main early effects of smoke exposure on ability to escape are on the behaviour of occupants when exposed. If the smoke concentration in the escape route is higher than in their flat they may decide to remain in place or they may decide to attempt escape. If they enter the smoke their ability to find their way to and down the stair is impaired and walking speed in smoke, particularly irritant smoke, is slower than under clear conditions. Once occupants attempt to move through dense irritant smoke they may decide to continue, or may turn back if conditions are considered to be too severe. Although there are physical difficulties in breathing and moving through dense smoke, the inhalation of irritant particulates does not generally cause collapse and the effects on the lungs can be reduced by using a damp cloth as a filter.

e) People’s behaviour in smoke depends on their individual characteristics and situation. When people are in the same room or flat as the fire and become engulfed in smoke they are highly motivated to escape even when the density in the room is very high. When they have a choice of remaining in a relatively clear flat, or entering a smoke-filled escape route, they are more likely to remain or turn-back when visibility is less than approximately 3 metres. In some situations people have attempted to escape through dense irritant smoke for a significant distance and then either succeed or collapsed, depending on the conditions.

41. Effects of exposure to asphyxiating gases:

a) The main components of smoke resulting in incapacitation and death during fires are the asphyxiating gases. The most important are carbon monoxide (CO) and hydrogen cyanide (HCN), with a contribution from carbon dioxide (CO2) and low oxygen. The effects of these gases individually are similar and they are basically additive in combination.

b) During inhalation of asphyxiating fire gases the exposure “dose” in the body of an exposed person increases depending on the gas concentrations (C) in the room multiplied by the exposure time (t) (Exposure dose ~ C x t). When the inhaled exposure dose reaches a critical threshold level the effects on an exposed person change rapidly from minor symptoms that the person is likely to be unaware of, though a brief period of dizziness and intoxication, to collapse and loss of consciousness. Once a person is unconscious, unless they are rescued, they continue to inhale the asphyxiating gases until they die as they stop breathing and their heart stops beating. During exposure in fires the collapse may occur very rapidly, after a minute or so, or after an extended period of an hour or more, depending on the fire conditions and in particular the concentrations of asphyxiating gases inhaled.

c) If a person is rescued after having suffered significant smoke exposure, and particularly if they are unconscious, they are treated with oxygen at the fire scene by the firefighters and ambulance crews. This treatment re-oxygenates the body and “washes out” the asphyxiating gas carbon monoxide. Depending on the severity of the exposure the person may make a rapid and complete recovery, may recover consciousness but suffer from some degree of permanent brain damage or personality change, or may remain comatose, not recovering consciousness and die, usually after a few hours or days in hospital.4

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d) The most important asphyxiant gas present in all fires is carbon monoxide. Inhaled carbon monoxide combines with haemoglobin in the blood to form carboxyhaemoglobin (COHb), which causes hypoxia by reducing the amount of haemoglobin available for oxygen transport and by reducing delivery of oxygen by the blood. The inhaled dose of carbon monoxide (CO) can be expressed in terms of percentage carboxyhaemoglobin in the blood (%COHb). This is routinely measured in fire survivors after rescue and at autopsy for persons dying at a fire scene. From this and other experimental data on CO toxicity it has been established that exposed persons start to show signs of intoxication above approximately 20%COHb, collapsing unconscious at around 30-40% COHb, depending on how physically active they are and their individual susceptibility. Survival is rare above 50% COHb, which is therefore considered a lethal level. 

e) Hydrogen cyanide (HCN) is produced under certain combustion conditions by burning materials containing nitrogen. These include fabrics used in upholstery, curtains and soft furnishing made from polyamide (“nylon”) or polyacrylonitrile (“acrylic” fabrics), melamine in kitchen work tops or furniture, wool, flexible polyurethane resins and foams (upholstered furniture and bedding) and rigid polyisocyanurate foams (insulation board as used in the Grenfell exterior cladding system). Hydrogen cyanide causes cellular hypoxia and its effects are considered directly additive with those of CO. An important difference to the effect of CO is that HCN is much more potent than CO. Also, short exposures to higher concentrations of HCN above 200 ppm (parts per million) causes rapid incapacitation within a minute or so. For fires involving nitrogen-containing materials, such as upholstered furniture fires, hydrogen cyanide is important as a rapid cause of collapse before exposed persons have time to inhale a significant dose of CO. Once a person has collapsed due to HCN, death is considered to be mainly due to the subsequent inhalation of CO, with an additive contribution from HCN.

f) Carbon dioxide (CO2) is important mainly because it stimulates breathing, which increases the rate of uptake of HCN and CO, but in some situations CO2 can itself cause incapacitation. Exposure to CO2 concentrations above approximately 2% causes a feeling of breathlessness and heavy breathing, while distress and collapse occurs above approximately 5%CO2 within a few minutes.

g) Since fires consume oxygen, persons are exposed to lowered oxygen during fires, which contributes to the hypoxic effects of the other toxic gases. In most cases incapacitation due to the effects of CO and HCN is predicted before significant lowering of oxygen occurs, but exposure to low oxygen may be an important factor under certain fire conditions.

h) High blood concentrations of cyanide have been measured in the blood of persons rescued from domestic fires and from fire fatalities. Blood cyanide is not routinely measured in the UK following fires. It is unstable in blood and tissue after death, so that interpretation of results presents difficulties where blood samples were not taken and analysed soon after exposure or death.

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42. Effects of exposure to heat:
   a) Heat exposure during fires includes both radiant and convective sources. Exposure to radiant heat can occur directly from flames by downward radiation from a hot upper smoke layer forming under a room ceiling. Exposure to convective heat occurs when a person is engulfed in hot air or smoke. The two sources of heat combine to provide a total heat exposure for a person. The effects depend on the radiation intensity (kW/m²), the air or smoke temperature, and the exposure time, in terms of the total received heat "dose".

   b) The first effect of heat exposure is pain to exposed skin, which occurs when the skin temperature at 0.1 mm depth increases to 44.8 °C. Higher heat "doses" result progressively in minor (1st degree burns), 2nd degree (blistering burns) and full thickness (third degree) burns.

   c) The heat exposure doses required to cause 2nd degree and full thickness burns are several times those required to cause pain and minor burns.

   d) Inhalation of very hot air can cause burns to the nose, mouth and throat, which can result in laryngeal spasm and breathing difficulties. Respiratory tract burns do not occur unless there are facial burns.

   e) Death from heat exposure during a fire results from cardiac arrest. Survival following rescue with full thickness burns depends on the body surface area burned, the age and health status of the victim and treatment.

   f) During fires, occupants of flats such as those at Grenfell can reduce their heat exposure and burn risk by taking refuge behind furniture or in rooms beyond the fire room. Thick clothing or use of items such as duvets offer significant protection from heat exposure.

43. Effects of exposure to lung irritants:
   a) In addition to the immediate, concentration-related, irritant effects of smoke, exposed persons also inhale an increasing dose of sooty smoke particulates and irritant vapours, which deposit in their airways and the alveolar regions of their lungs. The inhaled dose depends on the smoke concentration and the exposure time. Although the effects of these inhaled irritants are relatively minor initially compared with the effects of asphyxiant gases, after a period of several hours (typically when rescued persons are being treated in hospital), lung inflammation and oedema may develop. This results in breathing difficulties and hypoxia, which can be fatal in severe cases. Older persons are particularly at risk of developing broncho-pneumonia during the first few days after exposure, which can also be fatal.

   b) Exposure to the smoke and CO, combined with stress, may increase risk of heart attack or stroke in persons with pre-existing cardiovascular disease, during the days following exposure.

   c) Many persons with significant exposure to smoke and toxic gases during fires make a full recovery without long lasting respiratory or other health conditions. The main risk factors are the severity and duration of the exposure, and to some extent the age and health status of the exposed person.
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d) Long term health effects following a single exposure during a fire can include some continued respiratory or circulatory conditions.

e) Cerebral hypoxia resulting from exposure to asphyxiating gases can result in permanent neurological injury with personality changes or more severe deficits.

f) Exposure to sensitisers in the smoke (such as formaldehyde and isocyanates) can result in the development of allergic conditions. Especially when combined with acid gases and other smoke irritants, this can result in the development of reactive airways disease.

44. Effects of exposure to mineral dusts and fibres:

a) Fires can result in the release of mineral dusts and fibres which can cause chronic lung disease if inhaled. This generally occurs as a result of repeated, long term, exposure over several years, but can occur as a result of heavy exposure during or following a single major incident. This has occurred following the World Trade Center fire, which resulted in the towers collapsing and releasing very large amounts of mineral dusts and fibres.

b) Some fibres (including asbestos and ceramic fibres) are carcinogens, but risks due to exposure during a single incident are likely to be low.

45. Smoke also contains low concentrations of a range of organic carcinogens, including benzene, aldehydes and polycyclic aromatic hydrocarbons. As with the fibres, health risks from exposure during a single incident are low, with disease generally being related to long term occupational exposure or cigarette smoking.

Approach used for this report

46. In relation to this Phase 1 report, no measured data for toxic smoke and gases are available for the actual Grenfell incident. The scale and complexity of the incident are also too great for the conditions throughout the Tower to be replicated comprehensively by any experimental tests or computational modelling methodology, although such tests and methods can and are being applied to specific aspects of the incident. Also, the conditions directly affecting Grenfell occupants changed rapidly during the course of the fire, so that although useful information has been obtained by examination of the Tower since the incident, this is limited with respect to conditions at the time of exposure.

47. In order to estimate the conditions to which the Grenfell occupants were exposed, and the likely effects on their escape and survival, I have firstly considered in general terms how smoke and heat exposure conditions may have developed in Grenfell flats as flames and smoke spread on the building exterior and smoke spread into the lobby and stairs, and subsequently as the exterior fire broke into flats from the window area. For this I have relied upon the results of previous fire experiments that I have participated in, involving different fire scenarios commonly occurring in domestic dwellings (flats and houses). I have also made use of information from previous fire incidents. I have then used the fire test data to calculate the predicted effects on occupants in terms of time to and effects of exposure to visually obscure and irritant smoke, asphyxiating gases and heat. These calculations make use of the known physiological effects of exposure to different intensities or concentrations of toxic smoke products and heat. I have used these to describe how occupants remaining in their flats would gradually become incapacitated and unconscious due to inhalation of asphyxiating gases, and subsequently die, and the extent to which they may or may have been exposed to heat prior to death. I have also considered the effects on escape behaviour of encountering irritant smoke in the lobby and stair for occupants attempting to escape, and the effects of asphyxiating gases in causing collapse in the stair after a sufficient exposure.
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48. I am examining information on actual Grenfell fatalities whose bodies were recovered from flats, lobbies, the stair or outside the building to estimate how they were exposed and died during the fire and how this compares with the generic descriptions of fire conditions. This will be reported in detail in Phase 2.

49. I am examining, witness statements and transcripts of calls to the emergency services to further understand the conditions to which occupants were exposed during the fire and how they were affected. These will be reported in detail in Phase 2.

50. I have examined the reports of the other Grenfell experts on the construction and fire damage to the Tower, the fire development and spread outside and within the Tower during the incident and the general timings of escape of those who survived, in order to further understand the development of conditions inside the Tower during the incident and effects on occupants.

51. I have made two visits to the Tower to examine the extent of fire and smoke damage, the remains of the exterior cladding and insulation, the materials surrounding the windows, the flat interiors (including those in which occupants died) and the condition of the lobbies and the stair.

52. In order to estimate the likely contribution to the smoke toxicity of different burning materials present at Grenfell I have relied for this Phase 1 report on previous experimental studies of the toxic gases produced by a wide range of materials commonly occurring in building structures and their contents, generic versions of which were present at Grenfell, under a range of different fire conditions likely to have occurred at Grenfell.

53. I have examined the cladding materials on the Tower and their residues, the structural materials around the window assemblies, and considered the likely combustion products from these materials based upon my own and other published experimental data on the yields of different toxic gases from these materials when they burn under different combustion conditions.
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METHODS USED FOR THIS REPORT

Generic fire hazards and effects on occupants

54. In this report I have firstly considered in general terms how smoke and heat exposure conditions may have developed in Grenfell flats as flames and smoke spread on the building exterior and smoke penetrated into the lobbies and stairs, and subsequently as the exterior fire broke into the flats through the window area.

55. For this I have relied mainly on the results of previous fire experiments in domestic dwellings (flats and houses) that I have participated in and other published results from large fire experiments. I have also made use of information from previous fire incidents. Fires in domestic dwellings mainly develop in enclosed houses and flats, and are limited initially to relatively small, under-ventilated fires producing large volumes of toxic smoke into the fire room and then spreading throughout open areas of the dwelling (the hallway and other rooms). A series of experimental fires of this kind involving upholstered furniture, were conducted at the Building Research Establishment (BRE) enabling a study of the development of hazardous conditions both in the fire room and beyond for scenarios in which the fire room door to the hallway was closed or open, and in which other rooms on the same floor or above were either open or closed. I have also made use of a series of enclosed fire tests carried out as a reconstruction of the Rosepark nursing home fire, for which detailed comparisons were made of the predicted effects from the fire test results and the actual effects on exposed occupants during the incident.

56. Another common fire scenario occurs when a fire enclosure has significant ventilation to the exterior (often when windows fail during a developing fire or when exterior doors are opened). This results in large fires which may transition to flashover, when flames spread suddenly to involve the total combustible contents of an enclosure, conditions which are immediately lethal in the room of fire origin, and large volumes of toxic fire products are also involved which can spread throughout a building. From my examination of flats in the Tower following the incident and Prof. Torero's report I consider that many flat fires at Grenfell are likely to have progressed to this type of fire at some stage of their development and I have considered the likely products from these fires based upon published data. I have also considered the likely conditions of the external cladding fire.

Prediction of time to incapacitation and death from the effects of exposure to irritant smoke and the combined effects exposure to asphyxiant gases and heat

57. I have used the fire test data to calculate the predicted effects on occupants in terms of time to and effects of exposure to visually obscure and irritant smoke, asphyxiant gases and heat. These calculations make use of the known physiological effects of exposure to different intensities or concentrations of heat and toxic smoke products. I have used these to describe how occupants remaining in their flats would gradually become incapacitated and unconscious due to inhalation

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10 BRE PD 105/98 1998 A database of large scale enclosed fire with life hazard analyses for fire safety engineering design.
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of asphyxiant gases, and subsequently die, and the extent to which they may or may not have been exposed to heat prior to death. I have also considered the effects on escape behaviour of encountering irritant smoke in the lobby and stair for occupants attempting to escape, and the effects of asphyxiant gases in causing collapse in the stair after a sufficient exposure.

58. The method used for tenability assessment for any fire scenario is to carry out a Fractional Effective Dose analysis using the time-concentration curves for smoke obscuration, irritants, asphyxiant gases, convected and radiant heat for all occupants throughout their exposure, using the methods described in Purser and McAllister\textsuperscript{14} and in Appendix A to this report. The aim is to calculate the time at which the exposure concentrations of smoke and irritants, and the exposure doses of asphyxiant gases and of heat, reach FEC (Fractional Effective Concentration) or FED (Fractional Effective Dose) levels predicted to significantly impair escape efficiency, or at higher levels prevent escape or cause incapacitation, collapse or death.

59. The effects of exposure to irritant smoke at any time are instantaneous, depending on the combined concentration of irritant smoke particulates and gases, these are expressed as the FEC which is calculated as the irritant smoke concentration expressed as a fraction of the concentration predicted to significantly impair escape attempts (represented by FEC=1). Further details on smoke limits for escape impairment are given in Appendix A.

60. The asphyxiant gases considered are carbon monoxide (CO), hydrogen cyanide (HCN), carbon dioxide (CO\textsubscript{2}) and low oxygen hypoxia. The combined effects of these gases have been estimated according to the method of Purser\textsuperscript{12,15,16,17}. The method is a current British Standard (BS9899-2 1999)\textsuperscript{18} and an International Standard.\textsuperscript{19} Details of the methodology are provided in the references cited. An explanation of the basis of the methodology is presented in Appendix A.

61. Fires contain a mixture of asphyxiant gases, the concentrations of which tend to increase with time during the fire. In order to accommodate these changing concentrations the method uses the fractional effective dose (FED) approach.

62. The general principle is that for a subject exposed to any toxic gas, incapacitation (loss of consciousness) occurs at a certain "exposure dose" available for inhalation, which is expressed as the exposure concentration multiplied by the time required to cause incapacitation (concentration [ppm] x minutes). During a fire, the concentration of each gas is averaged over short periods and the exposure dose over this period is expressed as a fraction of the exposure dose required for incapacitation (FED). The FED for each successive time period is then summed throughout the fire until the fraction reaches unity, at which time incapacitation is predicted. (See Appendix A for further explanation).

63. Where mixtures of gases are present, the fractional doses for each unit of time and for each gas are estimated on the experimentally verified basis that the effects of CO and HCN are additive and that the presence of CO\textsubscript{2} increases the rate of uptake by causing hyperventilation (and increase in


\textsuperscript{18} Assessment of hazard to life and health from fire Part 2: Guidance on methods for the quantification of hazards to life and health and estimation of time to incapacitation and death in fires. BS 7899-2:1999 British Standards Institution.

\textsuperscript{19} Life-threatening components of fire – Guidelines for the estimation of time available for escape using fire data. ISO 13571 (2012).
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the volume of air breathed each minute). The effects of low oxygen hypoxia are also considered
to be additive with those of the other asphyxiants according to the following general equation:

\[ \text{FED}_{in} = (\text{FED}_{CO} + \text{FED}_{CN}) \times VCO_2 + \text{FED}_{hypoxia} \]

Where:

\( \text{FED}_{in} \) = overall fractional asphyxiant dose for any short time period

\( \text{FED}_{CO} \) = FED carbon monoxide

\( \text{FED}_{CN} \) = FED hydrogen cyanide

\( VCO_2 \) = hyperventilatory factor due to carbon dioxide

\( \text{FED}_{hypoxia} \) = asphyxiant effect of low oxygen hypoxia

Incapacitation (loss of consciousness) is predicted then the \( \text{FED}_{in} \) summed with time reaches 1

Death due to asphyxiation is predicted at an \( \text{FED}_{in} \) of approximately 2-3.

Prediction of %COHb in the blood of exposed subjects

64. In practice the \( \text{FED}_{CO} \) term is obtained by calculating the percentage carboxyhaemoglobin
(\%COHb) in the blood of an exposed subject and expressing it as a fraction of the \%COHb
predicted to cause incapacitation. As a separate indication of the exposure of a subject to carbon
monoxide, the predicted \%COHb with time for subjects in different locations has also been
calculated.

65. The \( \text{FED}_{CO} \) and the \%COHb calculations have been carried out using the experimentally derived
uptake model of Stewart et al.\(^{20}\) This provides a good prediction for adults when the carbon
monoxide concentration is well in excess of the air/blood equilibrium concentration.

66. The most important variables influencing the uptake of carbon monoxide (the \%COHb in the blood)
by each occupant are:

a) The time-concentration curve for carbon monoxide (and carbon dioxide) in the fire at each
occupant location

b) The time for which each occupant was exposed before death or rescue.

c) The respiration ventilation of each occupant (volume of air inhaled each minute). This
depends upon the level of physical activity and the stimulatory effects on breathing of carbon
dioxide from the fire.

\(^{20}\) Stewart, R. D. Peterson, J. E., Fisher, T. N., Hosko, M. J., Baretta, E. D., Dodd, H. C. and Hermann,
Using smoke density and visibility as a method to estimate time to incapacitation from the effects of asphyxiant gases

67. For situations where large scale test or fire modelling data are available for the time-concentration curves for smoke, toxic gases and heat, the FED methods described are used to calculate time to escape impairment and incapacitation. Although this approach based on generic fires is useful to estimate likely conditions experienced by exposed Grenfell occupants it cannot be directly related to the effects on actual Grenfell occupants because no data are available for toxic gas concentrations during the fires in each flat, each lobby or in the stair. The one item of contemporaneous information available from many occupants is the appearance of the smoke and the visibility conditions.

68. For occupants exposed in their flats or attempting to move through smoke, tenability and time to collapse ultimately depends on the concentrations of asphyxiant gases, especially CO, HCN and CO$_2$ in the smoke. The ratios between yields and concentrations of smoke particulates and these gases depends on the composition of the fuels and on the combustion conditions. From data on these ratios measured for different fuels in bench-scale or large-scale fire tests, it is possible to determine gas concentrations for different smoke densities and calculate times to incapacitation (collapse) from exposure to asphyxiant gases for these gas mixtures using FED analysis.

69. As a simple limiting value it can be established that for smoke from any flaming fire involving any fuel mix, at a visibility distance of 10 metres, the concentrations of asphyxiant and other toxic gases will be low enough to have no significant deleterious effects on escape or survival for exposure periods of up to approximately 60 minutes. At higher smoke concentrations the estimated exposure time before a person in a flat (or walking through a lobby or down the stair) would collapse from asphyxiant intoxication is therefore an approximate function of the smoke concentration and therefore the visibility distance. Escape below a smoke layer also requires a maximum upper layer temperature of 200°C so as to limit downwards heat radiation to a tolerable level.

70. Estimated time to collapse from exposure to asphyxiant gases as a function of smoke density has been calculated from the ratios between yields and concentrations of smoke, CO, HCN and CO$_2$ measured during flaming combustion of four materials (a cellulosic material - medium density fibreboard, polymethylmethacrylate (PMMA) and two nitrogen-containing foams (a combustion modified medium density polyurethane foam and rigid polyisocyanurate foam [PIR]) commonly used as insulation. The smoke and gas yield data used for these calculations have been chosen as indicative of a burning "mixed fuel" package representative of an approximate mix that might occur in a building (such as the cladding and combustible flat contents at Grenfell). Yield data have been used for two combustion conditions, well-ventilated flaming (equivalence ratio [$\phi$] = 1) and under-ventilated combustion ($\phi$ =1.5). For each of these the relationship between smoke density and its reciprocal (visibility for reflected light) and time to incapacitation has been calculated as the time to reach FED=1 (representing time to incapacitation for 50% of an exposed population) for asphyxiant gases using the FED expressions in Purser and McAllister. The results from the

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Four different materials have been averaged to give an indication of the effects of exposure to smoke from a mixed fuel package.

71. I have examined information on actual Grenfell fatalities whose bodies were recovered from the flats, lobbies, stair or outside the building to estimate how they were exposed and died during the fire and how this compares with the generic descriptions of fire conditions. That information consists of toxicology reports on blood analysis to measure carboxyhaemoglobin concentrations (%COHb) and photographs of the deceased. I have toxicology reports on 20 decedents. For 15 of these numerical %COHb values have been assigned, while for a further 3 COHb was recorded as present but not measurable. I have requested data for a further four individuals. I understand that, for the remainder of those who died, it was not possible for toxicology to be performed. I have access to photographs of the remains of decedents in the locations from which they were recovered from the Tower. I have reviewed photographs of the remains of all decedents for whom blood carboxyhaemoglobin measurements were made, and of the remains of some other decedents. Full analysis for those occupants for whom data is available will be addressed in my Phase 2 report.

72. I am awaiting post-mortem reports on all Grenfell decedents.

73. In addition to the Grenfell fatalities, once the oral evidence from those who were in the Tower has been completed, I will request information on identified persons who escaped from the Tower during the incident and were treated in hospital. From records of their treatment by the ambulance teams and on arrival and subsequently at hospital, I wish to establish their extent of exposure to smoke and heat and the immediate and subsequent health effects. In particular I have requested information on the timing of oxygen treatment immediately after the fire, the time at which blood samples are taken and the resulting in terms of %COHb and blood gases, their clinical condition, especially any burns, effects on consciousness, respiratory or cardiovascular signs. I am currently awaiting this information.

74. In order to investigate the experiences of Grenfell occupants during the incident, and in particular the sequence and timing and effects of their exposure to toxic smoke, I am examining witness statements of occupants and transcripts of calls to the emergency services, which will be more fully considered in Phase 2. I have attempted to establish when and how occupants in different flats first became aware of the fire, the information they obtained from different sources as the fire developed and how they responded to this information. I have attempted to establish when they first saw and became exposed to toxic smoke or flames, how they were affected by smoke exposure and how this influenced their subsequent behaviour. I have examined the reported effects on occupants who remained in their flats over an extended period as smoke concentrations increased and fire entered from the outside. I have examined the effects on occupants who attempted to leave their flats and enter smoke in the lobbies, and those who attempted to escape in the lifts or stair. I have considered the effects of exposure to irritant smoke on willingness and ability to enter and move through lobbies and on the stair. I have also considered signs of developing incapacitation resulting from exposure to asphyxiant gases in both flat occupants and those descending the stair. I have considered these accounts in relation to the timings of exposure in the flats, lobby and stair and in relation to the measured %COHb levels in fatalities who collapsed in these locations. Details of the results of these investigations will be presented in my Phase 2 report.
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GENERAL DESCRIPTION OF FIRE CONDITIONS AND HAZARDS TO OCCUPANTS LIKELY TO HAVE OCCURRED AT GRENFELL

Methods used to determine conditions during fires and effects on occupants

75. A number of different methods are used to determine the development of hazardous conditions during fires and the effects on occupants. Investigation of a fire scene combined with witness accounts of observations during the fire provide information on the basic fire conditions (the fire “scenario”), how and where fire started in the location examined (such as any Grenfell flat), the extent of fire and smoke spread within the rooms and the ultimate severity of the fire. In order to understand the developing hazards to occupants it is necessary to estimate the time-line of fire development and in particular the time-concentration curves for smoke and toxic gases, heat radiation and temperature.

76. One way to obtain this data for a particular incident is to carry out a full-scale reconstruction of the actual building (or the affected part of the building) and repeat the fire experimentally as far as possible under the same conditions as the actual incident. The developing fire hazards can then be measured directly. Since fire development can be variable, even under identical reconstruction conditions, such experiments cannot be guaranteed to replicate the exact conditions during the actual incident, but when combined with forensic data from the incident they can be very useful in estimating the actual conditions.

77. Where a full reconstruction is not feasible then it is possible to make an estimate of likely conditions and hazard development by comparison with full-scale experimental test data obtained under similar conditions to those in the incident of interest. In order to estimate likely conditions in Grenfell flats, stairs and common areas I have made use of experimental data from full-scale fire tests carried out at BRE in a simulated flat and a typical two-storey domestic house. I have also made use of data from a full-scale reconstruction of the Rosepark nursing home fire, as well as other published large-scale fire test data.

78. Another method used to estimate developing fire conditions is by mathematical modelling of fire. For this approach computer fire models developed over many years from experimental data, physical and chemical relationships are used to simulate the developing fire.

79. Several different methods and sources of information are also used to estimate the effects of exposure to fire hazards on occupants. Where occupants have survived exposure, details of the developing conditions up to the time of escape or rescue can be obtained from witness accounts. These are combined with clinical data including blood carboxyhaemoglobin concentration, extent of soot deposition on the skin or in the respiratory tract, and extent of burns.

80. Where occupants have died at the fire scene there may be witness accounts of conditions before they died, or as in the case of some Grenfell fatalities, telephone records from them of conditions immediately before they died. Important information is also provided by autopsy data on blood carboxyhaemoglobin or cyanide, smoke deposition and extent of burns. For these cases the blood levels represent those at the time of death, rather than those at the time of incapacitation. For burns it is not possible to determine whether they occurred before or after death. Due to the severity and long duration of the Grenfell fire, many bodies were reduced to ashes, so that limited autopsy data are available.

81. Another method for estimating the effects of exposure to developing fire conditions on occupants is to use physiological and toxicological calculation methods (known as Fractional Effective Dose [FED]) modelling methods. These methods are derived from studies of the effects of exposure on people to individual fire hazards including smoke, toxic gases and heat to determine the concentrations and exposure doses determined to cause incapacitation (effects likely to impair escape capability) and death. By combining these methods with the time-concentration or intensity curves for smoke, toxic gases and heat during the fire (obtained from experiments or fire modelling), it is possible to estimate when an exposed person would be incapacitated or receive a
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lethal exposure to each hazard during the fire. It is also possible to calculate the uptake of CO and so as to calculate the blood %COHb with time during the exposure.

82. The best estimates of conditions and effects on occupants during actual incidents is obtained by using a combination of these methods. For the Rosepark nursing home fire the measured data from the reconstruction fire were used to calculate the exposures with time of occupants in different locations, the time at which they would be incapacitated or receive a lethal exposure from smoke, toxic gases and heat, the predicted %COHb and extent of burns at rescue or death. These findings were then compared with timing and witness data from the actual incident, together with clinical and autopsy data, including burns and %COHb from the occupants. By combining information from all these sources it was possible to confirm the extent to which the reconstruction fire was a good replication of conditions during the actual incident, and to confirm that the uptake of toxic gases and effects of heat exposure were as predicted by the FED calculation methods.

83. For application to Grenfell I will use a combination of these approaches, depending on the information available. For this section of my report on generic fire hazards I have made use of experimental fire data from different full-scale fire experiments, and FED calculations on the effects of conditions in them, to estimate general hazard development in different locations at Grenfell. I have also made use of information from other incidents I have investigated or for which published information is available. For Phase 2 of my report I am examining witness accounts, autopsy data and other information on developing fire conditions for the Grenfell incident to estimate the developing hazard and effects on occupants there. For some occupants in some locations at Grenfell detailed information is available, while for others, particular for some of those dying in their flats, which were later burned out by the fire, I will have to rely more on data from experiments or other incidents under similar conditions from which occupants were rescued or bodies recovered without the evidence being destroyed by the later development of extreme conditions.

Development of hazardous conditions (generic fire scenarios) at different Grenfell locations

84. The developing fire hazards to occupants at different times and locations at Grenfell fall into several different categories (generic fire scenarios). In this section I have described how fire and hazardous conditions develop in such scenarios and the effects on exposed occupants, based on my previous experience of experimental data and fire investigations for similar fire scenarios using the methods described in the previous section. I have illustrated my description with some examples of experimental fire data and FED hazard calculations.

85. The main categories and stages of fire hazard scenarios to which Grenfell occupants were exposed are considered to have been as follows (Figure 1):

a) During early stages after fire breaks out from Flat 16 on the fourth floor, smoke from the cladding fire at lower levels of the Tower flows up the exterior, partly clinging to the building exterior surface (wall effect). The smoke entrains exterior air as it rises, lowering the concentrations of smoke particulates and toxic gases in the rising plume. Some of this smoke gradually infiltrates into flats all the way up the Tower through vents, gaps and penetrations to the building exterior, or any open windows.

i. Flat occupants on all floors begin to become aware of the fire from a variety of cues. These include sources such as noise and activity outside the base of the Tower, but also smelling smoke, seeing a haze or activation of smoke alarms. Flat occupants begin to investigate. They enter the lobbies and communicate with neighbours. There is no smoke or only a slight haze in the lobbies and stair. Some occupants decide to evacuate at this stage and are able to descend the stair (or lifts) safely without coming into contact with smoke.
As fire spreads up the East side of the Tower and the flaming exterior fire reaches each successive floor, dense smoke followed by flames from the exterior fire penetrate the flats (especially those in the Flat 6 location on each floor directly above flat 16).

i. Occupants of the first flats at each floor level penetrated by dense smoke and flames are alerted (sometimes by smoke detectors in their flats) and attempt to evacuate their flats. Since fire is penetrating from the exterior (via the windows) they are able to move away from the fire into the flat hallway and then out of the flat entrance door into the common lobby on each floor. In some cases they may have to move though relatively dense smoke within the flat, but are familiar with the flat layout and highly motivated to escape. Although the smoke contains toxic concentrations of asphyxiating gases, the exposure is in most cases too short for occupants to be overcome before they can evacuate the flat (within a few minutes of serious smoke and fire penetration). There is however a danger that deeply sleeping occupants could be overcome before they are able to escape.

ii. At this stage there is still little or no smoke in the landing or stair, so these occupants (for example those from Flat 6 on each floor level) are able to evacuate safely through the lobbies and down the stairs without significant smoke exposure. Some occupants may be concerned about how bad conditions might be lower in the Tower, so may decide to take refuge in other, so far unaffected, flats (for example those on the west side of the Tower).

c) As flats on the east side of the Tower fill with smoke, and after the occupants of these flats open their flat entrance doors to evacuate their flats, dense smoke starts to flow into the lobbies on each floor. The lobbies fill with dense smoke within a few minutes, especially from any fire-penetrated flats for which the flat door is left open as the occupants evacuate. The smoke flowing out of the open flat doorways forms a layer of dense smoke under the lobby ceiling, which rapidly fills and mixes down to near floor level within a minute or so. For floors where all the flat entrance doors remain closed, there is a more gradual increase in smoke density in the lobbies from smoke leaking into the lobbies via various routes through leakage paths and penetrations (especially around and under the edges of the fire flat entrance doors). After a few minutes the lobbies on most floors are filled with dense irritant smoke and visibility in the lobbies is very poor (a metre or so then close to zero). As fire spreads into penetrated flats and involves the flat contents the volume of smoke within the flats and penetrating the lobbies increases. After some time the top of the flat entrance door may burn through if a severe fire occurs in the flat, further increasing the flow of smoke (and in some cases flames) into the lobby.

d) Within flats on each floor not directly affected by fire there is then continued and increased infiltration of smoke from the burning Tower exterior as the exterior smoke plume flows up and around the Tower. The concentration of smoke particulates and toxic gases in the smoke is still relatively low, but increases as the fire gets closer to each affected flat. Smoke penetrate more rapidly through open or poorly fitted windows. Since the lobbies are now filled with dense, toxic smoke, this also starts to penetrate all flats on each floor by leakage paths from the lobbies into the flats, especially around the edges of the flat entrance doors.

i. At this stage the conditions in flats not directly penetrated by dense smoke and flames are relatively benign, with light smoke in the flats but several metres visibility. Initially the flat occupants are concerned and suffering from some eye irritation and minor breathing discomfort, but because the concentrations of asphyxiating gases (CO and HCN) are low, and because they have been exposed for only a few minutes, they are still alert and able to breathe without difficulty.
ii. Occupants may then consider evacuating the flats. When they open their flat entrance door they are confronted by dense irritant smoke and very poor visibility. The smoke has a strong smell and is difficult to breathe. The smoke in the lobby also contains high concentrations of asphyxiating gases capable of causing incapacitation (collapse) after a few minutes exposure. The flat occupants then face a difficult decision on whether to remain in the deteriorating conditions in the flat and await rescue, or whether to risk attempting escape through the thick lobby smoke and down the stair. Some occupants close the door at this point and stay in the flats. Others attempt to enter the lobby and feel their way to the stair entrance door, but become disorientated and return to their flat, or take refuge in other flats less affected by smoke. For those familiar with the lobby layout it should take only approximately 10-20 seconds to reach the stair door. If occupants become disorientated and breathe the lobby smoke for more than a few minutes they will be in danger of collapse from the accumulated dose of asphyxiating gases.

iii. Since the stair is separated from the lobbies on each floor by a self-closing fire door, the extent of smoke penetration into the stair should be considerably less than in the lobbies during the first 30 minutes or so of the fire. Those occupants reaching the stair should therefore find conditions somewhat better than in the lobbies, at least initially. Also, once in the stair they can hold and follow the bannister, enabling them to descend relatively rapidly. If the smoke density increases as they descend they may decide to turn back and return to their flats. As they descend the irritant smoke makes breathing difficult and they inhale a gradually increasing dose of asphyxiating gases.

iv. Depending on the severity of the smoke conditions in the stair they may be able to descend to the ground floor without collapsing (for example if visibility in the stair is a metre or so, and they complete the descent within 5-10 minutes), or they may start to feel weak or dizzy by the time they reach the lower floors, or even collapse (for example if the visibility is < 1 metre).

v. The probability of occupants collapsing in the lobbies or stair depends largely on the extent of their exposure in the flats. Occupants remaining in flats not directly penetrated by fire are exposed to gradually deteriorating conditions as smoke and toxic gas concentrations slowly increase. Visibility in the flat may decrease to <1 metre and occupants will suffer from increasing smoke irritancy and breathing difficulties. As the CO concentration increases to ~1000-2000 ppm over a period of an hour or more, the occupants accumulate an increasing dose of asphyxiating gases. If they attempt to evacuate after an hour or more, having accumulated a significant dose, then they may remain reasonably alert while sitting in the flat, but are then rapidly overcome by dizziness and collapse when they become physically active as they attempt to enter the lobby and walk down the stair. Also, as soon as they enter the lobby and stair, their accumulated dose of asphyxiants increases rapidly due to the higher CO and HCN concentrations in these locations. Occupants already close to collapse in the flat may then collapse in the lobby just outside the flat or on the first flight of stairs. Occupants may use wet towels to inhibit smoke ingress from lobbies, while more smoke ingress occurs if the flat entrance door is opened periodically. Those in more protected flats, with less smoke infiltration from outside (for example flats in the Flat 3 location on each floor), or those leaving after shorter periods in the flats, may accumulate lower doses while in the flats, so be able to tolerate a longer exposure in the lobbies and stair, sufficient for them to walk down to the ground floor without collapsing.

vi. If occupants remain in their flats for several hours, they are in danger of collapse and death from the prolonged exposure to asphyxiating gases, especially CO.
vii. Conditions in the stair vary at different times and heights in the tower from light smoke early on to dense toxic smoke as the fire develops and spreads. At some floors fire from open flats may penetrate the lobby and eventually the stair.

e) Occupants remain in their flat. The flat entrance door remains closed. After a period of smoke infiltration lasting from a few minutes to several hours (depending on flat location), the cladding fire appears outside the windows. Smoke and flames penetrate around the windows and start to burn the structural materials around the windows. The flat fills with high concentrations of toxic smoke within a few minutes. Gradually fire spreads to involve the flat contents near the windows, generating further toxic smoke. The windows remain in place for around 10 minutes while fire grows in the flat.

i. Occupants remaining in the flat may take refuge in areas away from the rooms where the fire is breaking in through the windows, closing the interior flat doors to these areas. These include other rooms or especially the flat hallway or bathroom, which are furthest from the fire entry points and have no windows. This protects them from heat exposure and somewhat delays exposure to the rapidly increasing concentrations of toxic smoke in the flat. These areas fill with high concentrations of asphyxiants within a few minutes, rapidly increasing the already accumulated dose of asphyxiants. Occupants collapse and lose consciousness within a few minutes from exposure to asphyxiants (CO and HCN). They then die a few minutes later as their breathing and circulation gradually cease. As the fire continues to burn and spread throughout the flat it consumes most or all of the combustible materials in the flat, including the bodies of the deceased.

ii. If occupants attempt to escape into the lobby their ability to escape down the stair depends on the time for which they were exposed in the flat before and after fire penetration. If fire penetration occurs at an early stage (as in Flat 6 on each floor), then occupants may have a low accumulated dose of asphyxiants and be able to descend the stair without collapsing. If fire penetration occurs after several hours of low level smoke exposure, and/or if occupants remain in the flat for more than a few minutes after fire penetration, then they may be close to collapse when they leave the flat, and may collapse in the lobby or stair close to the flat.

f) As above, but one or more windows are open or fail within a few minutes of cladding fire flames appearing outside. Rapidly growing flaming fire spreads within flat, progressing to flashover within ~10 minutes.

i. This is a variant or continuation of the previous case. If the fire develops rapidly to flashover the condition in the flat becomes lethal within seconds. The severe fire is then likely to consume most or all of the combustible materials in the flat, including the bodies of the deceased.

ii. A post-flashover fire in a flat may eventually burn through the upper part of a closed flat entrance door. After it does this, or if the flat door was left open, then the flaming fire will spread into the lobby, consuming combustible materials in the lobby such as wooden cupboard doors. If fire burns in the lobby for an extended period of an hour or more, then fire may also burn through the stair entrance door and spread into the stair (or spread into the stair if the stair door is wedged open during the fire).
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Figure 1: Basic Grenfell fire hazard scenarios

Developing hazard from exterior fire penetration into a flat

86. The deaths of 53 Grenfell occupants resulted from fire breaking into their flats from outside while they remained in them with the main door closed. These scenarios arose when occupants remained in their flats awaiting rescue, left their flat and took refuge in another flat on the same floor or a higher floor and/or because they were unable to leave their flats to enter the stair due to severe smoke contamination of the common landing and stair.

87. In many cases these flats were eventually burned out by the fires over several hours, so that limited physical evidence remains of the pattern of fire hazard development and effects on occupants. In order to describe the likely development of conditions in the flats and the effects on occupants I have therefore used data from previous experimental flat and house fire tests I have participated in. For Grenfell, witness evidence of the developing conditions is available in some cases from telephone calls to relatives and the emergency services, which I am in the process of examining for comparison with the general analysis described here and will refer to my Phase 2 report.
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Early fire development in an enclosed flat
The sequence of early fire development in an enclosed flat is illustrated in

88. Figure 2. Fires occurring in domestic dwellings (houses and flats) typically start in an item of room contents such as an armchair or an appliance of some sort. The fire development depends very much on the ventilation to the flat (whether exterior door and windows are closed or open). For most domestic incidents, where exterior doors and windows are closed, the fire itself is in most cases mainly limited to the item first ignited, with some fire damage to the immediate surrounding area. However the consumption of a few kilograms of fuel results in the production of significant heat and large volumes of toxic smoke, which spread rapidly to fill all open areas of the flat.

![Diagram of early fire development in an enclosed flat]

Figure 2: illustration of early fire development in an enclosed flat

89. The basic pattern of fire development is that initially a small flaming fire occurs in the item ignited. Initially the fire is well-supplied with air from the flat interior and grows over a period of 5 minutes or so to produce flames approximately a metre high. Combustion during this stage is efficient, so that the main combustion products are carbon dioxide, water, some smoke and heat. The hot smoke and fire gases rise and mix with air (air entrainment) to form a layer under the ceiling. During this early stage the hazards to flat occupants, either in the fire room or another open or closed room in the flat are minor. The diluted smoke layer is not significantly above room temperature, and is above head height for a standing occupant, so there is no exposure to the smoke. As the fire grows and more smoke is produced the upper layer gradually fills down towards the floor (like filling an inverted bath tub). Once the smoke layer falls down below the soffit above the doorway of the room containing the fire (room of origin), the smoke and gases flow out of the doorway (if the room door is open), and spread throughout the other open rooms in the flat. During experiments with this scenario I have found that when the flowing smoke plume (for example from a lounge furniture fire) spreads down a corridor into another room (such as a bedroom), it mixes with more air and cools, then as the plume reaches the end wall it flows and mixes down to near floor level, The cooler air near floor level then circulates back into the fire room.

90. The result is that smoke and gas concentration at lower levels in the flat increase, so that although a flat occupant would be able to reduce their exposure somewhat by remaining near the floor, they would start to become exposed to the smoke and toxic gases.

91. As the fire grows and the upper layer descends, the flames begin to burn in the somewhat oxygen-depleted upper layer. The re-circulated air entrained into the flames near floor level also becomes...
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Oxygen depleted. At this stage the combustion become inefficient (ventilation-controlled). The yields and concentrations of toxic gases that are products of inefficient combustion (mainly CO, HCN and smoke irritants) then increase rapidly, so that occupants become exposed to significant concentrations of asphyxiant gases, as well as somewhat irritant smoke. At this stage the upper layer in the fire room is hot, reaching several hundred degrees centigrade, and around 100°C near floor level. The result is that an occupant in the open of the fire room, even away from the immediate fire, is exposed to significant downwards heat radiation from the hot upper layer, as well as convective heat from the hot air around them nearer the floor. From around 8-10 minutes into a fire such as this, an occupant of the fire room would be exposed simultaneously to incapacitating concentrations of asphyxiant gases and heat. The exposure to asphyxiant gases leads to collapse with loss of consciousness within a few minutes, followed by death if exposure is prolonged, while the exposure to heat leads first to skin pain and then to burns. Whether incapacitation due to asphyxia occurs before pain from heat depends on the specific pattern of fire development, the materials burning and the location (and protective behaviour) of the occupant. In general for a fire such as this loss of consciousness due to asphyxia is predicted to occur just before or around the same time as the heat exposure would start to be painful, but before an occupant would suffer severe burns. If the occupant was able to limit the radiant heat exposure (for example by sheltering under a table, or a coat), or in another room in the flat with the door to the fire room closed, then asphyxia would be predicted before serious heat exposure.

Figure 3 illustrates the common timing, sequence and severity of fire hazard development during a typical enclosed flat or house fire. It shows the time-concentration curves of the main fire gases, smoke and heat in the lower floor fire room during the early stages of an experimental fire carried out in an enclosed two-storey house with an open door to the fire room, one open and one closed bedroom on the upper floor. Further information on two of these House Fire tests, one with the fire room door open and one with a closed fire room door is given in Appendix B.

Figure 3: Example of time-concentration curves for smoke, toxic gases and temperature at head height in the domestic lounge of a house during an armchair fire. The doorway to the hall is open but the house is otherwise enclosed. The time for activation of smoke detectors is shown.
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93. Figure 3 shows the fire growing slowly at first, but then rapidly after four minutes when the concentrations of smoke and gases in the fire room (open lounge) increase rapidly. The temperature also increases rapidly, reaching almost 300°C from 6 minutes. As the fire grows smoke flows out of the fire room into the hallway and fills the open areas of the landing and an open bedroom upstairs. Air, and then recirculated smoke, enters the room doorway from the hall, supporting combustion, but when this become oxygen depleted the fire self-extinguishes after 10 minutes.

94. Figure 4 below shows an analysis of the effects on a person during exposure to the smoke conditions presented in Figure 3. For each hazard plotted, when any line exceeds 1 on the Y-axis this means that the exposure concentration of smoke (FEC smoke) or irritants (FICirritants) has exceeded a level considered seriously to impair escape. When exposure doses of asphyxiant gases (FEDasphyxia) exceed 1 then collapse and loss of consciousness is predicted and when the exposure dose of heat (FED heat pain) exceeds 1 then pain to exposed skin due to is predicted.

Figure 4 Growing hazards from the heat smoke and toxic gases from armchair fire shown in Figure 3. For each hazard an incapacitation threshold is reached when FEC or FED exceeds 1.0 on the Y-axis. In this case the first hazard is escape impairment from irritant smoke after 1 minute, followed by loss of consciousness due to asphyxiant gases and pain to exposed skin from heat after 5.5 minutes. Serious burns for a seated person are not predicted until 3 minutes after loss of consciousness from the effects of asphyxiant gases.

95. For a person in the fire room but on the opposite side of the room from the fire, there is no initial exposure to either heat or smoke as the smoke from the early flaming fire collects under the room ceiling. Once the upper layer descends below the soffit of the door to the hall, the smoke starts to flow out into the hall and landing, further reducing the rate of descent of the upper layer in the fire room. For a person standing in the room the first exposure to smoke is predicted from one minute after ignition, when the upper layer descended to head height (1.7 meters). An FEC=1 for smoke density and FICirritants=1 for the effects of the irritant gases present in the smoke is predicted at 1 minute, after which a subject is predicted to suffer an impaired escape capability due to the optical obscuration from the smoke and the smoke irritancy, derived from a significant
content of both organic irritants and acid gases including HCl, HBr, HF and SO2, which were measured in samples from the test using ion chromatography. However, if the subject got down to near floor level (0.5 m), then they would be beneath the smoke layer until 4 minutes. Conditions deteriorated very rapidly from around 4 minutes, so that at 5.5 minutes an FED exceeding 1 is calculated simultaneously for both asphyxia and heat. At this time it is predicted that a standing exposed subject would start to suffer pain to exposed areas of skin, especially the head and hands, and would collapse unconscious due to the effects of inhaled asphyxiant gases, and in particular hydrogen cyanide. For a person sitting or crouching below the smoke layer up to this time the exposure to hot gases would be somewhat less, so that time to pain from heat for any unprotected skin is predicted at just before 6 minutes. As the exposure to heat continues an exposed subject would begin to suffer from burns, so that for a standing person fatal extensive full thickness (3rd degree) burns are predicted after 8 minutes and for a sitting person after 9 minutes. The FED heat curves then level off because by now the fire has self-extinguished and the temperatures in the room are dropping. A person in the room would be able to take refuge from the heat for some minutes, for example by sheltering under furniture or putting a duvet over their head, but could not avoid exposure to the asphyxiant gases.

96. The other two curves in Figure 4 (FED CO and CO2 only, and %COHb CO and CO only) have been included to consider the situation with regard to asphyxiant gases in the absence of hydrogen cyanide. For these upholstered furniture fires the hydrogen cyanide concentrations increased rapidly to well in excess of those observed to result in loss of consciousness in exposed subjects within two minutes. Cyanide is therefore the main driver of collapse from asphyxiation in these fires. If the fuels had not contained nitrogen (or < 1% nitrogen by mass), then the main asphyxiant gases present would have been carbon monoxide, carbon dioxide and reduced oxygen levels. Another factor would have been the high concentration of irritant smoke gases and particulates. It is considered that these would have made breathing difficult for exposed occupants, thereby adding to some extent to the asphyxiant effects of the inhaled gases. For the full form of the FIN model for asphyxia, the fraction of a lethal dose of irritants (FLDm) is included as an additive term, since the breathing difficulties associated are considered likely to add to those of the chemical asphyxia. When this is done for this fire (but without HCN) the main drivers of asphyxia are the inhaled doses of CO and these irritants, increased by the presence of high CO2 concentrations and with a small contribution for the lowered oxygen concentrations. The calculated time to FEDIN asphyxia due to the effects of CO uptake, is then 7 minutes. At this time it is calculated that the overall degree of incapacitation is likely to be sufficient to cause collapse and prevent escape. Since the extent of additive effects from the irritants is somewhat uncertain, the final curve shows the situation with this term removed from the analysis (FED CO and CO2 only). In the absence of cyanide the result shows loss of consciousness after 8.5 minutes as the blood CO level reaches 40 %COHb (on the %COHb CO and CO2 only curve), which happens to coincide with the time by which a person sitting or lying on the floor is likely to receive life threatening burns. After the point of loss of consciousness, a reduction in respiration occurs. This, combined with the lower CO concentration occurring around this time results in a reduction in the subsequent rate of increase in blood %COHb.

97. After 10 minutes the fraction of a lethal dose (FLD) for lung irritants is 0.25, indicating that severe post-exposure lung inflammation is unlikely if rescued at this time, although elderly subjects in particular have been found to be vulnerable to the development of fatal pneumonia from lung infection. Following rodent and primate exposures to combustion product atmospheres, signs of post-exposure lung inflammation were found to be minor up to a critical exposure dose level above which severe or fatal oedema and inflammation occurred during the first 12-48 hours.25

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98. Occupants of rooms beyond the room of fire origin (such as the bedroom in this lounge fire example) would also be exposed to incapacitating, and eventually lethal concentrations of asphyxiating gases, but the smoke temperature and radiant heat exposure would be much lower. So in these locations collapse from asphyxia is predicted without painful heat exposure.

99. Figure 5 shows the concentrations of smoke and toxic gases and hazard analysis for the open bedroom on the floor above the lounge fire. The analysis in Figure 6 predicts escape impairment due to irritant smoke exposure from 5 minutes after ignition of the fire and loss of consciousness from the effects of asphyxiating gases just by 7 minutes. A key difference from the hazards in the lounge is that the temperature in the bedroom peaked at around 50°C, after 9 minutes then cooled within a few more minutes, so there was no pain or burns hazard from heat exposure.

100. Similar results to those in the house fire tests occurred during the reconstruction of the Rosepark Nursing home fire, in which a short, violent, fire started in a cupboard and spread into an enclosed area consisting of a corridor and open or closed bedrooms off the fire corridor. In this case, while a person standing in the corridor would have been exposed more or less simultaneously to incapacitating levels of asphyxiating gases and painful heat leading to burns, occupants of open bedrooms off the fire corridor would have had similar exposure to asphyxiants leading to loss of consciousness within a few minutes, but would not suffer from heat or burns.

101. A full-scale reconstruction of the affected part of this building and the fire incident was carried out by the Building Research Establishment (BRE) on behalf of the Scottish Office and the Procurator Fiscal. FED calculations were applied to the fire test data to calculate timing and effects on the occupants, assuming the conditions in the reconstruction were similar to those during the actual incident. Forensic data, principally the %COHb concentrations and extent of burns in the decedents and those rescued from the fire were also examined. Figure 7 shows the time-concentration curves of toxic gases and heat in the fire corridor, which were very similar to those in the open bedrooms off this corridor. Figure 8 shows the FED hazard analysis for a standing corridor occupant.
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Figure 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.

Figure 8: Fractional Effective Dose hazard analysis for the corridor fire profile shown in Figure 7

102. The FED calculations show dense smoke from 4 minutes after ignition, with collapse from the effects of asphyxiant gases predicted after 5.5 minutes due mainly to the effects of HCN and CO, with a lethal (50% COHb) level of CO predicted by 6.5 minutes. Severe pain from convective heat exposure is predicted after 6 minutes in the corridor. The smoke and toxic gas conditions at bed height in the open rooms were similar to those in the corridor, but temperatures at bed height were much lower. It was therefore predicted that all open room occupants would have been overcome and died within a few minutes due to the effects of asphyxiant gases, with lethal %COHb blood levels but no burns, and this was the finding from the forensic data, with all room occupants dead (but unburned) at the fire scene when the fire service entered the area. These findings and the pattern of fire damage supported an estimation that the reconstructed fire conditions were similar to those in the incident.
103. If a Grenfell flat occupant took refuge in a closed room within the flat but beyond the fire room, then they would have considerable protection from both toxic smoke and heat. During the house fire experiments a simple closed interior door was found to be an effective barrier to smoke penetration. This is further improved if gaps are blocked by items such as wet towels. So if a Grenfell occupant were to take refuge in a flat bathroom without windows and situated against the internal wall of the flat, they would receive considerable protection for some time from the heat from a fire in the outer rooms of the flat. There would also be some delay in toxic smoke penetration, but this would gradually leak into the closed room.

104. For the experimental enclosed flat and house fires of the kind illustrated in Figure 3, the fire was limited to the armchair of origin and eventually went out when the oxygen supplying the fire decreased to around 15% O₂. Although the open areas of the flat or house were filled with high concentrations of toxic gases, capable of causing collapse within minutes, the smoke and gases penetrated only slowly into the closed room, so that an occupant would be predicted to be able to survive there for up to an hour or more before becoming incapacitated by the slowly increasing uptake of carbon monoxide. Similar slow smoke penetration into closed rooms occurred during the reconstruction of the Rosepark Nursing home fire. In this case there was a decreasing extent of exposure depending on proximity to the fire. As stated, a person standing in the corridor would have been exposed more or less simultaneously to incapacitating levels of asphyxiating gases and painful heat leading to burns, while occupants of open bedrooms off the fire corridor would have had similar exposure to asphyxiants leading to loss of consciousness within a few minutes but no serious heat exposure. For closed rooms off the corridor there was a slow increase of CO over a period of an hour or more. During the actual incident, occupants of open rooms of the fire corridor were overcome and died within a few minutes due to asphyxia but had no burns. Occupants of closed rooms suffered no heat exposure, but became intoxicated by CO inhalation over a period of up to 90 minutes before rescue.

105. These findings for closed rooms are illustrated in Figure 9, which shows the conditions in one of the closed rooms off the fire corridor from which the uptake of CO (%COHb) could be calculated for the room occupant. The time of rescue for this occupant is known as well as her subsequent treatment and the %COHb concentration in her blood, measured soon after her arrival at hospital. The FED analysis in terms of the forward-calculated %COHb from the fire data showed a good agreement with the back-calculated %COHb from the actual blood data of 46 ±3 %COHb after 70 minutes of exposure in the room.

![Figure 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.](image)
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106. The results show that, as for the house fire experiments, a simple interior door provides a considerable degree of protection from smoke and heat penetration, with the predicted time to incapacitation due to asphyxia from CO inhalation increasing from 5.5 minutes in an open bedroom off the fire corridor to 50 minutes when the door is closed, in this case with no heat hazard.

107. Based on the findings from these experimental fires and incident investigations, I consider that when a fire involving the external cladding ignited materials in the walls and room interior around the windows of an enclosed flat, and as long as the windows remained intact, Grenfell flat occupants would be able to take refuge in open or closed rooms within the flat, especially rooms away from the windows. In such a situation they would eventually be overcome and collapse unconscious due to inhalation of asphyxiant gases. Although they would suffer some heat exposure, which could result in pain and burns around the same time or soon after they became unconscious due to asphyxiant gases if they remain in the open fire room, by taking refuge in other open or closed rooms they could avoid serious heat exposure and delay time to asphyxia for some time.

108. A difference between the experimental fire scenarios and that of a flat fire at Grenfell is that whereas the house and care home fires were limited to a relatively small area and self-extinguished due to lack of ventilation, at Grenfell the fires broke in from the exterior and at some point there was failure of the windows, providing continued ventilation to the fires, which then continued to grow within the flats. Under these circumstances, although the early stages of fire development are likely to have been similar to those described above as long as the window glazing remained intact, at later stages the fires continued to develop and spread through the flats. While occupants remaining in the fire room or other open rooms in the flat are likely to have been overcome before this secondary fire development became significant, those taking refuge in a closed bathroom would be affected later as the fire continued to develop. During the Rosepark incident, the fire in the corridor partly burned through the upper section of the door of one of the occupied closed rooms some minutes into the fire. From this time the rate of penetration of smoke and CO into this room was significantly increased, so that the %COHb in the blood of that room occupant increased more rapidly than for the occupant of a nearby room with an intact door. It is likely that a somewhat similar pattern may have occurred in flats at Grenfell. As the fires in the open areas of the Grenfell flats grew, producing large quantities of toxic smoke, occupants sheltering in a closed bathroom would be initially exposed to a slowly increasing CO concentration. Once the upper part of the door had burned through there would have been rapid penetration of high concentration toxic smoke from the flat fire, leading to rapid intoxication and collapse before significant flame and heat penetration into the closed room.

Effect of an open window on fire development in a flat

109. A wide open window or windows has major effects on fire hazard development as illustrated in Figure 10. The very early stages of such a fire are similar to those in an enclosed flat. The flaming fire starts in one area and an upper smoke layer forms under the ceiling. The difference from an enclosed fire is that as soon as the smoke layer descends below the top of the window opening, the smoke plume begins to flow out of the window opening as well as internally within the flat. Also, fresh air from outside (of smoke rising from below) enters below the smoke layer through the lower part of the window. This air enables the fire to grow more rapidly than for the enclosed fire, and the flow dynamics maintain the upper layer at a fixed depth.
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Upper layer oxygen concentration lower than in an enclosed fire (down to 1-2%), with higher CO, HCN and smoke concentrations. This may limit combustion of fuel in inner areas until fuels behind widow area are consumed, including closed flat door. Conditions rapidly become unsurvivable. If flat door open, of after eventually burned though, dense toxic smoke and flames flow into lobby.

Fire grows initially using enclosure air, then after window fails settles to a maintained size depending on the window ventilation until most of the flat contents are consumed. Upper layer hot enough for radiation to ignite fuels beyond primary fire. Smoke flows out of the upper part of the window and air (or smoke rising from below) flows into the lower part. Fuel rich plume from window flames as it entrains fresh air outside.

Figure 10: illustration of early fire development in a flat with an open window and exterior fire ingress

110. The result for flat occupants is that they are able to remain below the smoke layer for longer, but that the fire grows more quickly and the conditions become hotter. Occupants are still able to take refuge from the heat by moving to inner rooms, and can delay their toxic smoke exposure somewhat by retreating to a closed inner room such as a Grenfell bathroom.

111. As the fire grows the upper layer in the fire room becomes very hot, and after it reaches approximately 600°C there is a transition to flashover, whereby the heat radiation from the upper layer is sufficient to ignite all combustible surfaces in the open areas of the flat. The fuel-rich toxic smoke plume from the fire flows to the outside, while fresh air enters at a lower level to support combustion.

Figure 11: Composition and temperature of the upper layer of the fire room entrance for a wood fire in a full-scale open room-corridor rig.
112. The conditions in this kind of scenario are illustrated in Figure 11 above, which shows results from an experimental fire in a room connected to by a doorway to a corridor open at one end. This simulated the conditions of fire in a flat with a large open window or door to the outside. In this series of experiments, 100 kg fire loads were placed in the fire room leading to an open corridor (Figure 11).\textsuperscript{26} Whereas the enclosed fires self-extinguished after consuming a few kilograms of fuel, these fires continued to burn until all the fuel was consumed. Under these conditions the smoke layer descends to provide continuous ventilation-controlled (under-ventilated) combustion. The toxic product yields and concentrations in the upper layer of the smoke plume flowing down the corridor are very high, while the oxygen is depleted almost completely to around 1% $\text{O}_2$, with 18%$\text{CO}_2$ and 4% $\text{CO}$ as shown in Figure 11. The temperature of the smoke layer was also very high, in excess of 700°C. For this experiment the fuel was wood only, which has a very low nitrogen content. In other experiments involving nitrogen-containing fuels, high HCN concentrations were measured.

113. Once conditions such as this occur, and particularly when they progress to flashover, the conditions in the fire room become lethal within seconds due to very high concentrations of toxic gases and extreme heat. Occupants of open rooms beyond the fire room are exposed to the smoke flowing from the fire room, containing very high concentrations of CO and HCN, and very low oxygen concentrations, but the temperature decreases as the smoke flows away from the fire. This combination causes almost instant collapse from asphyxia and death within seconds. It is therefore considered that occupants of open areas of the flat would collapse and become unconscious, possibly before they are exposed to severe heat and burns.

114. Occupants taking refuge in a closed room would still be exposed to increasing concentrations of asphyxiant gases, which would increase rapidly once the upper part of the door had partly burned through. They would then rapidly be overcome by the very high concentrations or toxic gases and low oxygen concentration in the smoke. They would be comatose and likely to be dead before exposure to extreme heat.

115. A flashed-over fire consumes all or most of the combustible contents of a flat, including the bodies of any occupants. Unless the fire is extinguished within twenty minutes or so the contents are likely to be reduced mainly to ashes.

Effects of external fire penetration to Grenfell flats

116. Although it is considered that fire hazard development in Grenfell flats will have been similar to those measured during experimental fires involving items of flat interior contents such as upholstered furniture, either enclosed or with open windows, a complication for the Grenfell flat fires is that the fire is penetrating from outside rather than from ignition of items inside the flat.

117. I consider that during the early stages of these fires, if the windows are closed and remain mainly intact, the interior fire hazard development inside the flat will have been similar to those in the enclosed experimental fires. Instead of the fire starting in an item of furniture inside the flat, it is likely that at any Grenfell flat as the fire spreads up the building exterior to that flat level from below, flames and dense smoke entering the flat are generated first by combustion of exterior insulation material just below or adjacent to the flat, then spreading to other combustible structural materials in the window area, around the window frames.

118. Dense smoke and flames enter the flat from the fire in the exterior void between the cladding and the insulation via further voids, gaps, penetrations and leakage paths around the window frames.

progressively involving combustible structural materials around the windows. Dense smoke and flames from burning exterior cladding and insulation also penetrate through any partly open windows or other openings such as the kitchen window vent.

119. Depending on the ventilation conditions under which this smoke is generated (the extent to which combustion occurs under open conditions or is under-ventilated in restricted voids), the products may contain relatively low or higher concentrations of smoke, CO and HCN. As with an interior fire the smoke will form a gradually spreading and deepening layer under the ceiling, and the fire will gradually spread to include interior contents material near the windows. As long as the windows remain relatively intact, the subsequent fire and hazard development, and effects on occupants will be similar to that observed in experimental flat and house fires.

120. The evidence from Grenfell is still being obtained, but from my ongoing review there are signs of fire and smoke penetration into flats around the windows via the exterior cavity, gaps and voids around the windows, especially near the columns. Witnesses have also described flame and smoke penetration around the windows. While some witnesses first described flames penetrating through the kitchen window vent or an open window, others described flats filling with dense smoke before flames penetrated the flat. At some flats there was early partial failure of window glazing, enabling flames to enter and flame spread to items of contents close to the windows, such as blinds.

121. The relative contribution to the development of the toxic smoke atmosphere inside the flat from exterior cladding and insulation materials, and from interior contents and furnishing materials, during the early stages of the fire will depend on the extent of involvement of exterior insulation materials around the windows, the extent of penetration of smoke from cladding material burning directly outside or rising up the outside of the building from below, and the timing and extent of involvement of the flat interior contents. It may be possible under certain conditions that the extent of toxic smoke generation and penetration into the flat may be sufficient to overcome the occupants before significant involvement of the flat interior contents. Or it may be that smoke ingress occurs during the early involvement of structural materials around the windows and is then rapidly combined with smoke generated from burning contents around the window area (such as curtains or blinds), subsequently spreading to interior furniture. In this case a major effect of the exterior fire is as an ignition source to start the interior content fire. In practice the toxic smoke inside the flat will be partly derived from smoke entering from outside or generated by burning structural materials around the windows, and partly derived from burning flat contents. The proportions from these two sources will have changed during fire development, so that initially all the smoke will be derived from the structural materials and exterior fire, while at later stages most will be derived from the burning contents.

122. For situations where one or more of the flat windows are open, or where they fail soon after the arrival of the exterior cladding fire at the windows, the situation should also be similar to that described for experimental interior fires. One difference could be the contribution to smoke in the flat from the exterior fire. As stated, once an interior fire becomes established and a window is open, part of the hot smoke plume from the interior fire flows out through the upper part of the window opening while cold air flows into the room from outside through the lower part of the window. During the Grenfell incident there are flames and smoke rising up the outside below the flat window opening. A proportion of this exterior smoke rising from below will therefore be entrained into the air flowing into the flat through the window opening and contribute to the toxic smoke within the flat.

123. Another consideration is how long it would take for a post-flashover fire in a Grenfell flat to burn through the flat entrance door and spread into the communal lobby. A difference between the room-corridor test and the flat fire is that the room-corridor test represented a scenario in which both the air supply to the fire and the smoke plume flowed through the corridor entrance, representing the door to the outside from a small flat. For a Grenfell flat fire case the air enters and smoke plume exits from the window, with much of the fuel for the fire, especially during the
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early stages of the fire, consisting of structural materials in the window area and room contents near the window. The flat door is some distance away from the fire and ventilation, most likely separated from the flat fire (starting in the lounge, kitchen or a bedroom) by closed internal doors and the flat hallway corridor.

124. Once the flat fire becomes large and approaches flashover temperatures, although the upper layer will be hot enough to ignite fuels within the deeper recesses of the flat away from the windows, the air in these areas is likely to be very oxygen-depleted and unable to support combustion.

125. For this reason a significant time may pass (perhaps 10-20 minutes or more) after flashover, before the fire attacks a closed flat door. This phenomenon was observed during experimental fires at BRE where large fire loads were set up in similar configuration.

126. If the flat door is open, then the flat fire is likely to grow more rapidly, with a hot dense smoke plume accompanied by flames flowing into the lobby, eventually resulting in fire spread into the lobby.

Effects of gradual slow infiltration of toxic smoke into flats not directly penetrated by fire

127. During the Grenfell fire, the entire east face of the building exterior was rapidly engulfed in smoke and flames. The exterior fire and smoke then eventually spread round all four sides of the building. In addition, the exterior fire penetrated an increasing number of flats at different floor levels, igniting the content of the flats, producing further sources of fire and smoke. As shown in Figure 1, a number of routes then became available for this toxic smoke to spread into the flats.

128. One route of smoke spread into flats is by gradual leakage through gaps, penetrations and other ventilation routes from the exterior smoke plume surrounding the building. Another route is via exterior smoke being entrained into flats with open windows, or by smoke generated locally outside a flat, also entering via penetrations in the structure, spreading through the tower structure through leakage paths. A further route is via smoke being entrained or flowing into the lift shafts and stair shaft. The source of this smoke will have been partly from the exterior smoke plume, especially during the early stages of the fire before fire penetrated into flats at different floors. Once fire has broken into any of the flats, some of the smoke generated will have leaked into the common landings, lift shaft and stairs, even where the flat entrance door and the door to the stair were closed at any particular floor. Where flat entrance doors were open or burned through by the fire, then dense smoke plumes will have flowed out into the common areas. Where the stair door at the same floor was open, then large amounts of toxic smoke may flow into the stair shaft or penetrate the lift shaft.

129. During the period of several hours while the fire was burning there were therefore several routes whereby toxic smoke was able to penetrate flats on many floors. Where the flats were not directly affected by fire and the windows and flat entrance doors remained closed, there was slow smoke infiltration over a period of several hours, as reported by a number of occupants while awaiting rescue. Although occupants were able to reduce smoke infiltration by blocking gaps under doors with items such as wet towels, this did not eliminate smoke penetration. The main hazard from this smoke is a slow increase in carbon monoxide concentration in the flat and a slow increasing uptake and increase in %COHb by the occupants.

130. The extent of this hazard will have varied between different flats on different floors and with time during the course of the incident. As described for the Rosepark incident, it is possible for occupants of closed areas away from a fire to be exposed to an incapacitating dose of carbon monoxide over a period of an hour or more, which may lead to intoxication and collapse in the flat, and to death if the CO ingress is sufficient.

131. Occupants who were exposed to low levels of smoke in their flats for several hours before rescue would certainly have inhaled some carbon monoxide over this period.

132. The main routes by which smoke could infiltrate into a flat are:
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a) Smoke flowing up the building exterior, a proportion of which leaks into the flat through normal ventilation paths, penetrations and leakage paths through the flat exterior from outside or through partially open windows.

b) Smoke infiltrating into the flat from the lobby, mainly around and under the flat entrance door, or through any vents or penetrations between the lobby and the flat.

c) Smoke infiltrating through the interior Tower structure between flats on the same or adjoining floors via leakage paths and penetrations.

133. Considerable volumes of smoke were visible flowing up the side of the Tower throughout the fire. This was mainly on the east face initially, but subsequently affected the north, south and finally the west faces of the building over a period of several hours as the fire spread around the Tower.

134. It is inevitable that a proportion of this smoke will have infiltrated into the flats through normal passive air change ventilation paths. Average daily ventilation rate through infiltration and natural ventilation in UK dwellings has been reported as 2.49 air changes per hour. 27

135. Due to the summer weather, many occupants had windows at least partly open. Also, since the refurbishment, many occupants complained of draughts around the windows, and being more aware of cooking smells from other flats. Occupants reported smelling smoke at a very early stage of the incident and of smoke alarms going off in their flats.

136. Infiltration of smoke through the structure was an important feature of interior smoke spread between flats during a previous cladding fire incident at Lakanal House, being cited by the coroner as a particular feature of older blocks of flats. 28

137. A number of occupants also reported seeing smoke infiltrating into their flats through and around the windows.

138. For these reasons I consider that a proportion of the smoke entering flats, and increasing in density over a period of 1-2 hours, originated directly from the smoke flowing around and up the sides of the building, initially from the cladding fire and subsequently enhanced by the fire and smoke plumes flowing out of the windows of burning flats. It is also likely that a component may have infiltrated through the building interior structure.

139. Flat occupants have mentioned smoke penetrating into their flats around and under the flat entrance door to the lobby, despite the fact that these doors were mostly recently fitted as part of the refurbishment, and were fire doors with smoke seals. From the witness statements and 999 calls from occupants during the fire, my impression is that smoke penetration from the lobby was the main route of smoke filling individual flats up to the point when the exterior fire broke in through the windows. Smoke penetration was greatly enhanced when occupants opened their doors on most floors after approximately 01:30 hrs, when dense toxic smoke was reported in the lobbies. Occupants attempted to restrict the smoke by placing wet towels around and at the bottom of the door, with some variable success, but smoke concentrations in flats increased gradually over a period of an hour or more.

Smoke penetration into the lobbies

140. The lobbies and stair are in the core of the building. The lobbies are protected from smoke infiltration from exterior fires on any floor by a series of barriers comprised of the building exterior, the fire resisting construction of the flats and the fire doors to the flats. Protection from smoke penetration from other floors is also provided by the fire resisting construction. The stair has additional protection by being in a fire resisting shaft, with self-closing fire doors (with smoke seals) on each floor.


28 Coroner’s letters regarding Lakanal House fire 3 July 2009 to LFB and DCLG 28th March 2013
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141. The main route for smoke penetration into the common lobby on any floor is by smoke or fire first penetrating and developing in one or more of the flats on that floor, and then leaking around the flat entrance door to accumulate in the enclosed lobby. This process becomes much more rapid and severe if one of the flat doors is opened temporarily, or especially if left open by an escaping occupant, or if a flat fire burns through the flat door, enabling smoke and then flames to pass into the lobby.

142. The lifts open into the lobby, so are open to smoke penetration from any lobby. Since the lift shafts open on all floors, they also provide a potential mechanism of smoke spread between the lobbies on different floors.

143. Each lobby has vents opening into ducts designed to provide ventilation during normal use and smoke extraction during a fire incident. The design and operation of this system is described in detail in Dr. Barbara Lane’s Phase 1 report dated 12 April 2018. Each lobby has two vents near floor level on the south wall and two vents below the ceiling on the north wall. During normal use, an environmental fan at level 2 blows air up the south vents to provide fresh air ventilation into the lobbies on each floor near floor level. A fan in the rooftop plantroom extracts air from the north vents on all floor to vents on the roof.

144. If the smoke detector in any lobby is activated (for example by smoke flowing into the lobby from a fire in one of the flats on a particular floor), then both the north and south vents on that floor remain open. The rooftop plantroom fan is set to smoke extract mode and extracts smoke from the north fire floor vents of the fire floor, to be released from the roof. The level 2 system is switched to engage a smoke extract fan which extracts air from the south vents on the fire floor. Make up air to that lobby is supplied from the stair, which has an inlet on the roof. The system is thus designed to clear smoke from the lobby of the fire floor, while also maintaining negative pressure with respect to the stair, to prevent smoke entering the stair and keeping the stair clear of smoke.

145. When the extract system is activated on the fire floor, both the north and south vents are designed to be closed by motorised louvres (automatically opening vents) on all other floors, so as to maximise smoke extraction from the fire floor and seal off all other floors.

146. There is some question as to the performance of this system on the night of the Grenfell fire. This is being investigated by Dr. Barbara Lane, and I am working with Prof. Anna Stec to obtain and analyse soot samples from the vents, ducts and other parts of this system to determine how it functioned during the fire. The product of this analysis will be addressed in my Phase 2 report.

147. If this smoke extract system malfunctioned during the incident it may present a mechanism for rapid smoke spread between the lobbies on different floors.

148. Since the system is designed to extract smoke from the lobby of one floor only, it does not clear smoke from the lobbies of any other floor other than that at which it was first activated.

149. Another potential mechanism for smoke spread between lobbies on different floors is by ingress of smoke from the stair into the lobbies of different floors if the stair becomes filled with smoke from lobbies on other floors. Since witness accounts describe lower smoke density in the stair than in the lobbies of different floors it is unlikely that significant, if any, smoke spread occurred from the stair into any lobbies.

150. During the fire rapid smoke filling of the lobbies was reported on many floors over a short period of a few minutes. Although the timing and filling rate varied somewhat on different floors, my preliminary analysis indicates that rapid smoke filling of the lobbies most likely occurred over a period from approximately 01:20-01:35 hrs. There is some evidence that smoke filling of the lobbies

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29 B. Lane, Phase 1 report to the Inquiry, 12 April 2018: Chapter 14 The Performance of the protected stairs and lobbies, BLAR00000009, and Appendix J BLAR00000025.
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may have occurred somewhat earlier on the middle floors of the Tower than on the upper floors (those above approximately the 17th floor).

Smoke penetration into the stair

151. The stair is protected from smoke ingress from the lobbies on any floor by the self-closing fire door from the lobby on each floor. The main route for smoke spread into the stair on any floor is from smoke in the lobbies. A closed stair door should effectively limit smoke spread into the stair from a lobby, although it may not prevent it entirely. Over a period of minutes to an hour or more during the incident it is predicted that if there was dense smoke in any lobby that was not being extracted, this smoke would slowly penetrate into the stair. If there was a fire or hot smoke in any lobby, then the overpressure would increase the rate of smoke penetration into the stair at that floor. Since the lobbies on many floors became heavily smoke logged, then this process of smoke leakage into the stair occurred on many floors.

152. If the door to the stair on a floor where there is dense smoke in the lobby is opened temporarily by occupants, and especially if the door then fails to close after an occupant passes through it (or if the stair door is held open – for example by firefighter hoses being passed through it), then large volumes of smoke will flow into the stair.

153. There are witness accounts of the smoke conditions in the lobbies and stair by occupants escaping down the stair at different times throughout the incident. These accounts are still being obtained, but from those I have reviewed so far my preliminary opinion is as follows:

   a) While the lobbies started to fill with dense smoke from around 01:20-01:35 hrs on many floors, the smoke concentrations in the stairs were low until after approximately 01:30-01:40 hrs, so that occupants descending the stair up to this period reported relatively good visibility and no or limited problems from smoke inhalation.

   b) During this period the smoke density in the stair was considerably lower than that in the lobbies on most floors.

   c) During this period an occupant descending the stair described good visibility in the stair initially, but that as he descended he saw other occupants opening the stair doors on floors above and below him, as they did so he could see smoke entering the stair from these lobbies above and below, and the smoke density on the stair gradually increased as a result.\(^{30}\)

   d) A number of escaping occupants descending the stair also reported that the smoke density appeared to increase as they descended to the lower floors (from around the 10th floor).

   e) Some witnesses reported that smoke entered the stair from floors where firefighters held the stair door to the lobby open in order to lay hoses through. This allowed smoke to flow from the lobby into the stair on those floors and if the entrance door to a burning flat was open at the same time, enabled smoke to flow from a flat via the lobby and into the stair.

   f) From around 02:00 hrs onwards both lobbies and stairs were filled with dense irritant and toxic smoke at essentially all floor levels above the 3rd floor. The smoke in the stair was somewhat less dense and toxic that that in the lobbies.

Exposure hazards to occupants attempting to escape via the lobbies and stair or lift

154. Many Grenfell occupants attempted to escape from their flats via the common lobbies, then using the lift or stair. Depending on their floor and the time during the incident, some were able to escape in clear or relatively clear conditions, especially during the early stages of the fire, while others reported encountering dense irritant smoke in the common lobbies and/or in the stair. From my analysis of witness statements by flat occupants so far, my preliminary view is that rapid filling of the lobbies by dense smoke from around 01:30 hrs was a major deterrent and obstacle to

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\(^{30}\) Inquiry Witness statement of Richard Fletcher, IWS00000233
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occupants attempting to escape from their flats. Some decided not to enter the smoke and remained in their flats. Others felt their way to the stair entrance door through dense smoke, some returning to their flats and succeeding only after more than one attempt.

155. Others attempted to descend the stair but were forced to turn back due to the density and irritancy or the smoke (resulting in breathing difficulties), or because they met other occupants ascending the stair who encouraged them to turn and go back up to their flats, or to ascend to higher floors. At present it is not entirely clear why these occupants descended several floors but then turned and walked back up. Other occupants who descended at this time were able to do so safely.

156. Others continued down the stair at different times over a period of several hours. Some descended through the smoke in the stair and reached the ground floor exit, while some collapsed on the way down and were assisted to escape by the fire service. A number of occupants attempted to descend the stair but collapsed and died on the stair after managing to descend a several floors.

157. A number of persons died in the stair. All had very high blood carboxyhaemoglobin concentrations in their blood, consistent with collapse and death due to inhalation of asphyxiant gases. However, throughout the incident, including the period when the stair was filled with dense smoke between approximately 02:00-03:30 hrs, some persons succeeded in walking down the stairs. Some occupants escaping after 02:00 hrs collapsed and were rescued by firefighters after walking down a number of floors, or walked down but almost collapsed. My preliminary opinion is therefore that there may have been no period during the fire when it was impossible for occupants to walk down the stair to the ground floor without collapsing, even from the 23rd floor, but that there was a significant hazard due to the dense smoke and high concentrations of asphyxiant gases (CO and HCN) present. It is likely that those who were able to walk down the stair unaided had managed to avoid significant exposure to asphyxiant gases while in their flats, so that they were able to endure a few minutes exposure in the stair without inhaling a sufficient dose to cause collapse. Those who collapsed in the lobbies or stair (after 02:00 hrs), may have inhaled a significant dose of asphyxiant gases before leaving their flats, which rapidly reached incapacitating levels as they attempted to reach and walk down the stair.

158. The sequence and time scales over which physiological and pathological toxic effects occur during attempted escape down a stair is summarized in Figure 12. A common scenario is for a fire involving room contents such as an upholstered armchair occurring on the lower floor of an enclosed two-story house with the bedroom door closed but the lounge door left open. In experiments re-creating this scenario, the fire self-extinguished after approximately 10 minutes due to oxygen depletion and the effluents then mixed evenly throughout the available space, giving the maintained toxic gas concentrations and temperature listed in the figure.
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Before entering

A few seconds

A minute or so

On opening door: decide whether to enter smoke

Immediate loss of vision depending on smoke density

Further loss of vision due to eye pain and closure, respiratory pain and distress depending on concentration of irritants

Collapse and coma from asphyxia when a sufficient dose of gases has been inhaled or due to heat and burns, followed by death

Smoke OD/m 6
CO 5500 ppm
CO₂ 5%
O₂ 14.5 %
HCN 850 ppm
Acrolein 2 ppm
Formaldehyde 5 ppm
Temp: 60°C

A few hours or days:
Injury or death due to pathological effects on lungs, heart or brain from irritants, asphyxiants or heat

Figure 12: Sequence of hazards affecting a subject escaping from a bedroom of an enclosed two-storey dwelling with a fire on the floor below

159. The sequence of hazards faced by a bedroom occupant if they open the bedroom door at this time then attempt to descend the stair is as follows:

a) On opening the bedroom door an occupant attempting to escape must first decide whether to enter the dense smoke, or close the door and remain in the bedroom. If they step out onto the landing the first physiological effect is immediate loss of vision due to obscuration by smoke, which is followed within a few seconds by further visual impairment and eye pain from the effects of smoke irritants, and pain to the nose and chest with breathing difficulties.

b) Behaviour at this point depends upon the characteristics of the occupant, the density, irritancy and temperature of the smoke and their assessment of the relative hazards of shutting the bedroom door and remaining in place or attempting to escape down the stair. This judgement was even more challenging in situations such as Grenfell, because occupants had to descend several floors and had a very limited idea of how bad the conditions would be lower down and if they would be confronted by fire in the stair. Research on decision making during other fire incidents has shown that on average people are unwilling to enter smoke, or turn back, if the
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visibility is less than 3 metres. They may also turn back due to breathing difficulties or if the temperature of the smoke increases as they descend.

c) When people continue to move through smoke, their waking speed is reduced depending on the visibility and irritancy of the smoke. Normal waking speed for an average adult down a stair is approximately 1 m/s, although this varies depending on the age and physical capabilities of the individual. When groups of occupants descend a stair their travel speed also depends upon the occupant density in the stair (persons/m²). For a narrow (1 m width) stair such as at Grenfell, space to overtake is limited so that progress may be limited by slower individuals. Progress can also be affected by firefighters or other occupants attempting to ascend the stair while others attempt to descend. The maximum flow on an unobstructed stair (persons/minute) is limited by the occupant density and the stair width. In practice at Grenfell the stair holding capacity should had been more than adequate for the numbers of occupants, so that crowding should not have occurred. The greatest flow of occupants down the stair occurred during the earlier stages of the incident when smoke contamination was limited. From witness reports of Grenfell occupants most people descending the stair in dense smoke did so either as individuals or in small family groups.

d) Walking speed of individuals in irritant smoke with a visibility of less than 5 metres has been measured at 0.3 m/s, which is waking speed in darkness. This may vary somewhat depending on the situation. In particular, people progress more rapidly if they have a handrail to hold on to, as they did in the Grenfell stair. On the other hand, at Grenfell witnesses report difficulties due to breathing problems and the need to hold cloths to their faces, and issues such as assisting older relatives and carrying or assisting children.

e) The next major hazard facing a person descending in smoke is that they are continually inhaling asphyxiating gases, especially CO and HCN, with a dose building up in their body. When a person is actively walking down a stair they are exercising. They therefore breathe more than when they were in their flat, which increases the rate of uptake of these gases. People at Grenfell may already have inhaled some asphyxiating gases from smoke in their flats before entering the stair. Any exposure in the stair is thus added to this accumulating dose. There are no immediate effects of inhaling these gases at low doses, but when the inhaled dose reaches a critical level (after a few seconds or minutes) this leads to collapse and coma, followed by death within a further few minutes. In the house fire example scenario illustrated in Figure 12 the smoke was hot (60°C), but not sufficiently to cause pain or distress within a few minutes.

f) Figure 13 shows an analysis of the effects on a person during exposure to the smoke conditions in Figure 12, for the smoke gas and heat conditions on the stair during a furniture house fire with an open lounge door. The figure shows the effects of exposure to fire effluent when the upper floor bedroom occupant steps out on to the landing 10 minutes after ignition of the armchair fire in the open lounge on the floor below. For each hazard plotted, when any line exceeds 1 on the Y-axis this means that the exposure concentration of smoke (FED smoke) or irritants (FICirr) has exceeded a level considered to seriously impair escape. When exposure doses of asphyxiating gases (FEDIN) exceed 1 then collapse and loss of consciousness is predicted and when the exposure dose of heat (FED Heat) exceeds 1 then pain to exposed skin due to is predicted.

g) Upon opening the door the occupant is immediately confronted by smoke with an FEC of 12, which means that the smoke density is 12 x the concentration predicted to seriously impair escape attempts. Within a few seconds, exposure to this smoke causes severe irritant pain to the eyes, resulting in reflex eye closure, further impairing and inhibiting escape movement onto the landing. The smoke is also quite hot (60°C), which may further deter escape, but not hot enough to cause distress. The result at this stage is that the occupant is likely to
Causes of incapacitation and death at Grenfell fire from exposure to toxic fire products

decide that escape is too hazardous, to shut the bedroom door, and take refuge in the bedroom. If the subject attempts to descend the stairs, the speed of descent will be slow, and the next occurrence depends on the subject’s breathing pattern. If the subject holds their breath before being exposed to the smoke, then there is no intake of toxic gases until they are forced to take a breath. At this point the inhaled breath will be a deep one, with immediate incapacitation due to the respiratory tract irritancy. Due to the high concentrations of asphyxiant gases present, inhalation of a few breaths, or even a single deep breath, may result in syncope (fainting collapse). If the victim is rescued alive after collapse, then they may recover, or may suffer a further set of health problems, including brain damage, heart attack or lung inflammation over a period of a few hours to a few days, all of which can be fatal.

Figure 13: Fractional Effective Dose plots for the static fire hazard condition in Figure 12

160. The analysis assumes the subject is breathing normally throughout, at a rate associated with a moderate level of activity. This results in uptake of asphyxiant gases (HCN, CO, CO₂ and low oxygen) from the time the subject steps onto the landing. Incapacitation (collapse and loss of consciousness) is predicted when the F₁₅ exceeds unity, which occurs after 0.2 minutes (12 seconds). This is mainly due to the effects of inhaling hydrogen cyanide, which was present at the high concentration of 850 ppm in this experiment. Also considered in the analysis is the calculated time to incapacitation assuming there was no nitrogen in the burning fuel (armchair), in which case the most important asphyxiant gas is carbon monoxide. Uptake of carbon monoxide (increased by the presence of CO₂ due to the stimulatory effect on respiration) results in accumulation of a dose producing an incapacitating level of carboxyhaemoglobin (approximately 30-40%COHb) after four minutes exposure, which represents an FEDI₅ (no CN) of 1. The accumulating %COHb is calculated as part of the analysis and is shown in Figure 13. Carbon dioxide also becomes distressing at the exposure concentration of 5% after a minute or so, and would itself be capable of causing incapacitation after approximately 30 minutes. Also shown in Figure 13 are the accumulating doses of heat (FED heat) and of lung irritants, both of which hardly rise above the baseline up to four minutes. Since the smoke temperature is only 60°C only minor discomfort is predicted over this timescale.

161. The predicted results from this analysis are then that if a subject attempted to escape through these conditions:
Causes of incapacitation and death at Grenfell fire from exposure to toxic fire products

a) They would find the effects of the smoke exposure to be painful and distressing and be likely to turn back and take refuge in the bedroom (or flat at Grenfell).

b) When they took a breath at any time they are likely to collapse more or less immediately from the effects of the high concentrations of asphyxiating gases, especially hydrogen cyanide.

c) If they collapsed on the stairs or near the door, they would die within a further few minutes, mainly from the effects of carbon monoxide, with a blood carboxyhaemoglobin concentration of around 40-60% COHb.

d) If they were rescued at 4 minutes and treated with oxygen, they would be likely to make a rapid recovery (depending on their pre-existing health status). They might suffer some eye and throat irritation the next day, and develop a minor productive cough, but would be unlikely to suffer significant lung injury. There would be a possibility of suffering a heart attack or stroke due to the inhalation of fine smoke particles and CO. There would be a possibility of suffering long-term brain damage due to cerebral hypoxia.

e) The hazards faced by escaping Grenfell occupants are considered to have been similar to those in the example described and in the same sequence. The main variables are the density of the smoke to which Grenfell occupants were exposed, the concentrations of toxic gases (especially CO and HCN), the ratios of HCN to CO (whether the smoke contained mainly CO or if significant concentrations of HCN were also present) and the duration of exposure. The main difference between the illustrated scenario and the situation at Grenfell is that with the latter, occupants had to descend many floors (up to 23) compared to the one floor in the house experiment. Following more prolonged exposure to smoke at Grenfell, the risk of inhaling sufficient irritant smoke to result in lung oedema and inflammation is likely to have been greater than in the example.

f) A similarity between the scenario described and Grenfell is that exposure to heat in the stair was not a serious hazard, although sensation of heat may have been a factor influencing those who decided to turn back. The accounts from Grenfell witnesses which I have examined so far have described dense irritant smoke and breathing difficulties in the stair, but not exposure to extreme heat or flames. From the expert reports on the fire conditions, it is possible that some fire penetration and damage occurred in the common areas and penetrated the stair at certain floors, but I have not yet found accounts of escaping occupants encountering these conditions in the stair. It may be that the heat damage in the stair occurred at a late stage of the Grenfell fire after the last occupants came down the stair.

g) In summary from an analysis of the fire conditions and accounts of escaping occupants my opinion is that the main hazards in the stair were:

i. Difficulty in deciding whether to enter the lobby and stair smoke from any floor or whether to stay put.

ii. Difficulty in entering or moving through smoke down the stair due to seriously impaired visibility, smoke irritancy and breathing difficulties.

iii. Risk of collapse and death on the stair due to inhalation of asphyxiating gases (mainly CO and HCN).

iv. For occupants surviving significant smoke exposure in the stair, risk of post exposure lung, cardiovascular or neurological health effects.
 IMPORTANCE OF FORENSIC DATA ON BLOOD CARBOXYHAEMOGLOBIN, BURNS AND SMOKE DEPOSITION

162. The percentage of blood haemoglobin in the form of carboxyhaemoglobin (%COHb) in the blood of fire fatalities taken at autopsy or from fire survivors taken on arrival at hospital, provides important evidence to determine the causes of incapacitation and death of fire victims, especially when considered in relation to other evidence including blood cyanide, the extent and seventy of burns and the smoke deposition in the respiratory tract.

163. In addition to being a major direct cause of incapacitation and death in fires, the inhaled dose of CO in as %COHb provides an indication of the relative duration of exposure to toxic smoke at the fire scene and since all other toxic smoke products are present with CO, the extent of exposure to these products.

164. In particular with regard to persons dying at the fire scene, since CO is always present in smoke, the following apply:
   a) A finding of severe burns with low %COHb indicates that a subject died quickly in the fire most likely as a result of exposure to heat or burns before they had time to inhale a significant dose of smoke and CO.
   b) A finding of severe burns with >-20%COHb but < -40%COHb indicates that a subject may have died mainly as a result of burns, but almost certainly inhaled smoke and CO for long enough to be unconscious before receiving fatal burns.
   c) A finding of >-40%COHb indicates that a subject almost certainly died from smoke inhalation. If burns are present, these are most likely to have occurred after death from asphyxia.
   d) A finding of >-40%COHb and no burns indicates death most likely to have occurred as result of asphyxia.
   e) A finding of <=40%COHb and no burns indicates death most likely to have occurred as a result of inhalation of toxic smoke, but with a contribution from other gases such as HCN.

165. Data on blood %COHb concentrations are available for some of the Grenfell fatalities but not from others whose bodies were eventually consumed by the fire. However, as for the experimental fires described in the previous section, data from other fire incidents with similarities to some of the Grenfell scenarios provide an indication of likely effects on Grenfell fatalities.

166. Evidence of the extent to which carbon monoxide contributes to fire smoke deaths is provided from a study by Nelson31, of the distribution of %COHb levels in non-burned fire fatalities and non-fire fatalities from carbon monoxide poisoning in a United States database. The results, summarized in

167. Figure 14, show a distribution of concentrations measured in decedents, with the mode in the 70-80%COHb range for both CO poisonings (mostly from faulty space heaters and suicides in young males using vehicle exhaust fumes) and from fire fatalities. Although there is a considerable similarity between CO and fire deaths, the distribution for fire deaths is somewhat shifted towards lower %COHb concentrations than the CO deaths, indicating that although CO appears to be the main cause of death in the fire victims, the contribution from other factors is significant, probably involving hydrogen cyanide and low oxygen hypoxia. Also, the “CO deaths” have not resulted from exposure to CO alone, but to fumes containing other combustion effluents, although CO is considered to be the dominant toxicant present in such cases.

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Figure 14: Distribution of fatal %COHb in non-burned fire victims and non-fire CO poisoning cases (After Nelson)

168. A further consideration with the CO lethality data is that in practice few people survive an exposure of more than 50%COHb even if rescued and treated, although much higher levels are found in the bodies of decedents. This is because once a subject collapses and becomes comatose due to CO intoxication, CO uptake continues until the point is reached at which respiration and circulation cease. This is illustrated by comparing Nelson's data with those from a study by Pach32 (Figure 15), which shows the proportions of survivors from a sample of 260 CO poisoning cases. The data show that survival is rare above 50%COHb, increasing to around 0.67 in the 40-50%COHb range.

169. Also shown on Figure 15 are %COHb concentrations and survival outcomes for elderly subjects exposed to toxic smoke during the Rosepark care home fire.33 Despite the age and compromised heath status of these persons, the effect of exposure agree well with those reported by Pach. During this incident, in which occupants were exposed for up to an hour to toxic smoke, two persons with %COHb concentrations below 35%COHb were rescued conscious from the scene and recovered rapidly. Four persons with 40-50%COHB were either comatose or semiconscious at the scene and died in hospital, while eight fatalities recovered from the scene had no burns but %COHb concentrations in the 48-85% range.

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Causes of incapacitation and death at Grenfell fire from exposure to toxic fire products

Figure 15: Comparisons of %COHb concentrations in Rosepark fatalities, those dying in hospital and survivors with data from Pach on proportions of 260 CO poisoning cases surviving following presentation at different %COHb concentrations.

Overall in dwellings fires, approximately a third of fire deaths result from burns and two thirds from smoke exposures.

Figure 16 and Figure 17 below shows data for fatal cases for the London area (for the period 2002-2006) in different ranges of percentage carboxyhaemoglobin (%COHb) achieved, with the incidence of burns and severe (potentially fatal) burns in each range. 34

Figure 16 is for victims dying in the room of fire origin. The %COHb achieved provides an indication of the approximate duration of exposure and the extent to which death is likely to have resulted from exposure to toxic smoke or from burns. A low %COHb (<30%COHb), coupled with severe burns, indicates that the victims most likely died from burns before they had time to inhale a high dose of carbon monoxide. A high %COHb with a low incidence of severe burns indicates that the victims most likely died from exposure to toxic smoke and in particular carbon monoxide, with approximately 45-50%COHb and above is considered to represent a fatal exposure. These results therefore confirm that for the majority of victims dying in the room of fire origin, burns are a major cause of death, but some subjects survive long enough to inhale a fatal dose of asphyxiant gases without suffering from burns. In contrast to this, Figure 17 shows that hardly any victims dying in rooms beyond the fire room have serious burns, and the majority have fatal %COHb concentrations, confirming that the spread of toxic smoke is the main cause of death. Figure 17 includes the London fires data and those from a single incident in Scotland (the Rosepark nursing home fire) in which 14 persons died from toxic smoke exposure in locations remote from the fire enclosure.

Causes of incapacitation and death at Grenfell fire from exposure to toxic fire products

Figure 16: Distributions of %COHb, burns and serious burns in 109 fire fatalities for deaths in the room of fire origin in London 2002-2006

Figure 17: Distributions of %COHb, burns and serious burns in 67 fire fatalities dying in rooms remote from that of fire origin. Data from London 2002-2006 and a multi-fatality nursing home fire in Scotland.

173. The overall findings from these studies are that the %COHb levels in fatalities and in survivors at the time of rescue, when combined with the extent of burns, can be used to determine the extent of exposure to heat, smoke and toxic gases during a fire and the cause of incapacitation or death. For fatalities, the %COHb concentrations indicate not only the main cause of incapacitation and death but for burned bodies, the extent to which they were exposed to and overcome by exposure.
Causes of incapacitation and death at Grenfell fire from exposure to toxic fire products to toxic smoke before they were burned, and the probability that serious burns occurred before or after incapacitation or death.
Causes of incapacitation and death at Grenfell fire from exposure to toxic fire products

USING SMOKE DENSITY AND VISIBILITY AS A METHOD TO ESTIMATE TIME TO INCAPACITATION FROM THE EFFECTS OF ASPHYXIANT GASES

174. Although the %COHb and burns data from fatalities and survivors can provide useful information to establish the extent of exposure to smoke and heat, and causes of incapacitation and death it is more useful and better validated when it can be combined with information on the actual smoke and heat conditions to which fire victims were exposed throughout their exposure. For Grenfell, %COHb data are available for only 15 of the fatalities, and no data is yet available for exposed survivors. No measured data are available for the actual smoke, toxic gases and heat to which occupants were exposed, and due to the complexity of the developing fire in different locations throughout the incident, it is extremely challenging to attempt computer modelling of the fire conditions (although this aspect may need consideration for Phase 2 of the Inquiry).

175. Valuable information on the conditions in different flats, lobbies and the stair at different times is available from the witness statements of survivors and from 999 calls made during the incident. Witnesses have described their experiences of exposure to smoke and heat, and in particular the effects on them of exposure to smoke including the effects on visibility at different times and locations.

176. Although the absolute concentrations of smoke and toxic gases vary as the smoke moves away from a fire source and mixes with air, the relative concentrations of smoke and asphyxiant gases in the combustion products remain constants. When any fuel material burns in the fire the combustion products released contain certain yields of smoke particulates (soot), CO, HCN and other toxic products. As the smoke forms above the fire and moves away through the building, the ratios between the concentrations of smoke particulates and these gases remain constant, although the actual concentrations vary with the extent of dilution with entrained air.

177. In past studies measurements have been made of the yields of smoke and toxic gases from a wide set of materials under different fire conditions. These included many materials, such as particular polymers, present at Grenfell and involved in the fire. From this data set it is possible to use the ratios between the yields of smoke and gases to calculate the approximate concentrations of CO and HCN present at any time or location from the smoke density or visibility.

178. Using this method I have calculated the concentrations of these gases generated from a burning fuel mix of combustible materials common in building structure and contents, such as those that might have been involved in the Grenfell fire, including both the flat contents and the exterior materials.

179. The ratios between yields and concentrations of smoke particulates and these gases depends on the composition of the fuels and especially on the combustion conditions. From data on these ratios measured for different fuels in bench-scale or large-scale fire tests it is possible to determine gas concentrations for different smoke densities and calculate approximate times to incapacitation (collapse) from exposure to asphyxiant gases for these gas mixtures using FED analysis. As a simple limiting value it can be established that for smoke from any flaming fire involving any fuel mix, at a visibility distance of 10 metres (for reflected light), the concentrations of asphyxiant and other toxic gases will be low enough to have no significant deleterious effects on escape or survival for exposure periods of up to approximately 60 minutes. At higher smoke

Causes of incapacitation and death at Grenfell fire from exposure to toxic fire products

concentrations the estimated exposure time before a person walking through an escape route would collapse from asphyxiant intoxication is shown in Figure 18. Escape below a smoke layer requires a maximum upper layer temperature of 200°C so as to limit downwards heat radiation to a tolerable level.

180. Figure 18 shows plots for a “mixed fuel” package considered representative of the approximate mix in the Grenfell fire, for two combustion conditions: reasonably well ventilated combustion (ϕ ~ 1) and under-ventilated combustion conditions (ϕ ~ 1.5). The plot represents time to incapacitation for 50% of an exposed population (FED=1). In practice the relationships between visibility and times to incapacitation were similar between the different individual materials in the fuel package (average coefficient of variation 28%).

![Figure 18: Calculated time to collapse from asphyxia at different smoke visibilities.](image)

181. Figure 19 shows the calculated concentrations of CO and HCN from this fuel package for well ventilated and under ventilated combustion conditions.
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![Graph showing concentrations of CO and HCN at different smoke visibilities](image)

**Figure 19:** Concentrations of CO and HCN at different smoke visibilities for the times to occupant collapse shown in Figure 18.

182. For these calculations the CO and HCN concentrations are proportional to the smoke density per metre (D). The visibility distance for reflected light is approximately 1/D.

183. The relationships between visibility and time to collapse are useful for the interpretation of the conditions faced by Grenfell occupants and the hazards they faced during the fire.

184. Occupants taking refuge in flats during the fire would likely have been exposed to slowly increasing smoke infiltration, with gradually deteriorating visibility. While they remained in the flat the increasing smoke would have caused distress and influenced their decisions on whether to remain or attempt escape. As stated, in other incidents people tend to become reluctant to enter smoke in an escape route (in this case the lobby and stair), when visibility is below 3 m. At this visibility the smoke in a flat would be quite obvious, and is likely to have been irritant and odorous, resulting in some breathing discomfort but no serious effects on vision or breathing. Importantly, at 3 m visibility the concentrations of asphyxiant gases are too low to have significant effects on exposed persons for well over an hour.

185. At a visibility of 2 m the concentrations of asphyxiant gases, especially carbon monoxide, start to become significant. If smoke infiltration into a flat resulted in exposure to smoke with this visibility for up to an hour, occupants would inhale sufficient asphyxiant gases to cause loss of consciousness. If a person waited in a flat under these conditions for more than 30 minutes, then attempted to escape through thicker smoke in the lobby and stair, they would be in danger of collapsing on the stair from asphyxia after a few minutes as the dose of asphyxiants already inhaled while in the flat then increased rapidly as they inhaled higher concentrations in the lobby and stair.

186. Alternatively if a person left a flat with a visibility greater than 3 metres after waiting there for no more than approximately an hour, then they would have acquired only a small dose of asphyxiant gases. If they then entered a lobby and stair with a visibility of 2 metres, they should be able to descend to the ground floor within 5-10 minutes without any risk of collapse from asphyxia.
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187. For a person attempting to escape from a flat with good visibility through dense smoke on a lobby and stair they would start to load a dose of asphyxiants gases from the time they left the flat. For a 10 minute descent time to the lobby they would be able to descend without risk of collapse at visibilities down to approximately 0.75 m. Once visibility decreases to 0.5 metre (more or less hand barely visible in front of the face), then time to collapse is around 7 minutes for the average adult. At this visibility the CO concentration is approximately 2000-3000 ppm and the HCN concentration approximately 80 ppm.

188. Essentially this means that for a person with no previous exposure, the stair could be descended in reasonable safety with respect to danger of collapse down to a smoke visibility of around 1 metre. Once smoke density increases sufficiently to reduce visibility below this level, then danger of collapse in the stair from asphyxia becomes a serious risk.

189. For a person who has remained in a flat for some time before attempting to escape, the risk depends on the time for which they have been exposed to visibility levels in the flat worse than approximately 3-4 metres. If they remained in the flat under conditions worse than this for more than an hour, then collapse on the landing or in the stair becomes a significant risk when visibility on the landing or stair is less than approximately 2 metres.

190. From the statements of escaping witnesses and the toxicology data for those collapsing in the lobbies and stair, it is evident that some occupants succeeded in escaping down the stair through dense smoke at different times throughout the incident. A number of these persons collapsed or almost collapsed on the way down, and were assisted to escape. In a few cases others attempting to escape during the same period collapsed while in the lobby or within a few metres of the flats they had taken refuge in for an hour or more.

191. Many who succeeded in escaping from high floors down the stair without collapsing did so at early stages of the incident (before approximately 01:40-02:00 hrs). Up to this time the extent of any smoke exposure within the flats was minimal and although there was dense smoke on the landings from around 01:30 hrs, the visibility in the stair was generally reported as quite good (equivalent to approximately 1-3 metres depending on the exact time of descent.

192. Some or those escaping between 02:00-04:00 hrs would have experienced significant smoke exposure within their flats before attempting to descend the stair. They therefore already had a significant dose of asphyxiants in their blood before the entered the lobbies and stair, which by this time had visibilities down below approximately 1 metre. They therefore continued to inhale toxic gases at an increasing rate after leaving their flats, and were in danger of collapsing in the lobby or on the stair within a few minutes. Young children are more susceptible to rapid collapse because they inhale toxic gases at approximately twice the rate of adults.

193. Other escaping occupants may have taken refuge in flats with limited smoke penetration before escaping into the stair, so were able to make the descent (or most of the descent) without reaching the point of collapse. There is also a range of susceptibility within the population, so that younger, fitter, adults were less likely to collapse than others.
Causes of incapacitation and death at Grenfell fire from exposure to toxic fire products

THE POSSIBLE TOXICITY PERFORMANCE OF MATERIALS PRESENT AT GRENFELL TOWER

194. Different materials contribute to toxic fire hazards depending on the extent to which their combustion products form components of the time-concentration curves for toxic smoke and gases within the breathing zone of each Grenfell occupant.

195. For the contribution from any specific burning material the time-concentration curve for the toxic products at any location depends on:
   a) the mass loss burning rate of the material (kg/s)
   b) the yields of each toxic product (for example kg CO per kg material mass burned)
   c) the volume into which the products are dispersed (kg/m³)

196. The yields of toxic products depend on:
   a) the elemental composition of the material
   b) the organic composition of the material
   c) the combustion conditions (for flaming fires, the fuel: air equivalence ratio [φ])

197. For a typical dwelling fire such as that illustrated in Figure 3, the time-concentration curves can be measured directly in a full-scale fire test or calculated with reasonable accuracy using a fire dynamics model. For the test data shown in the figure the item consumed by the fire was an armchair with a known mass and composition, the volume into which the combustion products were dispersed was the internal volume of a single flat or a two-storey house, the time-concentration curves for toxic gases were measured directly and the yields were calculated from the measured values.

198. For Grenfell, assessment of the contribution to the toxic hazards faced by occupants from different fuel items is more complicated, for the following reasons:
   a) Many occupants were exposed in many different locations within the Tower at different times, including the different flats, common landings and stair.
   b) Many different materials (fuel packages) in different locations were involved at different times during the fire.
   c) The volumes into which the combustion products were dispersed varied between the outside air around the Tower (for a proportion of the products from the cladding fire and the contents of any burning flat with an open window), the interior volume of different individual flats, the interior volumes of the common landings and of the stair.
   d) A proportion of the combustion products released into the fire and smoke plumes around the outside of the Tower at any floor level (derived either from burning external materials or from fire plumes flowing out from the window openings of burning flats) will have re-entered the Tower through leakage paths and window openings at higher floor levels.
   e) The mass burning rates of the cladding and insulation with time at different locations has not yet been fully evaluated.
   f) The times of fire ignition and development in each flat are not fully known, and the extent to which the fire and smoke plume from each flat flowed into the common lobbies and the stair at different floor levels and different times can only be estimated approximately.
   g) The patterns and extent of fire development in the combustible structural materials in the window surrounds for each flat can also only be estimated approximately.
   h) The combustible fire loads in each flat, and the identities and compositions of the materials involved are unknown and the combustion conditions under which they burned.
   i) While the mass and composition of the external cladding materials is known or can be measured from surviving samples, the exact combustion conditions under which they were decomposed during the fire are not fully established.
For these reasons estimates of the contributions of combustion products from specific materials to the concentrations of toxic smoke products in any particular locations within the Tower at different times are likely to be possible only within quite wide ranges of uncertainty. For this Phase 1 report I have considered the sources of the main fuel packages involved in the fire at different times, and their likely general contribution to the toxic smoke within the Tower at different times and locations. I have also made some simple calculations to illustrate the probability that different fuel materials are likely to have made a major or minor contribution to the effect of exposure on Grenfell occupants. It is intended that these assessments will be improved for Phase 2 of the Inquiry, as more information become available from tests, other investigations and from more detailed fire modelling calculations.

I have identified three major categories of fuel packages involved in the Grenfell fire, in terms of their location and effects on the developing fire and toxic smoke hazards:

a) The combustible parts of the cladding and insulation, consisting of the low-density polyethylene (LDPE) core of the ACM rainscreen cladding panels and the aluminium foil-faced Celotex polyisocyanurate (PIR) insulation.

b) The combustible materials in the window surrounds, including the aluminium-faced extruded polystyrene (XPS) sandwich panels between the windows, the polyvinylchloride (uPVC) window sills and panels, the rubberised panels beside the windows (EDPM damp proof course)\(^{38,39}\) and various pieces of PIR and polyurethane foam (PUR) used as inserts and fillers.

c) The interior flat contents (furniture and fittings and other general items of contents) and combustible items such as surfaces of the interior doors.

**Major fuel packages involved in the fire, their composition and combustion products**

Of these, the cladding and insulation materials are important because they are likely to have been the first items ignited other than in Flat 16, were present as a large mass of combustible material, and produced very large amounts of toxic smoke both during the early stages and throughout the fire, affecting almost all of the Tower.\(^{40}\) The combustible materials surrounding the windows, although present in smaller amounts than the insulation and cladding, were likely to have been important for the early stages of toxic smoke production and fire development in each flat, in combination with smoke and flames from the exterior cladding and insulation materials.

The combustible contents of each flat are important because for each flat and collectively, they constitute a set of large fire loads that were consumed during the incident. In relation to the hazards to occupants remaining in any individual flat, the contents became progressively involved in each flat fire, producing toxic smoke and heat which, together with toxic smoke from the window surrounds and exterior, led to incapacitating and then fatal conditions in each flat penetrated by fire. For occupants of flats not penetrated by fire, or occupants in the lobbies or on the stair, smoke from the burning contents of different flats (including any smoke entering those flats from the exterior fire or the window components) became a major source of exposure to toxic smoke spreading though the Tower interior.

**Fuel Mass**

The masses of different fuels involved are estimated as follows:

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\(^{38}\) B. Lane, Phase 1 Report to the Inquiry 12th April 2018: Section 8 The performance of the protected stair and lobbies, BLAR00000003_8 paras 8.10.34 (for XPS) 8.8.4 (for EDPM)

\(^{39}\) L. Bisby, Grenfell Tower Inquiry Phase 1 – Expert Report p 83 paragraph 328, LBYR00000001

\(^{40}\) J.L. Torero Grenfell Tower: Phase 1 report 23rd May 2018, JTOR00000001
Causes of incapacitation and death at Grenfell fire from exposure to toxic fire products

**Cladding and insulation**

204. The Celotex insulation on the spandrel panels consisted of two layers of 80 mm thickness aluminium foil-faced PIR foam (Celotex RS5080), estimated density 2.8 kg/m².\(^4\) That on the columns was 100 mm thickness foil-faced PIR foam (RS5100) estimated density 3.38 kg/m². Based on a total spandrel area of 2940 m² and total column panel area of 944 m² area of this gives a total PIR mass of approximately 19,650 kg. The aluminium faced Reynobond rainscreen cladding covered the same area and included a 3 mm thickness LDPE core.\(^5\) At an estimated density of 0.92 g/cm³ this gives 2.77 kg/m², and a total mass of ~11,544 kg.

**Windows**

205. On the outside face of the Tower between the windows were composite panels consisting of 2 mm thickness facings and 25 mm thickness core consisting of extruded polystyrene.\(^6\) There were 6 1.5 m² panels on the east and west faces of the Tower and 4 3 m² panels on the north and south faces. With an estimated density of 0.85 kg/m³ this gives a mass of 1.43 kg per narrow panel, representing a total of ~826 kg on the Tower.

206. The other main component associated with the windows was the inside sill, jambs, and architrave. This consisted of 9.5 mm thickness polyvinylchloride (uPVC) with a foam backing.\(^7\) At an estimated density of 1.5 g/cm³ this gives a mass of 14.25 kg/m², or 26.26 kg/window.

**Flat contents**

207. The total combustible fuel load in each flat and its composition is obviously variable depending on the items in each individual flat. In order to estimate the magnitude of this fuel package in relation to the other components I have summed the masses of a set of items of contents consisting of typical furniture, floor covering and contents in the lounge, bedrooms, kitchen and bathroom of a one or two bedroom flat. From this I have estimated a total approximate combustible mass of 660 kg in a two-bedroom flat and 470 kg in a one bedroom flat.

208. The different fuel packages are compared on a per flat basis in Table 1 below. In the table, the PIR and PE masses represent the mass of combustible components in insulation and cladding outside each flat. The PS panel mass per flat is also on the outside surface between the windows. The PVC is around the inside of the windows of each flat. Comparing these gives an indication of the approximate magnitudes of the potential sources of toxic combustion products for each flat.

| Table 1: Approximate masses(kg) of combustible fuels per flat |
|------------------|---|---|---|---|---|
|                  | PIR | LDPE | PS  | PVC | Flat contents |
| 1 bedroom flat   | 66.3| 35.3 | 2.9 | 78.8| 471 |
| 2 bedroom flat   | 158.4| 90.1 | 7.2 | 183.8| 661 |

209. This shows that the flat contents provides the largest combustible fire load, but that the PIR insulation and LDPE in the cladding also provide large fire loads of smaller but comparable magnitude. The PS presents a relatively minor component, but the PVC around the inside of the

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\(^4\) L. Bisby, Grenfell Tower Inquiry Phase 1 – Expert Report p73 paragraphs 284 and 286, Dimensions from Figure 5 p 26, Figure 8 p 28 and Figure 36 p 60 LBYR00000001.

\(^5\) Celotex RS5000 product data sheet. Celotex. Hadleigh. Ipswich IP7 6BA. See also CEL00000008

\(^6\) L. Bisby, Grenfell Tower Inquiry Phase 1 – Expert Report p 70 paragraph 264, LBYR00000001

\(^7\) L. Bisby, Grenfell Tower Inquiry Phase 1 – Expert Report p 88 paragraph 353, LBYR00000001
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windows of each flat also provide a large fire load, significant in comparison with the cladding, insulation and contents.

210. In comparing the significance of these different potential sources of toxic smoke within the flats and Tower interior, it is important to consider that the first three are burning on the outside of the building, so that only a proportion of the smoke evolved from them may enter a flat, but also that the order in which these components became involved in the fire runs approximately from left to right. So that the first smoke to which flat occupants were exposed came from the PIR, and LDPE then the PS, PVC and other minor window components and finally the flat contents. For occupants-taking refuge in flats remote from the fire for an hour or more, but exposed to smoke infiltration from the outside and the lobbies, or in the lobbies or stair, the source was derived from a mixture of all these sources in varying proportions at different times.

Composition of fuels

211. The toxic products evolved from burning materials depend partly on their chemical composition, in terms of polymer type and elemental composition, so it is necessary to make some assessment of the composition of the components of the different fuel packages in order to evaluate their contribution to toxic smoke in the Tower.

212. Although the exact compositions of the specific fuel materials present in the cladding, flat window surrounds and flat contents are as yet unknown, from the product specifications and related information on the different materials types present in the cladding and window materials it is possible to identify the main types of polymers present. From general information on the types of polymeric materials present in common items of flat contents (such as upholstered furniture, bedding, bookcases and cupboards) it is also possible to estimate the composition of the fuel material mix in the average flat contents.

213. Table 2 shows the measured net heat of chemical combustion, stoichiometric oxygen demand and elemental composition for each of 14 common polymeric materials used in furnishings and building products. These include the main polymer types present at Grenfell, and have been used for a detailed measurements of smoke and combustion gas yields over a range of combustion conditions considered relevant to the Grenfell incident. For the specific cladding, insulation and window materials present at Grenfell, samples have been obtained for which further testing is planned as part of Phase 2 of the Inquiry. Although there may be minor differences in the composition and toxic product yields between these specific materials and those from the samples of the same generic polymers used for the assessment in this Phase 1 report, I consider that these differences due to specific polymer formulations are likely to be small in comparison to the uncertainties in other aspects of the assessment.

Causes of incapacitation and death at Grenfell fire from exposure to toxic fire products

Table 2: Composition of test materials

<table>
<thead>
<tr>
<th>Material</th>
<th>( \Delta H_f )^1 ( \text{kJ.g}^{-1} )</th>
<th>( \gamma_o )^2 ( \text{g.g}^{-1} )</th>
<th>Elemental composition (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( C )</td>
<td>( H )</td>
<td>( O )</td>
</tr>
<tr>
<td>bouclé acrylic/ wool/ polyester 38/38/24 mixed fibre fabric</td>
<td>26.5</td>
<td>2.02</td>
<td>63.1</td>
</tr>
<tr>
<td>bouclé acrylic/ wool/ polyester 38/38/24, FR back-coated</td>
<td>25.0</td>
<td>1.91</td>
<td>59.0</td>
</tr>
<tr>
<td>CMHR polyurethane foam- FR</td>
<td>24.5</td>
<td>1.87</td>
<td>56.45</td>
</tr>
<tr>
<td>low density polyethylene (LDPE)</td>
<td>44.8</td>
<td>3.42</td>
<td>85.5</td>
</tr>
<tr>
<td>medium density fibreboard (MDF)</td>
<td>16.9</td>
<td>1.35</td>
<td>47.90</td>
</tr>
<tr>
<td>polyacrylonitrile (&gt;85%) fabric</td>
<td>30.5</td>
<td>2.33</td>
<td>65.62</td>
</tr>
<tr>
<td>polyamide 6</td>
<td>30.5</td>
<td>2.33</td>
<td>63.68</td>
</tr>
<tr>
<td>polyisocyanurate PIR rigid foam</td>
<td>24.5</td>
<td>1.87</td>
<td>63.5</td>
</tr>
<tr>
<td>polymethylmethacrylate rigid foam</td>
<td>25.2</td>
<td>1.92</td>
<td>60.33</td>
</tr>
<tr>
<td>polystyrene</td>
<td>40.2</td>
<td>3.07</td>
<td>92.26</td>
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<td>polyvinylchloride PVC</td>
<td>16.8</td>
<td>1.28</td>
<td>38.44</td>
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<tr>
<td>plywood</td>
<td>17.8</td>
<td>1.36</td>
<td>46.32</td>
</tr>
<tr>
<td>acrylic/ cotton/ polyester 52/31/17 velour mixed fibre fabric</td>
<td>26.2</td>
<td>2.00</td>
<td>64.4</td>
</tr>
<tr>
<td>wood Pinus sylvestris</td>
<td>18.1</td>
<td>1.38</td>
<td>49.2</td>
</tr>
</tbody>
</table>

\( \Delta H_f \) = net heat of chemical combustion \( \gamma_o \) = Stoichiometric oxygen demand

214. Apart from the general polymer type, the main relevance of the data in Table 2 is the carbon content, which affects the generation of smoke particulates and carbon oxides during combustion, the nitrogen content, which affects the potential to generate hydrogen cyanide, and the halogen content, which determines the potential to generate irritant acid gases.

215. The most important combustible polymers present on the Grenfell exterior were:

a) the low-density polyethylene (LDPE) in the ACM rainscreen cladding.

b) the polyisocyanurate foam (PIR) in the Celotex insulation.

Versions of both of these polymers are included in Table 2. Some Kingspan phenolic foam was used in some locations on the Tower as insulation instead of Celotex\(^{49}\). This is understood to have been mainly over the lower floors of the Tower, mostly below the areas burned in the fire.

216. The materials in the window surrounds at Grenfell included the following, versions of which are included in Table 2.

a) Polystyrene (in the sandwich panels between the windows).

b) Rigid PVC (in the window sills and surrounds).

c) Polyurethane foam (above the window interior).

d) Celotex PIR

The other main material not shown in Table 2 was the rubberised membrane material, which is mainly a carbon-containing product likely to have similar smoke and gas yields to LDPE and small amounts of Kingspan phenolic foam.

\(^{49}\) L. Bisby, Grenfell Tower Inquiry Phase 1 – Expert Report p 78 paragraph 304, LBYR00000001
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217. With respect to the flat contents, Table 2 includes examples of most common polymeric materials including:
   a) Cellulosic materials: wood, plywood, medium density fibreboard (MDF) commonly used in most items of furniture including, dining chairs and table, bookcases and cupboards and the structural components of soft furniture
   b) Upholstery and foam materials used in upholstered furniture and bedding, and in clothing fabrics (wool mixtures, polyacrylonitrile (acrylic), polyethylene, polyester, polyamide (nylon), combustion modified polyurethane foam).

218. I have used this data to make an assessment of the likely overall fuel mix and elemental composition of the contents of a typical Grenfell one or two bedroom flat in order to estimate the overall fuel carbon and nitrogen mass, for comparison with the fuel carbon and nitrogen masses present in the exterior cladding and insulation materials.

219. With respect to potential smoke toxicity, the most important elements in the materials burned are the carbon, nitrogen and halogen contents. The carbon content is important as the source of smoke particles, which are formed mainly of carbon soot, organic irritants, and as the source of the asphyxiant gas carbon monoxide (CO) and the respiratory stimulant carbon dioxide (CO₂). The nitrogen content is important as the source of the asphyxiant gas hydrogen cyanide and lung irritant nitrogen oxides (NOₓ). The halogen content (chlorine and bromine) is important as a direct source of acid gases (HCl and HBr), which cause eye irritation and breathing difficulties when present in the smoke (and potential lung problems after exposure in survivors). The halogen content is also important in reducing the efficiency of combustion, thereby enhancing the conversion of fuel carbon to CO and of fuel nitrogen to HCN. The percentages of these elements in materials producing toxic smoke at Grenfell are summarised in Table 3. It should be noted that although the molecular compositions of specific polymers from different sources are very similar, they can vary slightly in different commercial products. This can apply in particular to the nitrogen content of specific PIR and PUR products and the chlorine content of uPVC. Where halogens are present as flame retardant additives, the proportions of chlorine and/or bromine may vary somewhat in different product formulations. Any minor differences between the formulations of the actual Grenfell materials and the formulations described here will not significantly vary the results of this toxic hazard analysis.

| Table 3: Mass percentages of carbon, nitrogen and chlorine in Grenfell related materials |
|---------------------------------|--------|-------|--------|
| Polysocyanurate PIR             | 66.3   | 6.15  | 3.65   |
| Low density polyethylene LDPE   | 85.6   | 0     | 0      |
| Polystyrene foam (PS)           | 92.3   | 0     | 2      |
| Polyurethane foam (PUR)         | 56.5   | 8.2   | 2.53   |
| Polyvinylchloride (PVC)         | 38.4   | 0     | 56.7   |
| Mixed flat contents (approximate)| 50     | 3.7   | 2.0    |

Note: these proportions are for materials tested from Table 2, not for actual products present at Grenfell and may vary slightly in commercial products with different formulations.

220. The first five rows of Table 3 show data for the combustible structural materials in the Grenfell insulation, cladding and window assemblies. In order to compile the approximate data for the mixed flat contents I have estimated the carbon and nitrogen content of the common items of rigid and upholstered furnishings, floor covering, and other items used to assess the total fire load of the flats for Table 1. As Table 3 shows, all combustible materials have a high carbon content, so produce smoke particles, CO and CO₂ when they burn. They differ considerably in their nitrogen content, which is high in PIR and PUR, but absent from LDPE. PS and PVC. Items of flat contents contain a variety of natural and synthetic polymers, often in the form of composites with a mix of
different polymers in the same material or item. The total mass of flat contents is dominated by cellulosic (wood-based) items, mostly made from composite boards with a decorative laminate, giving a total estimated carbon content of approximately 50% by mass. Although the nitrogen content of wood is very low, that of composite materials is increased by the use of adhesives, and melamine in decorative laminates. The measured nitrogen content of the medium density fibreboard in Table 2 was 3.7%. Items of upholstered furnishings and bedding have a significant nitrogen content in the PUR foam cushions (~8%), and in the fabric covers (~11%). Taking these into account with other items I estimate a nitrogen content of approximately 3.7% for the total combustible contents of a typical dwelling such as a Grenfell flat. The halogen content of typical rigid furniture is generally low (0.62% Cl in MDF), but present as an additive in upholstered furniture and bedding foam, and in back-coated fabric covers (~8% Br in Table 2). Vinyl (PVC) materials have a high chlorine content, and are present as vinyl fabrics and in PVC power cables, vinyl laminates on shelving, and as additive in plastics such as TVs and PCs. These constitute a relatively small component of the total fuel load in the contents of a flat, giving an estimated average halogen content of around 2%.

221. Based on this assessment I consider that while all materials involved will have produced somewhat similar yields of smoke and CO, depending on the specific polymer and combustion conditions, a major potential source of HCN, especially during the early stages of fire involvement outside any individual flat, is the PIR insulation. Once fire penetrates a flat and involves the upholstered furniture and bedding, then this also becomes a major source of HCN. With regard to halogen acid gases, the PIR is a potential source, but the main potential source of large quantities of HCl is the UPVC window surrounds, which were involved as the flames started to break into any flat around the windows.

Yields of smoke and toxic fire gases from different materials under different combustion conditions

222. For all the materials described in the previous section the yields of smoke particulates, asphyxiant and irritant gases released when they burn are highly dependent upon the combustion conditions, and in particular on the fuel:air equivalence ratio (\(\varphi\)). When fuels burn under well-ventilated combustion conditions, with excess air (\(\varphi<1\)), then combustion tends to be efficient, with low yields of smoke and toxic gases. But when they burn in under-ventilated (fuel-rich) combustion conditions, air (\(\varphi>1\)), with insufficient air to support combustion, then combustion become inefficient, with large increases in the yields of smoke and toxic gases. A common example of this problem is the danger associated with poorly maintained gas appliances, when a poor air supply to the flame can result in the production of dangerous yields of carbon monoxide. Another aspect also reducing combustion efficiency are the presence of halogen fire retardants.

223. The effects of ventilation on the yields of the most important toxic gases (CO and HCN) from the polymers in Table 2 are shown in Figure 20 and Figure 21.
Causes of incapacitation and death at Grenfell fire from exposure to toxic fire products

Figure 20: Relationships between \( \varphi \) and CO yields for different materials\(^{35,36} \)

Figure 21: Relationships between \( \varphi \) and HCN yields for different materials\(^{35,36} \)

The results show that while there are some variations between different polymers, in almost all cases the yields of these two asphyxiant gases are low under well-ventilated combustion conditions, start to increase near stoichiometric conditions (equivalence ratio \( \varphi = 1 \)), then increase steeply up to an equivalence ratio of 1.5-2.0. Similar increases also occur for other toxic products of inefficient combustion, including smoke particulates and organic irritants. The main exceptions from this pattern are for materials containing halogenated fire retardants (mainly chlorine and or bromine), which reduce combustion efficiency across the range. This shows particularly for the high CO yield from PVC and for both CO and HCN yields from the halogen treated Boucle fabric.
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225. Table 4 shows the yields of smoke and combustion gases measured from each material under very well-ventilated flaming combustion conditions (φ=0.5) and under-ventilated combustion conditions (φ=1.5-2.0). Smoke yields are expressed in mass terms (g smoke particulates/g fuel mass burned) and in terms of visibility as smoke extinction area (ASEA) (=2.3 x Dm) (m²/kg). The average measured ratio between ASEA and particulate yield was 4.8 for well-ventilated fires and 7.1 for under ventilated fires.

<table>
<thead>
<tr>
<th>Polymer</th>
<th>Phi</th>
<th>Eff Ht</th>
<th>CO₂</th>
<th>CO</th>
<th>HC</th>
<th>O₂</th>
<th>Esmoke</th>
<th>ASEA</th>
<th>HCN</th>
<th>NO</th>
<th>NO₂</th>
<th>HCl</th>
<th>HBr</th>
<th>SO₂</th>
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<tr>
<td>LDPE¹</td>
<td>0.49</td>
<td>41.5</td>
<td>2836</td>
<td>15</td>
<td>85</td>
<td>3166</td>
<td>0.045</td>
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<tr>
<td></td>
<td>0.49</td>
<td>31.6</td>
<td>2644</td>
<td>61</td>
<td>82</td>
<td>2416</td>
<td>0.110</td>
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<td>Wood</td>
<td>0.51</td>
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<td>1696</td>
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<td>13</td>
<td>1293</td>
<td>0.005</td>
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<td>plywood</td>
<td>0.52</td>
<td>17.3</td>
<td>1774</td>
<td>6</td>
<td>11</td>
<td>1324</td>
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<td>1</td>
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<td>MDF²</td>
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<td>18.9</td>
<td>1680</td>
<td>7</td>
<td>24</td>
<td>1283</td>
<td>0.003</td>
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<td>PAN³</td>
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<td>39</td>
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<td>2320</td>
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<td>Polyamide 6</td>
<td>0.51</td>
<td>28.4</td>
<td>2216</td>
<td>3</td>
<td>34</td>
<td>2166</td>
<td>0.019</td>
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<td>PIR⁴</td>
<td>0.52</td>
<td>24.6</td>
<td>2340</td>
<td>48</td>
<td>1374</td>
<td>33</td>
<td>75</td>
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<td>PMMA</td>
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<td>1881</td>
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<td>CMHR PU⁵</td>
<td>0.59</td>
<td>25.3</td>
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<td>48</td>
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<tr>
<td>Boucle non-FR²</td>
<td>0.50</td>
<td>24.4</td>
<td>2128</td>
<td>60</td>
<td>19</td>
<td>1861</td>
<td>26</td>
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<tr>
<td>Boucle FR²</td>
<td>0.44</td>
<td>19.3</td>
<td>1486</td>
<td>130</td>
<td>81</td>
<td>1474</td>
<td>90</td>
<td>456</td>
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<td>Velour²</td>
<td>0.52</td>
<td>26.3</td>
<td>2240</td>
<td>41</td>
<td>51</td>
<td>2005</td>
<td>19</td>
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<td>Acrylic, cotton, PE 52/31/17</td>
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<td>PVC²</td>
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<td>10.7</td>
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<td>177</td>
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<td>815</td>
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</tr>
</tbody>
</table>

For the 14 material data set in Table 4, the average for ASEA/ Esmoke = 4.8 (standard deviation 1.45) for well ventilated flaming and 7.1 (standard deviation 1.29) for under-ventilated flaming. These ratios are somewhat lower than those obtained by Mulholland (ASEA/ Esmoke = 8.7), which may be
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due to the use of a white light emitter rather than a red laser.\textsuperscript{50} A human viewing incident or reflected light through smoke may be subject to similar effects, adding somewhat to the uncertainty relating to human perception of smoke obscuration.

227. For under-ventilated flaming conditions, the CO and HCN yields are sensitive to upper layer temperature, equivalence ratio and flame zone oxygen concentration, so can be closer to 0.2 kg/kg in some compartment fires, especially post-flashover.

Yields of smoke and toxic combustion gases under the combustion conditions at Grenfell

228. The data in Table 4 are relevant to the estimation of toxic smoke production at Grenfell because, as shown in Figure 20 and Figure 21, the yields depend on the combustion conditions under which the different fuel packages burned at different stages of the fire.

229. Apart from the local conditions in Flat 16, the first fuels to be involved in significant amounts producing a large fire and smoke plume on the Tower exterior are the LDPE in the ACM rainscreen cladding and the PIR in the insulation.

230. The LDPE cannot burn while encased in its aluminium skin, but does so when it melts and drips out from the aluminium outer layers and also when they start to delaminate and expose the LDPE core. Since these processes occurred in the open air on the outer surface of the Tower, it is likely that most of the flaming LDPE combustion occurred under well-ventilated flaming combustion conditions, with relatively low yields of CO and smoke, similar to those shown in the upper section of Table 4 (CO \textasciitilde 15 mg/g and smoke particulates 0.045 g/g (ASEA 268 m\textsuperscript{2}/kg).

231. The combustion conditions for the PIR insulation are more complex, because at least initially, it is believed to have been burning in the enclosed cavity behind the rainscreen cladding on the columns and spandrels, and also in cavities associated with the window surrounds. Under these conditions it is likely that the combustion conditions would rapidly become under-ventilated, resulting in relatively high yields of CO, HCN and smoke, somewhat similar to those shown in the lower section of Table 4 (CO 937 mg/g, HCN 20 mg/g, smoke particulates 72 mg/g (ASEA 495 m\textsuperscript{2}/kg). Where the rainscreen cladding then fell away, exposing some of the PIR insulation remaining (as occurred especially over many areas of the spandrels), then the polymer was exposed to more ventilated combustion, which is likely to have produced lower yields of CO, HCN and smoke closer to those shown in the upper half of Table 4.

232. For this reason it is likely that smoke generated from combustion of the PIR during the earlier stages of involvement around any particular flat, a proportion of which entered the flat via the cavities around the windows and other leakage paths, would have been produced with under-ventilated, higher yield conditions. Smoke carried up outside higher levels of the Tower, derived from the fully-developed fire lower down where the cladding had been lost, may have been produced under somewhat lower yield conditions, although still containing significant yields and concentrations of CO, HCN and smoke. This is partly due to the halogen content of the PIR somewhat reducing its combustion efficiency, even for well-ventilated combustion conditions. The smoke rising up the outside of the Tower would also have been considerably diluted by air entrainment, reducing the overall concentrations of smoke particulates and toxic gases compared with that generated in the cavities.

233. Where flames moving up the exterior of the building penetrated the cavities around the windows and ignited the combustible materials in the window surround it is likely that these also burned under relatively under-ventilated combustion conditions as long as the flames occurred within the cavities. This involves the smoke from the burning PIR cladding on the columns and spandrels,

\textsuperscript{50}Mulholland, G. and Croarkin, C., \textit{Specific Extinction Coefficient of Flame Generated Smoke}, Fire and Materials, 24(2000), pp. 227-230
and that from additional items of PIR, phenolic foam and PUR around the windows. Since the PS panels between the windows are on the outside for the building, once the PS is exposed by delamination of the aluminium facing it is likely that the PS burned under relatively well-ventilated combustion conditions. The CO yield then depends on the presence of any halogen additives, which are likely to have been present in the PS.

234. Once the flat contents in the area around the windows start to burn as fire develops inside the flat, the combustion efficiency depends initially upon the extent to which the flat has already filled with smoke from the burning exterior and window surround fuels, and the extent of involvement of the PVC window surround. As the fire grows, the fire within the flat becomes progressively more under-ventilated, producing high yields of CO and HCN from the burning contents, mixing with that from the cladding and window surround materials. When the windows fail completely, the fire transitions to immediately lethal flashover conditions, also with high CO and HCN yields.

**Contribution of different fuel packages to the development of fire hazards within the Tower**

235. The contribution of different fuel packages to the developing fire and toxic smoke hazards within different flats will have varied somewhat with time and their location within the Tower.

236. The first flats to be affected by the fire were those on the east side of the Tower, especially in the Flat 6 and Flat 1 position on each floor. During the early period after the fire spread from flat 16, involved the exterior cladding and insulation and spread up the tower (~01:15-01:25 hrs), there was minor smoke infiltration into these and other flats around the Tower based upon the fire spread dynamics and witness statements. Before the fire reached the exterior at the level of each flat this smoke was derived mainly from the diluted exterior smoke plume flowing up the side of the building, which in some cases activated flat smoke detectors, and the smoke was disturbing to flat occupants, visibility within the flats was generally good, varying from a slight haze, to denser smoke (for example flats on the east side with their windows partly open). As the fire came up closer below these flats more smoke entered the flats, so that some sleeping occupants awakened to find their flats filled with smoke. At this stage there was still a metre or more of visibility in even the most exposed flats insufficient to prevent occupants evacuating their flats and therefore containing low concentrations of asphyxiant gases.

237. Once fire travelling up the exterior cladding and insulation reached and involved the column and spandrel areas, and then the window surrounds of a flat, then the flats filled rapidly with smoke containing concentrations of CO and HCN likely to have been sufficient to cause incapacitation within a few minutes. Flats in the Flat 6 location on each floor were penetrated by smoke and flames (mostly at and around the kitchen windows). Overall, these occupants were alerted to events in different ways and were able to evacuate into the lobbies before they became seriously smoke-logged.

238. Some of this smoke then leaked out around the flat entrance door and any other leakage paths into the common lobby. Where occupants opened the entrance door of a burning flat, and especially where they failed to close it behind them, then large amounts of highly toxic smoke flowed into the lobbies at different floor levels (over the period ~01:20-01:35 hrs). It is likely that during this early stage the dense smoke and asphyxiant gases filling Flat 6 on each floor and flowing into the lobbies were derived mainly from the burning exterior cladding, insulation and structural materials around the windows.

239. As the fire then spread and developed within the flat contents, large quantities of combustion products were added to those entering the flat from outside or being generated around the windows. Any person remaining in a flat at this time would have been overcome by exposure to asphyxiant gases within a few minutes. In the event all occupants of Flat 6 on all levels left their flats (although some former Flat 6 occupants subsequently died elsewhere in the Tower (or outside it).
Causes of incapacitation and death at Grenfell fire from exposure to toxic fire products

240. This smoke, derived partly from smoke entering from the exterior, partly from burning structural materials around the windows and partly from the burning contents, then either gradually or rapidly continued to fill the common lobbies outside Flat 6 (depending on whether the flat door was closed or open). This resulted in dense smoke in the lobbies at all floor levels from around 01:30-01:40 hrs depending on the floor level and whether the Flat 6 door was shut.

241. As the number of flats developing interior fires, and the size of these fires increased, it is likely that the proportion of the smoke in the lobbies derived from burning flat interior contents increased compared with the proportion derived from the exterior and window surround materials.

242. Based on my assessment of the likely development of the smoke conditions and from my ongoing review of witness statements and 999 calls, it is likely that occupants who remained in their flats for an extended period (mainly those in Flat 5, 4, 3, 2 on each floor) were first exposed to slow infiltration of thin smoke derived mainly from the exterior smoke plume up to approximately 01:30 hrs. Visibility within the flats is likely to have been good and the smoke insufficient to have presented a direct hazard, but capable of activating smoke alarms within some of the flats. From around this time, as dense smoke filled the lobbies, the flats not directly affected by fire started to be penetrated by smoke infiltrating around the flat entrance door and other leakage paths. This process continued for up to two hours or more while some occupants took refuge in these flats. From witness accounts, although some smoke was reported as entering the flats from outside around the windows, the main source of smoke entering the flats before fire reached the flats from outside was likely to have been from the lobbies. For any flat where there were no flames at the exterior windows (and where flat windows were closed), but smoke flowing up outside, I consider that the concentration of smoke and toxic gases in the exterior plume were likely to have been considerably lower than those in the lobbies, due to the higher air entrainment ratios in the exterior plumes compared to those in the lobbies.

243. The result of these processes would have been that the concentrations of smoke and asphyxiant gases gradually increased over a period of an hour or more. Visibility within the flats decreased considerably and the occupants gradually inhaled asphyxiant gases (CO and HCN), with a significant dose building up in their bodies, but insufficient to cause incapacitation in most flats. The smoke and toxic gases in the lobbies from around 02:00 hrs will have consisted of an increasing component derived from burning flat contents as the fires spread within neighbouring flats, but also a significant component derived from the burning exterior and window surround materials.

244. When fire and toxic smoke eventually penetrated these flats from outside, then these occupants were rapidly overcome by asphyxiant gases. Those who attempted to escape via the lobbies and stair were then exposed to very dense smoke and high concentrations of toxic gases in the lobbies and to a lesser extent in the stair. Within each refuge flat, these materials were also the main source of smoke entering the flat, up until the time the fire reached the outside of that flat, at which point the large and rapid increase in toxic smoke concentrations inside that flat were derived initially from the burning exterior materials and window surround materials, but then the flat contents as these became involved in the fire (all over a period of a few minutes).

245. With regard to smoke and fire penetration into individual flats, the two-bedroom flats were most vulnerable because the aggregate areas of the windows and of the cladding and insulation outside them was greater than that for single bedroom flats. The two-bedroom flats are also most relevant because most occupants took refuge in them and most deaths occurred in two-bedroom flats. In the following sections I have estimated the potential contributions made by different materials to the developing hazards in a typical two-bedroom flat. For the exterior cladding and insulation materials, I have considered the main potential source of toxic smoke entering the flat to be derived from the column and spandrel materials outside that flat (effectively the materials covering one floor between the top of the windows of that flat to the top of the windows on the floor below). I consider that most of the combustion products entering any flat from outside while the fire is directly outside that flat, will be derived from these locally combusting materials. As the smoke plume...
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rises up the side of the building it is diluted by entrained air, but a small proportion may infiltrate flats at each progressively higher floor through gaps or more may penetrate through open windows. Greater amounts of smoke from this ascending plume may enter where windows higher in the tower are open or when the glazing fails and falls out.

246. Table 5 shows my estimates of the possible contribution to toxic smoke inside a flat derived from the main fuel package components in Table 1, from the time when the exterior fire starts to burn the cladding and insulation around a two-bedroom flat. These estimates are not intended as a calculation model of what actually happened during the fire, but as an illustration of the possible toxic smoke conditions developing in a two-bedroom flat (and the lobby beyond it) if the smoke products from the fuel masses shown in Table 5 in column 3 (Mass [kg] total) were present and burned, and if the products from the proportions of these masses shown in column 4 (Mass [kg] 5%) were dispersed homogeneously within the volume of the flat. The toxic gas concentrations and smoke visibility are calculated from the estimated mass concentrations in the flat for each fuel and the yield for each fuel shown in Table 4. Estimated time to asphyxia is the reciprocal of the FED, for incapacitation due to asphyxia calculated as described in Appendix B. These estimates should be treated as preliminary and subject to revision for Phase 2 as more information becomes available. They are intended to illustrate the possible comparative contributions from different fuels during progressive stages of flame and smoke penetration and development within a flat and the effects of the conditions to which occupants could be exposed.

247. Table 5 shows each fuel and the conditions under which it is combusted (ρ <1 represents well-ventilated combustion, while ρ>1 represents under-ventilated combustion). The mass (kg) of each fuel type is then shown, including that outside each flat, that around the windows and the total mass of mixed fuel contents inside a flat (from Table 1). For the LDPE ACM the mass shown is the total mass outside each flat. For Table 5 I have estimated that 100% of this is burned in the fire. This is based on my observations during visits to the Tower, that the ACM was lost outside flats badly affected by fire. In practice some of the PE may have been lost as molten droplets, or with sections of ACM cladding falling off the Tower during the fire rather than being burned in situ. For the PIR insulation the mass represents 50% of the total, on the basis that approximately 50% may have been burned while 50% remained on the building exterior after the fire (based on my observations during visits to the Tower). For the exterior PS panels it is estimated that 100% was burned during the fire. For the PVC and flat contents the total fuel masses are shown in column 3, since these components are both inside the flat.

248. The next column shows the masses of fuel materials decomposed, for which the combustion products are accumulated into the flat. For the LDPE, PIR and PS the masses represent a theoretical estimate that the smoke products from 5% of the mass of the exterior fuels burned penetrate into the flat, while 95% is carried away in the smoke plume up the outside of the building, and therefore does not enter the flat. For the PVC around the window interior the estimate is based on decomposition of 5% of the PVC mass during the early stage of the fire, with 100% of the products from this mass generated into the flat. For the flat contents the data are based on combustion of 0.5% of the total flat fuel mass during the early stage of the fire. The following columns in the Table show the calculated concentrations of CO₂, CO, HCN and the visibility through smoke if these fuel masses were decomposed and the products distributed evenly throughout the interior volume of the flat. The final column shows the calculated time to asphyxia (loss of consciousness) for flat occupants exposed to the smoke products at these constant concentrations. From this I have estimated the relative contributions of the smoke products from the different fuels to the developing toxic hazards in each flat and the lobbies beyond them.
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### Table 5: Two bedroom flat – potential mass concentrations and gas concentrations from different fuels

<table>
<thead>
<tr>
<th>Material</th>
<th>Mass (kg) total</th>
<th>Mass (kg) 5%</th>
<th>Mass Conc Kg/m³ (5%)</th>
<th>CO₂ %</th>
<th>CO ppm</th>
<th>HCN ppm</th>
<th>Smoke Visibility (m)</th>
<th>Time to Asphyxia (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LDPE ACM</td>
<td>&lt;1 90¹</td>
<td>4.7</td>
<td>0.025</td>
<td>3.5</td>
<td>598</td>
<td>0</td>
<td>0.25</td>
<td>160</td>
</tr>
<tr>
<td>PIR insulation</td>
<td>&lt;1 79²</td>
<td>4.0</td>
<td>0.022</td>
<td>2.1</td>
<td>2157</td>
<td>95</td>
<td>0.39</td>
<td>23</td>
</tr>
<tr>
<td>PS window</td>
<td>&lt;1 71</td>
<td>0.4</td>
<td>0.002</td>
<td>0.02</td>
<td>94</td>
<td>0</td>
<td>2.66</td>
<td>&gt;180</td>
</tr>
<tr>
<td>PVC window</td>
<td>&lt;1 184</td>
<td>9.2</td>
<td>0.051</td>
<td>1.7</td>
<td>4414</td>
<td>552³</td>
<td>0.22</td>
<td>13</td>
</tr>
<tr>
<td>Flat contents</td>
<td>&gt;1 661</td>
<td>3.3⁴</td>
<td>0.018</td>
<td>1.5</td>
<td>2506</td>
<td>164</td>
<td>0.29</td>
<td>10</td>
</tr>
</tbody>
</table>

¹Estimated 100% burned ²Estimated 50% burned ³HCl ⁴0.5% burned

During actual fires the fuel burning rates and concentrations of smoke and toxic products are not constant, but increase continuously as long as the fire is burning as illustrated in Figure 3. The times to asphyxia shown in Table 5 indicate relative toxic hazards in terms of tolerance times once the concentrations in the table have been reached.

### Contribution to smoke within flats and lobbies from rain screen ACM cladding

249. **Table 5** shows that there was an estimated total of ~93 kg of LDPE in the ACM panels outside each two-bedroom flat, and almost all of these panels have burned away from the flats attacked by the fire. For the purposes of this assessment I have therefore estimated that all the LDPE was consumed in the fire as the panels burned and delaminated. In practice the situation was somewhat more complex as some of the panels fell off and some of the LDPE fell away as flaming droplets.⁵¹ Because the LDPE was exposed on the outside of the building exterior I estimate that combustion would have been relatively efficient, producing low yields of smoke and toxic gases. The calculations in the table are based upon yields measured at a ϕ value close to 1. Depending on the exact local combustion conditions at different locations the yields could have been slightly lower or higher in practice (between 0.5 – 2 times the values used for the table). The results show that if the combustion products from 5% of the LDPE burning on the Tower exterior outside each flat penetrated into the flat, then the flat would contain dense smoke with virtually no visibility (24 cm). The smoke would contain approximately 617 ppm CO, which would slowly accumulate in flat occupants as they inhaled it, but if the conditions remained constant at these levels it would take 155 minutes for occupants to accumulate blood carboxyhaemoglobin levels causing loss of consciousness.

250. Based on this assessment it is my opinion that if as little as 5% of the combustion products from the burning ACM outside each flat penetrated the flat before the windows failed, then the flat would be filled with very dense smoke and almost zero visibility. This would result in some distress and breathing difficulties, but would not cause serious incapacitation (other than on escape capability) for an extended period. If the amount of products penetrating the flat was only 1% of the total, the smoke would still be very dense with a visibility of around 1 metre inside the flat or in the lobby if the flat door was held open.

251. On this basis I estimate that sufficient smoke from the burning LDPE outside a flat may have penetrated into and beyond the flat during the early stages of the fire, so as to cause distress and affect escape capability from other flats where it penetrated into the lobbies.

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⁵¹ J. Torero Grenfell Tower: Phase 1 Report, 23rd May 2018, JTOR00000001
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Contribution to smoke within flats and lobbies from PIR insulation

252. The contribution to smoke within the flats and lobbies from the burning Celotex PIR is more complicated to assess due to its location on the Tower exterior, due to the combustion properties of the material and its combustion behaviour during the Grenfell incident.

253. Celotex PIR is a rigid foam insulation board with an aluminium foil covering on each side. The PIR foam is relatively resistant to ignition, containing some halogen fire retardant additives. Also, as an insulation product it is normally installed within walls, or behind a layer of low combustibility or inert lining such as plasterboard. As such it would not normally be exposed to fire and since most fires occur in a flat contents (as with the original Grenfell fire in Flat 16), any PIR present is unlikely to be involved at all in a typical domestic fire, and particularly not during the critical period of early fire growth when the contents are involved and when hazardous conditions develop inside a dwelling.

254. This was the case with an example large scale fire test account provided for my consideration by Kingspan, involving measurement of hazard development during a fully furnished room burn. For this test a fire was ignited in a furnished room rig. The back wall of the rig was covered by a layer of plasterboard, behind which was placed a layer of PIR insulation in one test, with inert mineral wool insulation in another test. The results showed that in both tests lethal amounts and concentrations of toxic smoke were produced in the test room, with high concentrations of both CO and HCN similar to those shown in Figure 3 for the BRE house and flat furniture fires. A finding from the tests provided by Kingspan was that the toxic product concentrations were similar in the tests with and without the PIR, indicating that the PIR had remained protected and was not decomposed during the fire.

255. I found somewhat similar results when I participated in full-scale ISO9705 room corner tests at BRE, involving a room fully lined with aluminium-foil covered Celotex PIR. In these tests a fire of a specified heat output was set in the corner of the room, to measure the extent of fire involvement and spread of fire and the toxic products evolved from the wall linings. In these tests the medium size flame source proved insufficient to ignite the wall linings, which were protected to some extent by the aluminium foil covering (as was the PIR on the Grenfell exterior panels), so that little or no smoke of toxic products were evolved, except from the corner source fire. I have also found exposed PIR foam to be somewhat resistant to ignition and steady burning when tested in the ISO9700 tube furnace, requiring a high furnace temperature of 700°C to provide maintained flaming. This resistance of the product to combustion was also demonstrated by another paper provided to the Inquiry by Kingspan, in which an insulation and cladding a system was subjected to a relatively small fire source in a medium scale ISO 13785-1 standard test carried out by Efectis. In these tests, while there was considerable combustion of the ACM-PE, the involvement of the PIR insulation, and the production of combustion products from it, was minor.

256. When PIR and aluminium foil faced PIR foam are tested in other configurations and conditions the results can differ somewhat. For the BRE ISO room tests, and later room-corridor tests, aluminium

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faced PIR boards were cut into strips to form cribs. In this form the PIR ignited rapidly using a small alcohol ignition source and burned vigorously. The purpose of these tests was to measure the yields of smoke and toxic products from PIR when it burns with flaming combustion, over a range of combustion conditions. When tested in this way PIR not only burned vigorously, but produced high yields of smoke, CO and HCN during under-ventilated flaming, with yields similar to those shown in Table 4. In other tests of a PIR panelled room in the ISO 13784-1 test, with the standard burner and with an additional room fuel contents load in the form of a wood crib, considerable involvement of the PIR panels was obtained and high concentrations of HCN were evolved.\textsuperscript{56}

257. In order to assess the combustion performance of Celotex PIR at Grenfell it is necessary to compare the findings from these tests with the fire conditions and performance during the Grenfell fire. From the reports of other Grenfell experts and my examination during my visits to the Tower, it is clear that, while large amounts of partially decomposed Celotex insulation survived the fire and remain on the building, large amounts were also burned away during the fire. Although a detailed quantification of the mass of PIR burned during the fire has not yet been completed, I observed significant differences between the fate of the PIR on the columns and that on the spandrels. The PIR on the columns is almost completely burned away over most of the Tower. For the spandrels, the PIR is completely absent in some areas and almost intact in others. The PIR on the spandrels was in the form of a double layer of aluminium foil-faced panels. The inner panels were placed against the Tower exterior, with the windows installed within them, and the outer panels were placed onto the inner panels facing into the cavity behind the ACM panels. Over most of the exterior surface of the burned floors of the Tower, the outer PIR panels have been burned away or are badly charred. The inner panels are relatively intact or only slightly charred in most areas. Based on these observations I have estimated (subject to further assessment) that over the burned areas of the Tower approximately 50% or the PIR outside each flat has been combusted.

258. In order to estimate the likely yields and masses of smoke, CO and HCN evolved from the burning PIR it is necessary to consider both the mass burned and the combustion conditions under which it was burned. In Table 5 I have presented two sets of data, one set for a case under which all the PIR combusted was burned under relatively well-ventilated combustion conditions, at an equivalence ratio just below 1 (producing relatively lower yields of CO, HCN and smoke) and another case under which all the PIR combusted (50% of the total present) was combusted with under-ventilated combustion conditions at an equivalence ratio of 1.5-2.0.

259. During the incident at Grenfell the actual combustion conditions will have varied somewhat in different locations at different stages of the fire. Based on my observations at the Tower and the accounts in the reports of Prof. Bisby and Prof. Torero, as well as witness accounts I consider it is possible that fire spread to involve the exterior PIR insulation and ACM cladding on the column adjacent to the kitchen windows and the spandrels. The fire appears to have burned in the cavities behind the ACM cladding. Flames are likely to have spread within the cavity over the column, up from each floor and into a flat on the floor above near the window. Flames may also spread within the cavity on the spandrel. The smoke from this fire is likely to enter the flat above around the window, as well as the fire appearing to involve combustible materials around the window, as was observed by witnesses. Spread of fire up the columns was also clearly evident in the images from the Grenfell fire. On a preliminary basis I consider that any fire burning the PIR inside the cavity behind the spandrel and particularly behind the column ACM, is likely to have become rapidly under-ventilated, producing higher yields of smoke and toxic gases penetrating into the flat above.

260. As the exterior fire developed to the extent that the ACM panels fell away, then any remaining insulation material would be exposed to an increased air supply, so that combustion at this later stage should be more efficient, with somewhat lower yields of smoke and toxic gases.

\textsuperscript{56} Crewe R et al. Fire Performance of Sandwich Panels in a Modified ISO 13784-1 Small Room Test: The Influence of Increased Fire Load for Different Insulation Materials. Fire Technology 6 April 2018.
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261. Also, some of the PIR surface may have been decomposed under non-flaming conditions. Under these conditions the rate of decomposition is slow, but relatively high yields of smoke and toxic products may be formed.

262. The calculations in Table 5 are based upon yields measured at a $\phi$ value close to 1 and between 1.5-2.0. Depending on the exact local combustion conditions at different locations, the yields could have been slightly lower or higher in practice (between 0.5 – 2 times the values used for the table).

263. The results for the well-ventilated case ($\phi < 1$) show that if the combustion products from 5% of the PIR burned on Tower exterior outside each flat penetrated into the flat, then smoke density in the flat would have increased until there was virtually no visibility (34 cm). The smoke would then contain approximately 2200 ppm CO and 95 ppm HCN, which would slowly accumulate in the flat occupants as they inhaled it. If the conditions remained constant at these levels it would take only around 20 minutes for occupants to accumulate blood carboxyhaemoglobin and cyanide levels sufficient to cause loss of consciousness.

264. In practice I believe that the combustion conditions producing the early smoke penetrating the flat are more likely to have been under-ventilated ($\phi > 1$), with higher yields of smoke, CO and HCN producing concentrations in the flat closer to 6000 ppm CO and 390 ppm HCN. At these concentrations flat occupants inhaling the smoke are predicted to collapse, mainly as a result of cyanide inhalation, after approximately two minutes of exposure.

265. Based on this assessment it is my opinion that if as little as 5% of the combustion products from the burning PIR outside each flat penetrated the flat after the flames reached the flat exterior but before the windows failed, then the flat would be filled with very dense smoke and almost zero visibility. This would result in some immediate distress and breathing difficulties. If the flat occupants did not evacuate immediately, then after a few minutes exposure (between approximately 2-25 minutes depending up on the exact conditions), they would collapse unconscious due to the combined asphyxiant effects of inhaling CO and HCN.

266. If the amount of products penetrating the flat was only 1% of the total, the smoke would still be very dense with a visibility of around 1-2 metres inside the flat, or in the lobby if the flat door was held open, but the lower asphyxiant gas concentrations could be inhaled for an extended period in excess of 40 minutes if the conditions remained constant.

267. On this basis I estimate that sufficient smoke from the burning PIR outside a flat may have penetrated into and beyond the flats during the early stages of the fire outside any flat, to cause distress and affect escape capability from other flats where it penetrated into the lobbies. I also estimate that the concentrations of asphyxiant gases in the flat would be sufficient to cause collapse within a few minutes exposure, depending on the pattern of fire development outside and within the flat.

Contribution to smoke and toxic gases within flats and lobbies from PS panels between windows

268. Where flats were seriously affected by fire, the aluminium-faced polystyrene panels between the windows are no longer present. During the fire I believe the polystyrene would have melted and the panel delaminated, exposing the dripping PS to flaming combustion. For the analysis in Table 5 I have therefore estimated that 100% of the PS was burned. Since the PS was on the outside face of the building the combustion conditions would have been well-ventilated. The data in the table are for an equivalence ratio just below 1. The material shown in Table 2 from which the yields were measured was for PS without any flame retardant additives. It is likely that the PS in the Grenfell panels contained some halogen additives, which increase the yields of CO and smoke, as well as releasing acid gases.

269. Although the PS panels covered a large area outside each flat, the low density and limited thickness of the panels resulted in the exposed PS mass being much lower than that of the LDPE
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and PIR, at approximately 7 kg per flat. Also, because of its position, it is likely that most of the combustion products were carried away in the exterior fire and smoke plume. For the table I have estimated that combustion products from 5% of the PS penetrated each flat. Since burning PS produces high yields of irritant smoke, this would have made some contribution to the accumulating smoke inside the flat, but the contribution to the CO concentration in the flat would have been minor.

270. On this basis I estimate that sufficient smoke from the burning PS outside a flat may have penetrated into and beyond the flats during the early stages of the fire outside any flat, to cause distress and affect escape capability from other flats where it penetrated into the lobbies. I estimate that the contribution to the concentrations of asphyxiant gases in the flat from this source would have been minor.

Contribution to smoke and toxic gases within flats and lobbies from PVC panels around the window interior

271. The wide window sills and linings at Grenfell contained a large mass of PVC for each flat. From the dimensions in Prof. Bisby’s report I estimate a total of approximately 184 kg for a two-bedroom flat. As the heat and flames from the exterior fire penetrated and developed around the windows this PVC began to decompose and then burn. PVC dehydrochlorinates rapidly at temperatures above 280°C, producing a high yield of the irritant acid gas hydrogen chloride (HCl), and when ignited burns to release high yields of CO. As this HCl mixes into the burning fire plume consisting of the partially burned gases from all the fuel materials, it reduces the combustion efficiency, and increases the yields of smoke, CO and HCN from these other burning fuels.

272. At Grenfell the pattern of PVC involvement would have been gradually increasing decomposition in local areas around the windows as the flames penetrated into the flat around the window cavities, especially in the area near the columns. During this early stage of a flat fire, as the flat filled with smoke entering from the burning exterior materials, a proportion of the combustion products from the PVC (and other window surround materials including items of PIR and PUR foam and the rubber membrane at the side of the windows), would add to the smoke. For illustration in Table 5 I have used a point where 9.2 kg (5%) of the PVC has decomposed, and the products are dispersed throughout the flat. Under these conditions the first toxic products of concern derived from the PVC alone, are dense smoke sufficient to produce effectively zero visibility (0.22 m) and a hydrogen chloride concentration of 562 ppm, which would be painful to the eyes and throat, causing breathing difficulties. The calculated CO concentration in the flat derived from the PVC is 4414 ppm, which is sufficient to cause collapse in exposed occupants after 13 minutes.

Combined effects of toxic smoke originating from the exterior ACM cladding, PIR insulation, PS panel, and the PVC window surround

273. From this analysis it is my opinion that fire and smoke hazards within each of the flats developed in a sequence as follows:

a) Slow minor infiltration of smoke from the exterior smoke plume derived from the exterior ACM cladding, insulation and PS fire flowing up and around the Tower as the fire grows up the east side of the Tower.

b) Rapid penetration via voids and cavities around the windows of dense toxic smoke and then flame from fire involving exterior PIR insulation materials, particularly in the cavities on the columns, but also those of the spandrels as the fire reached the level of each flat. This also involves some products derived from the PS panel and the ACM panels.

67 L. Bisby, Grenfell Tower Inquiry Phase 1 – Expert Report p 84 paragraph 333, LBYR00000001

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c) Rapidly developing involvement (over a time frame of a few minutes) of combustible materials surrounding the windows, including items of PIR and PUR foam, rubber and PVC.

As described, the contribution from each of the major products individually is sufficient to produce dense toxic smoke within the flat and adjacent lobby within a few minutes. But in practice the contributions from each burning item are summed as they penetrate into the flat, further increasing the concentrations of irritant smoke and toxic gases. On this basis I consider that the toxic smoke and gases penetrating a flat during the minutes before the flat contents become significantly involved are sufficient to present a substantial hazard. Although the smoke may not prevent flat occupants from escaping into the lobby (assuming this is the first flat to suffer fire penetration on any floor), once it has spread into the lobby (for example from the open door of the flat of fire origin on that floor), then the dense smoke in the lobby may inhibit escape attempts via the lobby by occupants of other neighbouring flats on the same floor.

d) Subsequent rapid spread and involvement of the flat contents, with the formation of lethal conditions within minutes inside the flat and then the lobby.

Transition to involvement of the flat contents

274. After the fire spreads to include the window surround, it then spreads to include items of flat contents close to the windows. From my assessment of the likely items of contents of a typical two-bedroom flat and the composition of the materials of which they are composed, I have estimated a total combustible fire load of 661 kg (including the contents of the lounge, two bedrooms, kitchen and bathroom). From the main materials of which these are constructed I have estimated a mass of approximately 328 kg of carbon, 25 kg of nitrogen and 13 kg of halogens, giving an average fuel carbon content of 50% and an average nitrogen content of 3.7%. For Table 5 I have chosen a point in the fire development when a very small proportion (0.05%) of this fuel mass (3.3 kg) has been consumed during the first few minutes of fire development within the flat. I have assumed at this point that the windows are still closed and intact, and that the flat entrance door is closed, so that most of the fuel is burned with under-ventilated combustion conditions (p>1). By the time the combustion products from this small fuel mass are dispersed within the flat they are sufficient to fill the flat with dense smoke producing effectively zero visibility (0.29 m), and concentrations of CO (2506 ppm) and HCN (164 ppm) sufficient to cause loss of consciousness of occupants after 10 minutes exposure. These products are added to those already penetrating into the flat from the exterior and window materials, further increasing the concentration of smoke and toxic gases into the adjacent lobby via leakage around the entrance door or rapid filling if the flat door is open.

275. The overall pattern of fire and hazard development up to this point is that the combustion products from any small mass of fuel of a few kilograms can create within minutes high smoke concentrations within an enclosed flat capable of producing near zero visibility and causing loss of consciousness within a few minutes followed by death from asphyxia. These are initially derived from the penetration of combustion products from a small proportion of a large fuel mass burning on the building exterior, followed by the decomposition of a small mass (a few kg) of structural materials (PVC), followed by contents materials inside the flat. The smoke penetrating the flat together with that generated inside it is sufficient to produce dense toxic smoke conditions in the common lobby on that floor, with gradual subsequent infiltration into neighbouring flats.

Subsequent fire development within a flat and beyond

276. The fire development described in the previous sections is for the early stages of fire outside and within any specific flat. The scenario considered is one in which the flat is totally enclosed, so that the flat entrance door is closed and the flat windows are closed and intact (or only slightly open). Under these conditions a dense lethal smoke atmosphere develops within the flat within a few
minutes and the basic fire hazard development is quite similar to that typical of domestic fires starting in items of contents such as furniture or an appliance as in Flat 16 at Grenfell and as shown in Figure 3. Up to the point where the conditions in the flat become lethal, the size of the fire within the flat is quite small, and largely limited to the area close to a window in one or more rooms.

277. From the descriptions of Grenfell witnesses there is evidence that the flat fires did develop initially in this way, with smoke and then fire developing around the windows in one room of the flat. The occupants then took refuge away from the rooms with windows and in location such as the hallway, where they could close the room doors and avoid the smoke and heat for some minutes. From my ongoing examination of the transcripts of 999 calls from occupants in the Tower and of the available blood toxicology, my preliminary impression is that these occupants were gradually overcome by exposure to an increasing concentration of smoke and asphyxiant gases, but not to flames and excess heat. This is consistent with the scenario I have described.

278. In many domestic fire incidents in enclosed dwellings, the fire may self-extinguish at this point due to lack of oxygen, as occurred during the BRE house fire tests shown in Figure 3. When these fires are investigated after the event, in most cases, even of fatal fires, the area of fire damage is confined to the first item ignited such as a bed or chair, and a small area of the room of fire origin around it. The dwelling has however filled with a dense toxic smoke during the fire, which is rapidly lethal to the occupants.

279. Although this kind of scenario is typical of the early stages of many fires, the later stages of fire development can be very different if there is significant ventilation from outside, as described. In such a situation the fire can continue to grow and a flashover event is likely to occur, whereupon the entire flat contents become involved in the fire.

280. At Grenfell the main event likely to precipitate transition to flashover was the failure of the windows, creating a large area of ventilation for the fire to the outside. From the description of fire development in Prof. Torero’s report and from my ongoing examination of descriptions given by occupants, and my experience of experimental fires, I believe it is likely that the effects of the fire on the glazing of a flat as the flames reached it from below will have varied somewhat depending on the specific local conditions. For some flats the glazing on some windows appears to have remained reasonably intact for some time, while smoke and flames penetrated around the window frames and through any open windows or vents. There may then have been some loss of the outer glazing pane for a period while the inner remained mainly intact. From the description of fire development in Prof. Torero’s report and from my ongoing examination of descriptions by occupants, I believe that the fires in most flats developed in this way during the early stages up to around the time that conditions in the flat became lethal. It is possible that for some flats, the fire size and heat from the flames appearing outside them was sufficient to cause rapid glazing failure, before there was significant smoke and flame penetration into the flat. In such a scenario the speed of fire development within the flat would be very rapid and involvement of the flat interior materials would have occurred earlier in the sequence and to a greater proportional extent than as described for the intact window case. There would still have been rapid filling of the flat with dense toxic smoke, but the occupants would be more likely to have suffered rapid exposure to heat and burns than in the intact window scenario, and from the forensic data this does not appear to have happened in at least most cases.

281. It is clear from photographs of the Tower during the fire, and from the totally burned out status of many the flats after the event (especially those on the upper floors), that after some time during fire development in many of the flats the glazing did fail and flashover occurred. This then resulted in almost complete burnout of all the combustible contents of these flats. For some flats, especially on the lower floors of the Tower, although fire penetrated around the windows in one or more rooms, the damage is limited to part of the rooms, mainly the areas near the windows, while other rooms show less fire and smoke damage, with some items of contents remaining intact.

58 JTOR00000001
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282. For those flats in which a considerable proportion or all of the combustible contents have burned out, the mass of fuel eventually consumed (over a period of hours during the fire) is large. Table 1 shows an estimated total fuel content of 661 kg for a two-bedroom flat. During the middle phase of a fire in such a flat, when the windows have failed and combustion occurs under post-flashover conditions, large masses of smoke CO and HCN are produced. As long as the flat entrance door remains closed and intact, most of these combustion products flow out through the upper part of the window openings, mixing with the smoke plume from the burning exterior insulation and cladding. The flames flowing out of the window openings further combust any insulation and cladding materials still present. Air to support combustion flows in through the lower part of the window openings, and this contains combustion products from the burning insulation, cladding and any flats burning at floor lower floor levels (Figure 22).

Some smoke leakage into common lobby round entrance door while intact. Rapid flow of smoke and flame into lobby if door is open or partially burned through

Fire and smoke plume from burning flat flow out from windows and up the

A proportion of air and smoke from below flows into the burning flat to support combustion

Figure 22: Combustion product flows during post-flashover flat fire

283. Combustion of the flat contents begins mainly in the rooms with windows and with the fuel closer to the windows. If the internal flat doors are closed there will be some delay before fire burns through into the hall of the flat, and then a further delay before fire attacks the flat entrance door. Depending on the fire development the flat entrance door may remain intact, suffer a partial burn through of the upper part of the door, or be completely burned away. During my visits to the Tower I observed examples of all these states for different flats on different floors.

284. While there is a large fire in a flat, and especially once the entrance door is open or breached by the fire, then large masses of toxic smoke, gases and flames flow out of the flat into the common landing. Under these circumstances the smoke and gases are derived partly from the burning contents of that flat, and partly from smoke and combustion gases entering through the window opening. The contents of the smoke entering from outside is derived from burning external insulation and cladding and burning flat contents of flats lower down the Tower. Because the fuel mass inside the flat is about twice that of the burning cladding, insulation and window surround materials and because it is burning inside the flat, it is likely that during these post-flashover fires, the proportion of the combustion products entering the lobby derived from the burning flat contents will be significantly greater than the proportion derived from the burning exterior insulation and cladding materials. It is also likely that for fires on any specific floor, the contribution to combustion products flowing into the lobby derived from flat burning contents will increase with time over a period or an hour or more during the fire, while that derived from the burning exterior insulation and cladding materials will gradually decrease.

285. Where fire penetrates a flat but is confined for some time to a room with the room door closed, then occupants in other rooms within the flat are protected from heat exposure and exposed to limited smoke for some minutes. Smoke then fills these areas before the flames break through.
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GENERAL EFFECTS OF TOXIC SMOKE AND GASES ON ESCAPE AND SURVIVAL OF GRENFELL OCCUPANTS

286. Requirement B1 in Approved Document B states:

"Means of warning and escape

B1. The building shall be designed and constructed so that there are appropriate provisions of the early warning of fire, and appropriate means of escape of fire from the building to a place of safety outside the building capable of being safely and effectively used at all material times."

For blocks of flats such as Grenfell this is achieved for each individual flat by the internal flat construction, the provision of detection and alarm systems in the flat and means for escape from the flat via the flat entrance door, the common lobbies and the protected stair.

287. In addition each flat is required to be of fire resisting construction with a self-closing fire resisting entrance door to prevent fire (i.e. smoke and flames) occurring in any one flat from spreading to any other flat or into the common lobbies, or the building exterior. It is recognised should a fire occur in any individual flat some smoke may escape into the lobbies on that floor, and for that reason provision is made for ventilation of the lobby. At Grenfell this was via a mechanical ventilation and extraction system. It is also recognised that although most fires occurring in individual flats are usually small, with limited fire and smoke spread, in more extreme cases it may be advisable for occupants of neighbouring flats on the same floor to be alerted and to evacuate.

288. Should some smoke from an individual flat fire enter the common lobby this should therefore be limited, and in particular the escape stair has a further level of protection by being situated in the middle of the Tower, in a fire protected shaft, with the stair entrance protected at each floor by a self-closing fire door. The stair also has some limited ventilation, with a vent required at the top of the stair to facilitate air circulation and ventilation of any small amounts of smoke penetrating the stair itself. The mechanical smoke extract system is designed to extract smoke from the affected lobby, with make-up air from the stair. This therefore creates a negative pressure with respect to the stair so that air flows into the lobby from the stair rather than from the smoke filled lobby into the stair.

289. The escape stair thus has a double protection from a fire in any flat, firstly due to the fire resisting construction of each flat and its entrance door, and secondly by the fire resisting construction of the stair shaft and fire door to the stair on each floor.

290. Due to this level of protection, for all building occupants, the escape stair is designed to be a place of temporary safety in case of fire. For occupants of any flat other than the flat of fire origin, their flats are also designed to be safe refuges due to their fire resisting construction and that of the other flats, lobbies and stair. For these reasons the provision for means of escape for flats are based on the assumption that:

a) the fire is generally in a flat;
b) there is no reliance on external rescue (e.g. by a portable ladder);
c) fire resisting construction measures "provide a high degree of compartmentation and therefore a low probability of fire spread beyond the flat of origin, so that simultaneous evacuation of the building is unlikely to be necessary and

d) although fire may occur in the common part of the building, the materials and construction used there should prevent the fabric from being involved beyond the immediate vicinity..."

291. Also:

59 Approved Document B (Fire Safety) Volume 2 — Buildings other than Dwelling Houses 2006, incorporating 2013 amendments (referred to here as Approved Document B)
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B4 (1) The external walls of the building shall adequately resist the spread of fire over the walls.

292. In summary the design and construction is intended to limit any fire to the flat of origin, to prevent flame spread and limit smoke spread into the common lobbies and to prevent flame and smoke spread into the common stair, so that the lobbies remain a safe, smoke-free escape route into the stair should occupants or flats on any floor need to evacuate, and the stairs remain a flame and smoke free temporary refuge and means of escape for as long as necessary.

293. This is the basis of the “stay put” principle that occupants may generally remain safely in their flats during a fire in a tower block unless they are in the flat of fire origin or possibly another flat on the same floor as the flat of fire origin, but that safe means of escape should always be available should they choose or need to evacuate.

294. Clearly all these design requirements of the Building Regulations as constructed at Grenfell have failed to perform adequately at different times during the incident of 14th June 2017. In the following sections of my report I have considered:

a) The timing and extent of fire and smoke penetration into individual flats, lobbies on different floors and the stair at different levels.

b) The effects on Tower occupants in terms of their behaviour, especially with respect to their decision to evacuate or seek refuge (stay put), either in their own flats or in those of neighbours.

c) The effects of exposure to irritant, toxic smoke on occupants attempting to evacuate through the lobbies and down the stair in terms of their ability to continue and time taken to descend.

d) The effects of inhalation of asphyxiant gases on occupants remaining in the flats and descending the stair in terms of time to collapse and incapacitation.

e) The causes of death of occupants found dead in their flats or in the lobbies or stair.

Suitability of the Grenfell stair for total simultaneous evacuation of multiple or all Tower floors

295. During the Grenfell incident there is a stark contrast between the occupants who remained in their flats, where many deaths occurred, and the much greater number who evacuated using the stair (and a few via the lift) of whom only a small number collapsed and died in the lobbies or stair (excluding those reported as being found outside the building and deaths occurring afterwards). So in addition to the effects of smoke on entry and evacuation via the stair, an issue arises as to the stair escape capacity and what would have happened if those present on the night of the fire had decided to evacuate simultaneously during the first 30-40 minutes of the incident, before there was any or significant smoke on the stair.

296. The “stay put” principle and the fire resisting construction of blocks of flats such as Grenfell anticipates that simultaneous evacuation is very unlikely to be necessary, and that the most likely simultaneous use might be for the occupants of a single floor on which a fire had occurred. In Approved Document B, where multi-storey buildings are designed for simultaneous evacuation into protected stairs, then the stairs are designed as a place of temporary safety capable of accommodating essentially the entire building population (population served), assuming a maximum density on the protected stair and landings of 4 persons/m². This would represent crowded conditions with standing room only. In practice I have found during experimental evacuations of multi-storey buildings that occupants tend to a maximum density of 2 persons/m². For a 1 metre wide stair (and landings) such as that at Grenfell this represent a maximum standing capacity on the stair of approximately 460 persons (~20 persons per floor).\textsuperscript{60,61}


\textsuperscript{61} Boyce, K.E., Purser, D.A. and Shields, J. Experimental studies to investigate merging behaviour in a staircase. Proceedings of the 4th International Symposium on Human Behaviour in Fire, Robinson
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297. If a cohort of 293 persons approximately equivalent to the entire Grenfell population had entered the stair simultaneously over 23 storeys, this would result in approximately 13 persons per floor, so that even in this situation congestion on the stair and landings would not have been an issue.

298. The time required to clear the building using the stair assuming simultaneous evacuation depends on two main aspects, the height of the building (number of floors) and the maximum flow capacity of the stair.

299. The maximum time required for an able-bodied adult occupant to descend to the ground floor depends on the rate of descent (time to descend each storey) x the number of storeys.

300. During a visit to the Tower I measured my descent time (73 year old male wearing protective clothing and heavy boots) at 9.3 seconds per floor, representing a nominal descent time over 23 floors or 3.5 minutes.

301. The standard flow capacity for a stair is 60 persons/minute/metre effective width, where effective width is actual width – 0.3 m. For a 1 metre stair this gives a maximum flow capacity of 60 x (1-0.3) = 42 persons/minute. For 293 occupants this gives a simultaneous flow time to clear the building of approximately 7 minutes.

302. Although a more accurate assessment can be made by more precise modelling or calculations using the exact dimensions of the Grenfell stair, the simple estimates I have reported here demonstrate that if there had been a general alarm system in the common areas capable of alerting all those present in the Tower to evacuate simultaneously, the stair capacity was sufficient for them to have done so within minutes, without crowding on the stair or landings.

303. In practice descent times are likely to have been slightly longer due to the presence of slower, more elderly occupants and young children, and the need to assist occupants with limited mobility. But I estimate that in a situation such as this it would be possible essentially to clear the building within approximately 15 minutes.

304. Once there was sufficient smoke in the stairs that escaping occupants were moving essentially in darkness, then movement speed on the stair can be expected to slow somewhat. Walking speed in irritant smoke with a visibility of less than approximately 2 metres has been measured at ~0.3 m/s compared with approximately 1 m/s on a clear stair. However experimental studies of movement in smoke have shown that people move more quickly if they have a guide to follow, such as a hand rail, as at Grenfell. For a few Grenfell occupants escaping down the stair in dense smoke it is possible to estimate approximate descent timing information from when they made a 999 call just before leaving a flat or on entering the stair, to that time when they were captured on CCTV in the ground floor lobby. These timings are being examined in detail for Phase 2, but a preliminary analysis indicates descent times from upper floors of a few minutes, with descent rates varying between approximately twice to three times my measured rate of 9.3 seconds per floor.

305. In practice most occupants descended the stair alone or in small family groups over the 7.2 hours from the start of the fire (00:54) until the last occupant left at 08:07. There are several references to congestion on the stair, for example when Naomi Li stated that she attempted to descend from the 22th floor but could not do so because she was blocked by a group of occupants ascending the stair at this time (estimated to have been ~01:28 hrs). Depending on the number of occupants ascending the stair at this point (believed to have been less than 20 persons and to have been


Dr. Naomi Chia-Yuan Li witness statement, IWS00000515; See also Helen Gebremeskel IWS00000933
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people from Floor 18 and above) it is possible that any blockage would have been temporary, after which descent of the stair may have been possible. Several persons describe having to walk across the bodies of others who had collapsed on the stair, and other obstacles such as fire hoses, as well as sometimes needing to pass firefighters with bulky equipment. Obstacles to descent such as these need to be considered in relation to effects on descent times.

306. Another issue with stairs is the ability for faster descending occupants to overtake slower ones. Although the stair was quite narrow at just over 1 metre width, I have confirmed myself that it is possible to overtake on the stair. One occupant (recorded on CCTV as exiting at 1.35hrs) describes assisting his elderly father down the stairs and being passed by other occupants who were also coming down the stair. Another occupant (also recorded on CCTV as exiting at 1.35 hrs) who was unwell describes assisting a fellow resident from the 9th floor level and being encouraged to move more quickly by others descending behind them, who then overtook them.

307. Several persons describe having to walk across the bodies of others who had collapsed on the stair, and other obstacles such as fire hoses. as well as sometimes needing to pass firefighters with bulky equipment.

308. The main obstacle to obtaining a rapid simultaneous evacuation of the Tower is that there was no system for simultaneously warning all occupants to escape. Those who did escape, including 23% of the total (67 persons) who evacuated by 01:24 hrs and 56% of the building occupants (165 persons) who evacuated within the first hour, were alerted and decided to evacuate as a result of a variety of fire cues and warnings received as discussed in the following sections.

Lifts

309. Some occupants escaped using the lifts rather than the stair. The south lift was taken out of use by the fire fighters from 01:01 hrs. Eight Tower occupants escaped using the north lift. The last to do so were Nadia Jafari and Rhea Rojo. They are shown on CCTV leaving the lift in the ground floor lobby at 01:26:30. Black smoke is visible flowing from the lift as it opens. Nadia Jafari reported that she had entered the lift on the 11th floor with her 82-year old father who was a heart patient. After they descended one floor (10th) the lift filled with choking smoke. Nadia became separated from her father and continued to descend in the lift. This evidence confirms that the lifts were working and that the north lift was used for escape for up to 33 minutes after the fire started. A problem with the lifts was that they were not enclosed in a separately protected lift lobby as were the stairs. When significant smoke contamination occurred in any lobby, it entered a lift when it opened on a smoke-logged floor.

Influences on escape behaviour of Grenfell occupants in relation to fire and smoke spread

310. The behaviours of Grenfell occupants would have been were influenced by a range of considerations and conflicting influences through the fire incident. The responses of any building occupants during fires involve a sequence beginning with a "recognition period" during which they become aware of various cues that something is wrong that they need to attend to. At Grenfell many occupants were sleeping when the fire started, although some were awake, especially those who had been observing Ramadan. Some became aware of the fire initially due to noises and lights from the emergency services around the base of the Tower, or smelled smoke, or saw the

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63 B. Lane. Phase 1 Report — Section 14 12 April 2018. The performance of the protected stair and lobby. Table 14.8 p14-60, BLAR00000009
64 Inquiry Witness Statement of Mohammed Rasoul, IWS00000070; CCTV exit time spreadsheet at MET00016072
65 Inquiry Witness Statement of Sid-Ali Atmani, IWS00000070; MET00016072
66 MET00016072
67 See CCTV still, INQ000000426
68 Inquiry Witness Statement of Nadia Jafari, IWS000000683
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flames and smoke spreading up the Tower. Others were alerted by neighbours knocking, smoke alarms sounding, or telephone calls from friends and relatives.

311. Once aware of the fire, occupants' first actions (response behaviours) involve a variety of activities as they seek further information and decide what actions to take.

312. Often the intended actions are to alert other flat occupants and evacuate. This applies to any individual flat at Grenfell in which a fire develops, as occurred in the flat of fire origin, Flat 16 on the 4th floor, and later in flats on other floors. For almost all other categories of buildings other than multistorey blocks of flats, detection and alarms systems are provided to sound throughout the building and warn all building occupants to evacuate, either simultaneously or in a phased sequence on different floors, depending on the building design.

313. Grenfell occupants on floors other than the 4th floor, and particularly those on higher floors, faced a crucial decision or whether to stay put or to evacuate. Some occupants made a decision to evacuate within a few minutes and escaped via the lifts or stair. Others attempted to escape and started down the stair, but turned back and sought refuge either in their own flat, in another flat on the same floor on a side of the Tower away from the fire, or sought refuge in flats on a higher floor. These occupants, and others, who initially decided to remain in their flats were faced with the same decision of whether to stay or evacuate at intervals over the next hour or so as the fire and smoke spread around and within the Tower.

314. An initial decision to stay put was supported by the stay-put strategy and advice. Another consideration supporting an initial decision to stay for some residents was the difficulty of evacuating elderly and mobility impaired individuals or small children. Another strong motivation to stay was the advice of authority figures, especially the fire services. When occupants called the fire service before their time of the change in advice, they were generally advised to remain in place.

315. Against this was motivation to evacuate. Tower occupants became increasingly aware of the increasing emergency services activity around the Tower and the growing severity of the exterior flames and smoke spreading up the Tower during the period from approximately 01:15-01:30 hrs.

316. This was especially the case for occupants of flats with windows facing the east side of the Tower, particularly those in the Flat 6 position, and to a lesser extent the Flat 1 position, all the way up the Tower. The flames ignited the exterior cladding outside Flat 16 at 01:15 hrs, then spread up the column and slightly towards the north east side of the Tower, reaching the 12th floor by 01:21 hrs and the 23rd floor by 01:24 hrs.\(^{69}\)

317. Occupants all the way up the tower in the Flat 6 position saw flames outside approaching their windows and some smoke and flames entering their flats. They were forced to evacuate their flats during this period, and it is notable that there were no deaths in Flat 6 on any floor (Table 6 below) (although some former Flat 6 occupants subsequently died elsewhere). During the early minutes of this period, between approximately 01:15 hrs and 01:30 hrs there was little or no smoke in the common lobbies on each floor, so occupants of flats on the east side of the Tower were able to move out of their flats without much difficulty. During this period the Flat 6 occupants in particular left their flats and warned neighbours of the fire severity, they then either took refuge in other flats on the same floor, or entered the stair, initially with the intention of descending.

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\(^{69}\) L. Bisby, Grenfell Tower Inquiry Phase 1- Expert Report 2nd April 2018, LBYR00000001

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Table 6: Fatalities by flat floor and position

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318. Another strong incentive to evacuate was provided by many telephone calls to flat occupants from friends and relatives outside the Tower who could see the severity of the developing fire from approximately 01:15 hrs. Flat occupants therefore received conflicting advice and information about whether and when to remain or evacuate, throughout the period when they remained in the flats.

319. Towards the end of this period, and especially after approximately 01:30 hrs, dense irritant smoke started to accumulate in the common lobbies. Although some floors may have been affected before others, variations in timing between some floors appear to have been minor. Gradually lobbies on almost all floors became heavily smoke logged, which made it increasingly difficult for occupants to move out of their flats, either to other flats on the same floor or to enter the stair. Also, from around 01:45 hrs the smoke density in the stair started to increase to concentrations which rendered descent of the stair difficult, frightening and increasingly dangerous due to the density, irritancy and asphyxiant gas concentrations in the smoke.

320. Occupants who remained in their flats were affected by gradually increasing toxic smoke infiltration, from outside, through internal leakage within the building and by infiltration from the lobbies, mostly around and under the flat entrance doors. As the fire spread progressively on and around the exterior of the Tower, increasingly more flats were affected by fire occurring in the structural materials around their windows, window failure and fire development with increasing smoke exposure in the flats. During this period of increasingly deteriorating conditions in the flats, many calls were made to the emergency services, with frequent attempts in some cases to evacuate by opening the flat entrance door with the intention of entering the lobbies and stair. In many cases, especially during the later stages of the fire after approximately 2 am, the flat
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... occupants felt forced to close the entrance door and remain in their flats due to the density and irritancy of the smoke in the lobbies.

321. When conditions became very bad due to smoke and heat in flats after fire entered from around the windows, some occupants took refuge in flat hallway corridors or bathroom areas. These inner spaces without windows and nearer the building core could be closed off from the lounge, bedrooms and kitchens, which had windows and were where the fire entered the flats. These occupants were eventually overcome by toxic smoke exposure and died in the flats.

322. Other occupants left their flats when conditions became extreme after fire penetration into the flat. In doing so (especially after around 2 am) they were forced to enter what they described as pitch black smoke with zero visibility on the lobbies and in the stair.

323. Although many occupants evacuated during the early stages of the fire before many of the lobbies and the stair became seriously smokelogged (i.e. before approximately 01:30-01:45 hrs), others evacuated via the stair individually or in small family groups at intervals throughout the incident up to ~06:00 hrs and succeeded in escaping. Some of these individuals walked down to the ground floor unaided, some carrying or assisting elderly relatives or children. Others (especially some children and older residents) collapsed on the stair and were carried or assisted down by firefighters or other occupants. Most of those descending after 2 am reported zero visibility and difficulty in breathing and moving down the stair. Some reported dizziness and near collapse, needing treatment for smoke inhalation. The bodies of several persons were reported as having been recovered from lobbies or in the stair, while others reported as being recovered outside the Tower may have collapsed on the stair and their bodies carried out at some later time. From my preliminary analysis, I consider all of these individuals to have collapsed in the lobbies or on the stair due to the effects of inhalation of asphyxiant smoke gases (CO and HCN), with fatal blood carboxyhaemoglobin concentrations.

324. In general those who remained longest before attempting to evacuate were those in the flats affected later by the fire, especially Flat 3 on the 23rd, 22nd and 14th floor and Flat 2 on the floors 15-23.

325. From these findings it is evident that the stair was relatively clear of smoke, offering little or no difficulty or disincentive to evacuation up to around 01:30-01:45 am, during which period many persons evacuated from floors at most levels in the Tower. From around 01:30 am the smoke density in the stair began to increase, being reported as thicker at certain floor levels, so that from around 02:00-02:20 hrs it was difficult and increasingly dangerous to breathe the smoke in the stair and descend to ground level. Despite this, the fact that some occupants succeeded in evacuating down the stair and escaping from all floors in the Tower at intervals up to 04:20 hrs demonstrates that the stair was physically survivable and escape possible down it throughout this period. However the collapse and death of persons in the stair at different times during this period also demonstrate how dangerous the conditions were.

Heat and smoke damage in stair

326. Accounts of conditions in the stair by evacuating persons at different times after 2 am, especially those from the upper floors, describe dense smoke varying somewhat at different floor levels. Some accounts describe thicker smoke lower down on the middle floors of the Tower, while others describe thicker smoke at higher floor levels. Two accounts describe hotter conditions in the stair at middle floor levels. One account describes the metal handrail getting progressively hotter during descent, until at a certain level it was too hot to hold.70

327. As described in detail in Dr. Lane’s report,71 although there are no indications of flaming fires in the stair at any level, the light fittings in the stair have been softened by heat (around 200°C) between

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70 Inquiry Witness Statement of Nicholas Burton, IWS00000064.
71 B. Lane, Phase 1 Report to the Inquiry 12th April 2018: Section 14 The performance of the protected stair and lobbies, BLAR0000009
the 13th and 16th floors, but not above or below. Although some of the doors to the stair have been removed, from those that remain and the fire damage in the lobbies but not in the stair, Dr Lane has concluded that the fire doors were present and mostly closed throughout the Tower during the fire. However, although they may have prevented flames entering the stair, some gradual leakage of smoke is likely to have occurred over many floors where the lobbies were heavily smoke logged or penetrated by fire. Also, as described by one escaping occupant, when occupants of smoke-filled lobbies opened the fire door to the stair at different floor levels in order to enter the stair, smoke flowed into the stair while they were doing so.72 A difficulty in interpreting conditions during the fire from the state of the Tower afterwards is that since the fire burned for more than 24 hours, and the combustible materials on the upper floors especially were largely burned away, it is difficult to determine when damage, such as the heat damage to the light fittings, occurred. However, it is possible to make a reasonable assessment from contemporaneous accounts of occupants combined with the post-fire damage pattern. My conclusion is that although the fire protection to the stair did not prevent it becoming seriously smoke-logged from around an hour after the fire started, the conditions in the stair remained considerably better than those in the lobbies and some flats during the first three hours of the fire, were relatively smoke free for approximately the first 45 minutes of the fire, and remained survivable, but dangerous for escaping occupants throughout the period from ~02:00 hrs. The last two occupants to escape from the 23rd floor (Shekeb and Flora Neda) exited from the ground floor at 02:42 hrs73, while the last escaping occupants from the 22nd floor (Lydia Liao and Naomi Li) did so at around 03:22 hrs74, which confirms that the stair was survivable (although smoke-logged and dangerous) at least up to these times, all the way from the 23rd and 22nd floor down to ground level.

Lobbies smoke

328. The conditions in the lobbies with time during the incident are more difficult to determine than those in the stair since there are more of them and fewer occupants passing through them at recorded times. From the occupant accounts reviewed, the lobbies at some levels became badly smoke-logged from ~01:25—1:35 hrs, with the extent of fire and smoke penetration varying with time and extent at different floor levels. My impression is that for many occupants trapped in their flats, the dense irritant smoke in the lobbies, which they encountered when attempting to open their flat entrance doors, was a major factor inhibiting or preventing escape attempts, with the result that they did not move through the lobby as far as the stair, where conditions may have been somewhat less extreme.

329. One reason for this is that many occupants affected in this way were those that had made a decision to stay put during the first 1-3 hours of the fire, so that by the time they attempted to escape (especially after conditions in their flats became extreme and the emergency service advice was changed from “stay put” to “evacuate”), the lobbies, especially those of the upper floors, were very heavily smoke-logged with zero visibility. From around 2 am the stair was also heavily smoke logged to the extent that visibility in the stair by this time was also very poor to non-existent.

330. Flat occupants attempting to escape through the lobbies with zero visibility were faced with a considerable challenge to feel their way to the stair entrance door on each floor, in addition to enduring breathing difficulties resulting from exposure to the toxic smoke. In practice almost all those who attempted to do this either did not leave their flats at all when confronted by the conditions, or went into the lobby and succeeded in finding the stair entrance door, although in some cases this required more than one attempt. The concentration of asphyxiant gases in the smoke is approximately proportional to the smoke density as described, so occupants remaining for an extended period for more than a few minutes on a heavily smoke-logged landing would have inhaled a significant dose of CO and HCN, which could have resulted in collapse. Of the bodies reported as being found in lobbies there is some doubt as to whether they collapsed there or if their

72 Inquiry Witness statement of Richard Fletcher, IWS00000233
73 See CCTV exit times spreadsheet at MET00016072
74 MET00016072
bodies may have been moved out of the stair by firefighters during the incident to make way for those passing on stair. From my ongoing examination of the toxicology evidence and my estimation of the likely conditions, it is likely that bodies found in the lobbies or stair close to a flat they were taking refuge in may have suffered a considerable exposure to toxic smoke before leaving their flats, so that they are likely to have become rapidly disorientated and collapsed. The conditions in both the lobbies and stair after approximately 02:00 hrs involved irritant, almost zero visibility smoke.

331. Other escaping occupants spent a short time (less than approximately 1-2 minutes) in thick lobby smoke, during which period they would have inhaled some asphyxiant gases, but not enough to cause incapacitation. Once in the stair, they then continued to increase their inhaled dose of asphyxiants as they descended, the rate of increase depending on the smoke density and hence the CO and HCN concentrations in the stair at different times and different floor levels.

332. A key determinant of whether many occupants survived or not was the density of the smoke they were confronted by when they opened their flat doors and the effect this had on their decision to continue to the stair and attempt escape or to shut the door and remain in their flat. An important aspect of the incident is therefore to estimate when the smoke density in the lobbies at each floor level became so dense as to seriously deter and inhibit escape attempts.

333. I am using the witness evidence to make this assessment, and am compiling detailed information for my Phase 2 report. The earliest mention is of some smoke entering the 4th floor lobby before 01:00 hrs as Behailu Kebede left the door of his flat open while he warned his other 4th floor neighbours to escape the fire in flat 16. He then closed his flat door on leaving which should have limited smoke spread from Flat 16 into the lobby. Mr Kebede is seen on CCTV at ground floor level at 00:58:20 hrs. Miquel Alves reported some smoke towards the ceiling when he and his wife left the lift on the 4th floor at 00:57 (as captured on CCTV). The visibility was sufficient for him to leave the lift and then continue up the stair (which at this time was clear of smoke).

334. I have considered the development of toxic smoke in the flats, lobbies and stair mainly for the upper floors where occupants were trapped and many lives were lost. From the witness accounts examined it is possible to identify the times at which some observations were made, partly from estimates mentioned by occupants, partly from observations made during timed 999 calls and partly where observations can be timed in relation to the logged CCTV times when occupants exited the building (allowing for estimated time to descend the stair). I intend to address this in detail in Phase 2. On this basis however there are a few observations made at around 01:20 hrs on different floors, all of which described minimal smoke on lobbies. On the 22nd floor a slight smell was mentioned in the lobby at 01:21 hrs, but no visible smoke. The 21st floor lobby was occupied at 01:26 hrs but no mention of smoke was made, while at 01:30 hrs some smoke was mentioned at ceiling level. On the 20th floor at 01:18 light smoke was observed entering from a smoke extract vent, but none in the lift. On the 19th floor there was only light smoke in the lobby as late as 01:32 hrs, none mentioned up to 01:28 hrs on the 18th floor and up to 01:22 hrs on the 17th floor.

335. I estimate that on these upper floors of Floor 17 and above, where most fatalities occurred, the smoke conditions in the lobbies were minimal or provided good visibility up to ~01:25 hrs and in most cases up to ~01:30 hrs. At around these times smoke at all upper floor levels became dense in the lobbies, and there is some evidence that this dense smoke with near zero visibility occurred earliest at the middle floors of the Tower. Dense smoke was reported in the 10th floor lobby at around 01:25 hrs and by 01:29 hrs on the 15th floor. On the 16th floor dense smoke was reported at 01:20-25 hrs, and it was stated that this may have resulted from a flat door being left open. Around 01:25-01:30 hrs was the period when the fire was moving rapidly up the north east side of the Tower (above and outside Flat 16 towards Flat 206).

76 INQ00000395; Inquiry Witness Statement of Miquel Alves, IWS00000538
336. By a few minutes later, after around 01:30 hrs smoke was beginning to be reported as entering under flat doors from the lobbies of the upper floors, and dense, zero visibility smoke was encountered when occupants attempted to escape into the lobbies from their flats. Moving up the Tower dense lobby smoke was reported at 01:20-25 hrs on the 16th and 01:25 hrs on the 17th. On the 18th no smoke was reported at 01:28 hrs but dense smoke by 01:37-01:40 hrs. On the 19th smoke was still light at 01:32 hrs. On the 20th thick smoke was reported at 01:36 hrs, soon after 01:30 hrs on the 21st floor, at 01:30 hrs and 01:50 hrs on the 22nd and 01:29 hrs on the 23rd floor.

337. There was some variation of the timing of dense smoke development on different floors, and the times I have estimated of my Phase 1 report are preliminary subject to further examination of witness statements and evidence. However, I currently estimate that smoke conditions on lobbies of the upper floors (Floors 18-23), did not become severe until after ~01:30 am. After ~01:30-01:35 hrs visibility became so bad as to deter many occupants from leaving their flats in an attempt to reach the stair. During the period up to around 01:30 hrs there was a lot of communication and movement in the lobbies between flats on each floor, and between floors via the stair.

338. During the few minutes between ~01:16 hrs and 01:30 hrs, occupants on the east side of the Tower were becoming increasingly affected by the advancing fire, and were forced to leave Flat 6 at each level. Many occupants moved to other flats, or entered the stair with the intention of descending to ground level. Some continued to do this while others turned back and went up the tower to seek refuge on other floors, especially floor 23. Soon after 01:30 hrs the smoke density in the lobbies was so bad that occupants then remained in their flats, or in the flats in which they had sought refuge, and felt unable to make further escape attempts. These “refuge” flats were mainly those on the west side (the side opposite the fire – Flats in the 5, 4 and 3 position on each floor), and on the south-east side (Flat 2). The last flats to be affected were Flats 3 so that 17 people took refuge in Flats 203 and 193 on the 22nd and 23rd floors. Occupants tended to remain in these flats or in some cases left when conditions in the flats deteriorated, up to around two hours later.

**Behaviour and interactions with toxic smoke, especially of upper floor occupants (Floors 18-23) during the first hour of the incident**

339. A critical aspect of the incident affecting survival was the behaviour of occupants during approximately the first hour of the incident, particularly between approximately 01:00 hrs and 01:40 hrs as occupants of different flats became aware of the fire and responded to the developing emergency. Approximately half of Grenfell occupants rapidly made a decision to evacuate over this period, and were able to leave their flats, cross the lobbies and descend the stairs in reasonably clear conditions without significant or any exposure to toxic smoke. Other occupants decided to “stay put” in their flats, moved to other flats on the same floor less affected by the fire or moved up to higher floors to take refuge in flats above the immediate fire. Some occupants attempted to descend the stair, but for some reason then turned back after descending some distance, walked back up the stair and took refuge in an upper floor flat.

340. The sequences of behaviours of different individuals were influenced by a variety of factors, including the location of their flat within the Tower, how they were alerted that something was wrong, their family situation in their flat (presence of children and elderly), what they could see and hear of the situation around the Tower, their direct experience of smoke and fire on the Tower exterior, or smoke in their flat, their interactions by telephone with the emergency services and with friends and relatives outside the Tower, and interactions with neighbours on their floor or other floors.

341. Many occupants became aware of the fire at an early stage, before there was smoke in the lobbies or stair. Some came into the lobbies and interacted with their neighbours, or were warned by them, especially those from Flat 6, whose flats were penetrated by fire at ~01:25-01:30 hrs. Many evacuated down the stair at this time, but some decided to stay put. For example because a family member would have difficulty descending the stair, or because some occupants on the upper floors
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decided it would be better to stay put. Some flat occupants were lone individuals who did not
become aware of the fire until there was dense smoke in the lobbies. Those who remained after
~01:35 hrs found dense smoke in the lobbies and were inhibited from escaping. Some decided
to evacuate through the dense lobby smoke, found better conditions in the stair and escaped.
Others were afraid to enter the lobby smoke and remained in their flats until they were forced to
evacuate by smoke or flames in the flat. Some of these then succeeded in escaping down the
stair, while others collapsed and were either rescued or died in the stair. Others remained in their
flats until they were rescued or died there.

342. From a preliminary examination of the witness statements and 999 call transcripts, and the
recorded times at which evacuating occupants exited the Tower, there is a considerable difference
between the behaviours and survival outcomes for occupants on the upper floors of the Tower
compared with those lower down. Tower occupants on all floors appear to have become aware of
the developing fire incident at an early stage of fire development and within a short time frame of
each other. While those in the lower and middle floors (Floors 4-17) tended to evacuate very quickly
however, those on Floors 18-23 were much more likely to delay evacuation or stay put. In
particular, the behaviour of occupants on the top six floors was affected by communication and
interactions between them and the decision of a number to move up the Tower and take refuge on
higher floors rather than to evacuate during this early stage of fire development.

343. From my preliminary analysis, the pattern and timing of evacuations from different levels in the
Tower is illustrated in Figure 23. The figure shows the pattern throughout the incident up to 04:25
hrs (a few further persons left the Tower after this up to 08:07 mainly from the lower floors).

344. The curves show the time occupants are estimated to have entered the stair, rather than the time
they exited the Tower for three sets of 6 floors (18-23, 12-17, 6-11) and for floors 4 and 5. The red
vertical line at 01:30 hrs represents the time by which dense smoke is believed to have filled most
of the lobbies on all floors of the Tower, while the black vertical line at 02:00 hrs represents the
time by which there was dense smoke in the stair throughout the Tower. The pattern shows many
occupants evacuating before the lobbies became smoke logged at ~01:30 hrs, especially from
floors 4 and 5, and from the lower and middle sets of six floors in the Tower. Fewer occupants
leave floors 18-23 during this period, but this does not mean that they remained in their flats, since
some moved between flats on the same floor, while a group came down a few floors then ascended
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to the 23rd floor (and Flat 6s on all floors were cleared). Figure 23 then shows a plateau period of around 30-60 minutes, when very few persons evacuated, then more occupants evacuating at intervals from all floors throughout the period.

345. The first occupants to enter the stair are from floors 4 and 5 from 00:58 hrs, followed by the first from floors 12-17 from 01:04 hrs, from floors 6-11 at 01:09 hrs and floor 18-23 from 01:22 hours, indicating that occupants are aware of the fire and starting to evacuate from all levels of the Tower at an early stage (in some cases before the exterior fire started outside Flat 16). This is followed by rapid evacuation by 01:30 hrs of most occupants of floors 4 and 5 (28 of 36), more than half of those from floors 7-11 (40 of 74) and 12-17 (39 of 76), but only 3 of 86 from floors 18-23. During this period both the lobbies and stair are totally or reasonably smoke free. After the lobbies fill with smoke some occupants continued to evacuate, especially from floors 4 and 5, and from floors 7-11. Then evacuation ceases for ~30 minutes after remaining occupants stay put in their flats or take refuge in others. After this, evacuation continues at intervals from all floors at intervals through dense smoke in both lobbies and the stair as the flats become untenable.

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77 B. Lane. Phase 1 Report – Section 14 12 April 2018 The performance of the protected stair and lobby. Table 14.8 p 14-60, BLAR00000009
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FURTHER INVESTIGATION AND ANALYSIS IN PROGRESS OR PLANNED FOR PHASE 2

Analysis of witness statements and emergency calls

346. For Phase 2 I am making a detailed examination of witness statements (occupants and fire fighters), oral evidence given at the inquiry and transcripts of emergency (999) calls and any information as to other calls made by Tower occupants during the incident. In addition to the accounts available from the documentary and oral witness evidence, I am taking particular note of any timing information relating to occupant activities and observations. Timing information is available from some witness accounts, in relation to 999 calls and in relation to the CCTV recordings from the lifts, and particularly from the ground floor lobby, can be used to identify occupants entering or leaving the Tower, and in particular the times at which individual occupants reached the ground floor as they evacuated.

347. I am undertaking this detailed examination in order to determine as far as possible what Grenfell occupants actually experienced in relation to fire development and exposure to toxic smoke.

348. Specifically I am examining this evidence in relation to the following:

a) How and when flat occupants first became aware of the fire and their experience of smoke and flame outside the Tower, their subsequent behaviours and interactions with their neighbours, other Tower occupants and others outside the Tower (including the emergency services).

b) How and when fire and smoke first entered the flats on all floors, the extent to which smoke penetrated from outside and from the common lobbies. The extent to which fire and smoke entered from outside, involved the window surround and spread to involve the flat contents.

c) How flat occupants were affected by exposure to toxic smoke.

d) How rapidly and at what times the lobbies on each floor filled with dense toxic smoke and the possible source of the smoke. How and when smoke in the lobbies affected the behaviour and ability of occupants to evacuate into the stair (or lift).

e) How rapidly, at what times and to what extent the stair filled with smoke, and the possible source of the smoke. How evacuating occupants were affected by smoke in the stair in terms of behaviour, visibility and toxic effects.

f) How fire and smoke entered the first flats affected (especially Flat 6 on each floor), how occupants became aware of the fire and how smoke and flames affected the behaviour and escape of occupants.

g) How occupants of other flats became aware of the fire, their first experience of smoke in the flat, their behaviour and response to smoke in the lobbies and stair.

h) How occupants escaping into the lobbies and then the stair at different times were affected by toxic smoke.

i) Why some occupants remained in their flats or took refuge in other flats on the same or another floor. How toxic smoke in the flats, lobby and stair affected their escape decision making and behaviour.

j) The development of smoke in these flats over a period of an hour or more, later fire penetration from outside and causes of incapacitation and death in flats, lobbies and stair.

k) Any reported effects of exposure to smoke on visibility in the flats, lobbies and stair, and toxic effects such as irritancy, breathing difficulties, dizziness or collapse. Any reported experience or effects of exposure to heat.

349. My purpose in examining this information is to determine as far as possible what Grenfell occupants actually experienced in relation to fire development and exposure to toxic smoke.

350. In particular I am attempting to establish the timing of flame and smoke penetration into individual flats, the lobbies on all floors and the stair and how this affected the escape capability and survival of all occupants.

351. For occupants who survived I am attempting to establish the conditions they were exposed to, especially in terms of toxic smoke, and the effects on their escape behaviour and capability.
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352. For occupants who died in the flats, lobbies or stair, I am attempting to establish the timing and extent of their exposure to toxic smoke and heat, how the exposure affected their behaviour and how they were eventually overcome and died.

Analysis of blood toxicology and autopsy data

353. I have examined information on actual Grenfell fatalities whose bodies were recovered from the flats, lobbies, stair or outside the building to estimate how they were exposed and died during the fire and how this compares with the generic descriptions of fire conditions. The information I have obtained consists of toxicology reports on blood analysis to measure carboxyhaemoglobin concentrations (%COHb) and photographs of the deceased. I have toxicology reports on 20 decedents. For 15 of these numerical %COHb values have been assigned, while for a further 3 COHb was recorded as present but not measurable. I have requested data for a further four individuals. I understand that for the remainder of the 70 persons who died in the Tower the remains are insufficient for toxicology to be performed. I have access to photographs of the remains of decedents in the locations from which they were recovered from the Tower. I have reviewed photographs of the remains of all decedents for whom blood carboxyhaemoglobin measurements were made, and of the remains of some other decedents.

354. I am in the process of examining these data (in combination with information from emergency (999) calls from flat occupants) to establish the extent to which occupants who collapsed and died in the flats, lobbies and stair were overcome and then died as a result of exposure to toxic smoke or burns.

355. The smoke generated during the Grenfell fire is likely to have contained significant concentrations of hydrogen cyanide, and there have been some reports of Grenfell survivors being treated for cyanide poisoning. I have therefore requested that cyanide measurements should be made in some of the stored blood samples from Grenfell fatalities. If this information becomes available I will consider its relevance to causes of incapacitation and death of Grenfell fatalities.

356. I am awaiting post-mortem information on all Grenfell decedents and will consider that in my Phase 2 report insofar as it is appropriate to do so.

357. In addition to the Grenfell fatalities I am considering making specific requests for information on persons who escaped from the Tower during the incident and were treated in hospital. From records of their treatment by the ambulance teams and on arrival and subsequently at hospital, I may wish to establish their extent of exposure to smoke and heat and the immediate and subsequent health effects. In particular I may request information on the timing of oxygen treatment immediately after the fire, the time at which blood samples are taken and the resulting in terms of %COHb and blood gases, their clinical condition, especially any burns, effects on consciousness, respiratory or cardiovascular signs.

Contribution of different materials to the generation and spread of toxic smoke at Grenfell – further examination and testing

358. For my Phase 1 report I have considered generic fire scenarios and ways in which the exterior cladding and insulation, and window surround materials may have generated smoke penetrating the flats. For Phase 2 I plan to examine the results of any large-scale tests that may be carried out on behalf of the Inquiry or by other parties to establish the fire development and combustion conditions on the Tower exterior and the routes and extent of flame and smoke spread and penetration into the flats. Also for Phase 2 Prof. Stec has collected and is in the process of analysing material and soot samples taken from the Tower exterior and from sites inside the Tower (including flats, lobbies, the stair and smoke extraction system). I plan to examine the results of this work to determine the extent to which it contains evidence relating to the decomposition products of different materials and the spread of smoke into and through the Tower.
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359. For my phase 1 report I have based estimates of the yields of toxic smoke and gases on data from generic examples of materials present at Grenfell rather than the actual materials present. For Phase 2 a series of bench-scale combustion toxicity tests is under consideration to measure smoke and toxic gas yields under a range of combustion conditions from samples of actual Grenfell materials removed from the Tower. If data from these tests become available I will amend my estimates of toxic smoke generation accordingly.
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**SCIENTIFIC REFERENCES CITED IN FOOTNOTES THROUGHOUT THIS REPORT**


Causes of incapacitation and death at Grenfell fire from exposure to toxic fire products


Causes of incapacitation and death at Grenfell fire from exposure to toxic fire products

Appendix A: Basis of hazard assessment methodology

Assessment of effects of exposure to irritant smoke

A1 The effects of exposure to smoke on visibility are instantaneous and depend upon the smoke concentration in terms of obscuration (optical density) and to some extent on odour and irritancy.

For this incident I am endeavouring to evaluate the following with respect to smoke:

a) Approximately at what times the first traces of smoke would have penetrated:
   i. Into individual flats on different locations on each floor and on different floors of the Tower,
   ii. Into the communal lobbies on each floor
   iii. Into the stair at different floor levels

b) The extent to which the appearance of smoke in the flats might, in combination with other cues, have alerted orflat occupants either awake or asleep when the fire started

c) From what time the irritancy and density of the smoke in these locations, especially the lobbies and the stair would have reached a level sufficient to deter occupants from attempting escape via the stairs.

d) The extent to which occupants would have been able to descend the stairs before the smoke density on the stairs would have reached a level sufficient to deter or prevent her from continuing to do so.

e) The effects of prolonged exposure to irritant smoke on Tower occupants who remained in their flats for up to approximately 2.5 hours.

f) The effects of exposure to occupants in the flats, lobbies and stair to asphyxiant gases (CO, CO₂ and HCN) in the smoke. In order to estimate this I have made use of witness reports of the smoke density (in terms of visibility) in different locations combined with data on the relationship between visibility and the concentrations of asphyxiant gases obtained using bench scale and large scale combustion experiments on a range of common materials (including material types present at Grenfell).

A2 As part of this work I have examined test data on smoke optical density, gas concentrations and temperatures in different locations during the BRE house fires tests with the fire room door closed and with it open, and the BRE Rosepark Care Home fire reconstruction tests, and considered these data in relation to witness accounts of the smoke during the Grenfell fire and with the patterns of smoke stains and soot deposition following the fire. I have also viewed videos of two of the BRE house fire tests, showing the smoke conditions in the hall and landing area.

A3 I have then considered the increasing smoke concentration in these areas, and formed an opinion on the time at which the smoke density became so high that a person in an accidental fire would be unlikely to feel able to escape from flat, through the lobbies and down via the stairs, bearing in mind that they would not know how serious the fire conditions might be in the stair at lower levels of the Tower.

A4 Research has been carried out on how escape behaviour, movement speed, and capability is affected by smoke exposure during fires both in laboratory experiments and from incident investigations, and this work has been used to develop exposure limits for design purposes. This work and the development of calculation methods from it are described in a number of scientific publications and standards that I have been involved in producing. However, it is difficult to

predict the behaviour of individual subjects in different situations, since in some fire incidents persons have felt unable to escape through relatively low density smoke, while in others persons have attempted to escape through very dense irritant smoke. In some cases they have succeeded and in others they have been overcome and died in the attempt. In my opinion the nature of the specific situation is important as well as the smoke density and the temperament of the individuals concerned.

A5 Based upon my experience of research in this area it is my opinion that subjects in such a situation are likely to decide not to attempt escape down the stairs from a first floor, through the smoke from a ground floor lounge fire, once the smoke density increases to and optical density of approximately 0.5-1 (approximately 1-2 metres visibility). Although a proportion of subjects are likely not to attempt escape through smoke at three metres visibility and others may attempt escape through very dense smoke. For example if a person finds themselves in the same room as a fire, (for example after fire broke into Grenfell flats from outside) then they are more likely to attempt escape away from this area no matter how dense the smoke.

A6 During the house fire tests with an open fire room door, some penetration of smoke occurred into a closed bedroom on the floor above after several minutes. This may serve to alert closed bedroom occupants to the presence of a fire, but an extended period was required (>10 minutes) before there was a significant smoke density in the closed bedroom. There was minimal smoke penetration into the closed bedroom when the fire room door on the floor below was also closed (see Appendix C).

A7 In order to assess behaviour in response to smoke exposure I have considered the results of published laboratory research on this topic and the results of a detailed study of occupant experiences and behaviour during 98 fire incidents involving significant smoke exposures (mostly in domestic dwellings) that I was involved in.69,70

A8 The basic approach for a design limit for impairment of escape capability by smoke is summarized in Table 1, with a detailed description in [1 and 4]. The basic concept is that the design has failed if the visibility is insufficient for occupants to make an efficient and timely escape. Based on the consideration that smoke in tunnel fires is likely to be derived from burning vehicles or trains, or tunnel facilities such as cables, and therefore likely to contain a significant content of acid gases and organic irritants from burning polymeric materials, it is recommended that smoke from all tunnel fires should be considered irritant. On this basis occupants are likely to move as if in darkness in smoke optical densities exceeding —α 0.2 (α 0.5) (where α is the linear decadic absorption coefficient [or optical density] per metre and α is the light extinction coefficient per metre [α = 2.3α]). At this density, although the nominal visibility of light reflecting objects in diffuse illumination would be around 5 metres (—1/α), visibility is further impaired by eye irritation and reflex closure. It has also been found that in fire incidents, approximately 30% of people turn back rather than enter smoke with a density of 0.33 (around 3 metres visibility). For this reason α 0.2 (visibility 5 m) is recommended as a maximum acceptable smoke density for safe escape from small enclosures (such as from a bus or railway carriage). For a large enclosure, or travel distance to a tunnel or station exit, occupants need to be able to see at least 10 metres to orient themselves and navigate escape routes and exits, giving a tenability limit of α 0.08 (Table 1).

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Causes of incapacitation and death at Grenfell fire from exposure to toxic fire products

Table 1: Smoke design tenability limits

<table>
<thead>
<tr>
<th>Smoke density and irritancy</th>
<th>Approximate visibility in diffuse illumination</th>
<th>Reported effects</th>
</tr>
</thead>
<tbody>
<tr>
<td>None</td>
<td>Unaffected</td>
<td>Walking speed 1.2 m/s</td>
</tr>
<tr>
<td>0.2 (0.5) irritant</td>
<td>Reduced</td>
<td>Walking speed 0.3 m/s</td>
</tr>
<tr>
<td>0.33 (0.76) mixed</td>
<td>3 m approx.</td>
<td>30 % people turn back</td>
</tr>
<tr>
<td>0.5 (1.15) non-irritant</td>
<td>2 m</td>
<td>Walking speed 0.3 m/s</td>
</tr>
</tbody>
</table>

Suggested tenability limits for buildings with:
- small enclosures and travel distances;
- large enclosures and travel distances.

Some occupants exposed above these levels will enter smoke and may be able to escape. Ability and willingness to enter and move through smoke therefore depends on the following aspects:

a) Scenario related: subjects are more likely to attempt to move through smoke if already immersed in it, but may turn back or remain where they are if they can avoid entering smoke. Movement is easier and faster if guided by a handrail or wall.

b) Behaviour related: depends on the experience and sensitivity of the individual subject

c) Visibility related: visibility distance and irritancy affects willingness to enter and move through smoke and walking speed once exposed.

Prediction of time to incapacitation and death from the combined effects of asphyxiant gases

A8 Exposure to a sufficient inhaled dose of an asphyxiant gas results in cerebral hypoxia (insufficient oxygen available to brain tissue), which leads to collapse with loss of consciousness followed by death if the exposure is prolonged. Fire effluent contains a mixture of asphyxiant gases of which the most important are carbon monoxide (CO) and hydrogen cyanide (HCN). These have been shown to be additive in their combined effects. The presence of carbon dioxide in fires is also important since it causes hyperventilation (an increase in the volume of air inhaled each minute), which increases the rate of uptake of CO and HCN. Fire effluent is depleted in oxygen; so direct low oxygen hypoxia also contributes to the overall level of hypoxia, although this effect is usually minor.

A9 Time to incapacitation (loss of consciousness) in a fire is considered to depend upon the overall effects of the mixed asphyxiant gases present in the fire effluent. The method described in this section has therefore been applied to the asphyxiant gases measured during the BRE house fire tests and the Rosepark fire reconstruction tests to calculate the time at which occupants would be predicted to have lost consciousness during the fire.

A10 The yields and concentrations of hydrogen cyanide during fire depends upon the nitrogen content of the burning fuels and the combustion conditions. Upholstered furniture has relatively high nitrogen content, especially in the foam cushioning material. During fires involving primarily upholstered furniture, such as the BRE house test fires, hydrogen cyanide yields and concentrations were high, so that hydrogen cyanide was considered to be a major cause of rapid incapacitation for exposed subjects.

a) For the Grenfell Tower fire the toxic smoke entering any specific flat or lobby, or the stair at different times and locations was generated by combustion of fuel materials in different locations. The extent to which smoke in these locations within the Tower was derived from these different locations is under investigation. Those under consideration include the following:
Causes of incapacitation and death at Grenfell fire from exposure to toxic fire products

b) External cladding components including the polyethylene core of the rainscreen cladding and the polyisocyanurate (PIR) foam. Of these, the foam has a high nitrogen content.

c) Combustible components of structural materials surrounding the flat window assembly. These include a number of components as described in Dr. Lane’s report, including polystyrene panels, a rubberized strip, polyvinylchloride window sill and side components. Polyurethane foam strip and polyisocyanurate foam. Of the polyurethane and PIR have a high nitrogen content, the PVC produces high yields of irritant hydrogen chloride when heated above a critical temperature and the polystyrene produces high yields of irritant styrene monomer.

d) The combustible hard surfaces in the flats (mainly cellulosic materials such as room and cupboard doors, dressers, kitchen units) Although cellulosic (wood-based) materials have a low nitrogen content, the composite materials may include polyurethane adhesives and melamine, which have a high nitrogen content.

e) The combustible “soft” materials contents of the flats consisting mainly of curtains, carpets, clothing, upholstered furniture and bedding. These are comprised of a range of different materials, some of which (such as cellulosic components and polyester fabrics) are low in nitrogen while others (such as polyacrylonitrile, nylon, wool and polyurethane foams) have a high nitrogen content. The overall mix of these soft materials tend to have a relatively high nitrogen content.

I am considering the extent to which the combustion conditions from these different materials may have contributed to the smoke to which occupants were exposed at different times, and the relative importance that CO and HCN are likely to have had in causing incapacitation and death of Grenfell occupants.

A11 In the absence of hydrogen cyanide the main cause of asphyxia during fires is carbon monoxide. It is known that Grenfell fatalities inhaled a significant dose of carbon monoxide during the fire (from the blood carboxyhaemoglobin concentrations measured in some decedents after the fire). I have therefore paid particular attention to calculating CO uptake during an exposure. Although the methodology described in the following paragraphs was used for this case, the most important aspects are considered to be the effects of the combined fire gas exposure on the uptake of carbon monoxide, and the formation of carboxyhaemoglobin in the blood of exposed Grenfell occupants.

A12 After a person becomes unconscious due to the effects of these asphyxiant gases, they continue to breathe, and inhale the gases at a reduced rate, so that their condition gradually further deteriorates until death occurs (at approximately 2-3 times the dose of asphyxiant gases as that causing loss of consciousness).

A13 The asphyxiant gases considered are carbon monoxide (CO), hydrogen cyanide (HCN) carbon dioxide (CO₂) and low oxygen hypoxia. The combined effects of these gases have been estimated according to the method of Purser81,82,83. The method is a current British Standard (BS9899-2 1999)84 and an International Standard85. Details of the methodology are provided in

81 See 2 Purser and McAllister 2016
84 Assessment of hazard to life and health from fire Part 2: Guidance on methods for the quantification of hazards to life and health and estimation of time to incapacitation and death in fires. BS 7899-2:1999 British Standards Institution
85 Life-threatening components of fire – Guidelines for the estimation of time available for escape using fire data. ISO 13571 (2012)
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the references cited. An explanation of the basis of the methodology in presented at the end of this appendix.

A14 Fires contain a mixture of toxic gases, the concentrations of which tend to increase with time during the fire. In order to accommodate these changing concentrations the method uses a fractional effective dose (FED) approach.

A15 The general principle is that for a subject exposed to any toxic gas, incapacitation (loss of consciousness) occurs at a certain “exposure dose” available for inhalation, which is expressed as the exposure concentration multiplied by the time required to cause incapacitation (concentration [ppm] x minutes). During a fire, the concentration of each gas is averaged over short periods and the exposure dose over this period is expressed as a fraction of the exposure dose required for incapacitation (FED). The FED for each successive time period is then summed throughout the fire until the fraction reaches unity, at which time incapacitation is predicted.

A16 Where mixtures of gases are present, the fractional doses for each unit of time and for each gas are estimated on the experimentally verified basis that the effects of CO and HCN are additive and that the presence of CO₂ increases the rate of uptake by causing hyperventilation (and increase in the volume of air breathed each minute). The effects of low oxygen hypoxia are also considered to be additive with those of the other asphyxiants according to the following general equation:

\[ \text{FED}_n = (\text{FED}_{CO} + \text{FED}_{CN}) \times \text{VCO}_2 + \text{FED}_{hypoxia} \]

Where:

- \( \text{FED}_n \) = overall fractional asphyxiant dose for any short time period
- \( \text{FED}_{CO} \) = FED carbon monoxide
- \( \text{FED}_{CN} \) = FED hydrogen cyanide
- \( \text{VCO}_2 \) = hyperventilatory factor due to carbon dioxide
- \( \text{FED}_{hypoxia} \) = asphyxiant effect of low oxygen hypoxia

Inc incapacitation (loss of consciousness) is predicted then the \( \text{FED}_n \) summed with time reaches 1

Death due to asphyxiation is predicted at an \( \text{FED}_n \) of approximately 2-3.

Prediction of %COHb in the blood of exposed subjects

A17 In practice the \( \text{FED}_{CO} \) term is obtained by calculating the percentage carboxyhaemoglobin (%COHb) in the blood of an exposed subject and expressing it as a fraction of the %COHb predicted to cause incapacitation. As a separate indication of the exposure a subject to carbon monoxide, the predicted %COHb with time for subjects in different locations has also been calculated.

A18 The \( \text{FED}_{CO} \) and the %COHb calculations have been carried out using the experimentally derived uptake model of Stewart et al.\(^{86}\). This provides a good prediction for adults when the carbon monoxide concentration is well in excess of the air/blood equilibrium concentration.

Causes of incapacitation and death at Grenfell fire from exposure to toxic fire products

A19 The most important variables influencing the uptake of carbon monoxide (the %COHb in the blood) and other fire gases an exposed occupant are:

a) The time-concentration curve for carbon monoxide (and carbon dioxide) in the fire at the occupant location

b) The time for which each occupant was exposed

c) The respiration ventilation of each occupant (volume of air inhaled each minute). This depends upon the level of physical activity and the stimulatory effects on breathing of carbon dioxide from the fire.

A20 During the BRE house fire tests CDT16 (closed fire room door) and CDT18 (open fire room door) and the Rosepark reconstruction fire tests (open and closed rooms off the fire corridor) the conditions in terms of gas concentrations are considered likely to have been generally similar to those that occurred during the early stages of a fire developing around the window area and subsequently involving the contents of a Grenfell flat. I have also considered how much the conditions in Grenfell flats might have differed from those during the BRE experiments.

A21 The time for which Grenfell occupants were exposed is being estimated from fire development and occupant activity time-line information, from occupant and firefighter descriptions of conditions at different times and locations and from transcripts or reports of 999 and other telephone calls made by occupants during the incident.

A22 An variable affecting the rate of uptake of asphyxiating gases during fires is the volume of air breathed each minute (VE) by the exposed person. This depends mainly on the physical activity of the person, but also on the inhaled carbon dioxide concentration. The effect of carbon dioxide is allowed for in the uptake calculation. For the activity related component for an adult I have estimated a resting base ventilation (VE) of 8 litres/minute while in a flat and 20 litres/minute while descending the stair. This is then increased according to the carbon dioxide concentration (using VCO₂). For the period when a person is considered to have been unconscious a figure of 4 litres/minute has been used and a VCO₂ of 1.

Comparison of the incapacitating effects of exposure to hydrogen cyanide (HCN) and carbon monoxide (CO)

A23 For exposure periods of up to approximately an hour the effects of CO are that when a sufficient dose has been inhaled, the subject is unaware that CO is being inhaled until there is a brief period of a minute or so of lethargy and effects similar to alcohol intoxication, followed by collapse and loss of consciousness. The time at which this occurs depends on the dose inhaled, which in turn depends on the exposure concentration and the exposure time. This can be expressed as the Ct product exposure dose (ppm x minutes) or in terms of the %COHb in the blood. For CO exposure the Ct product dose is approximately constant, so that the effects of a short exposure to a high CO concentration are the same as those to an equivalent lower concentration for a longer period. This is illustrated in Figure A1, where primates exposed to CO became unconscious at a Ct exposure dose of 27,000 ppm.minutes.
Causes of incapacitation and death at Grenfell fire from exposure to toxic fire products

Figure A1 x Comparison to time to incapacitation (loss of consciousness) during exposure to carbon monoxide or hydrogen cyanide.

A24 In contrast to this, the effects of exposure to hydrogen cyanide depend partly on the inhaled dose, which vary considerably depending on the concentration inhaled. When subjects are exposed to hydrogen cyanide, the inhaled dose also increases gradually as with CO, and the subject may be unaware that they are being exposed, apart from an increase in breathing volume. As with CO at a critical dose, they become unconscious. But the main differences from the effects of CO are that as shown in Figure A2, a short exposure to a relatively high concentration of HCN causes incapacitation much more rapidly than a longer exposure to a lower concentration. HCN is also a much more potent toxicant than CO. The result is that a short exposure to 200 ppm HCN caused incapacitation after two minutes exposure, while exposure to 100 ppm HCN required 20 minutes to cause incapacitation.

A25 In domestic fires involving materials with a high nitrogen content, such as upholstered furniture, HCN concentrations can rapidly reach concentrations in the 500-1000 ppm range, which result in rapid incapacitation of exposed occupants. This can occur before the uptake of CO is sufficient to cause incapacitation. For this reason, HCN is considered to be a major cause of rapid incapacitation preventing escape from fires. Once a subject becomes incapacitated in a fire, their breathing and hence rate of uptake of both HCN and CO decrease. The result is that while HCN may be a cause of initial incapacitation, the main cause of subsequent death is carbon monoxide poisoning, with some possible contribution from the effects of HCN.

Carbon Monoxide Toxicity as a Function of %Carboxyhaemoglobin in blood

A26 Carbon monoxide toxicity results from hypoxia, especially cerebral hypoxia due to the deleterious effect of inhaled carbon monoxide on oxygen carriage and delivery in the blood. During an acute exposure, the percentage of haemoglobin converted to carboxyhaemoglobin (%COHb) is a good predictor of the severity of the toxic effects.

A27 These are summarized in Table A1 which shows physiological effects measured in human
Causes of incapacitation and death at Grenfell fire from exposure to toxic fire products

Exposures and in studies I performed on effects on non-human primates. The findings are that for otherwise healthy individuals (without heart disease), the effects are very minor up to approximately 20%COHb, above which human subjects report headache and early flu-like symptoms. These minor symptoms persist up to a threshold level above which there is a sudden change to much more severe effects leading to collapse and loss of consciousness. The %COHb concentration at which this sudden transition from minor to major effects occurs depends upon the level of activity and oxygen demand of the subject. A subject at rest may be minimally affected up to %COHb concentrations of around 40-45%COHb, while an active subject, for example attempting to escape from a building, may be seriously affected at lower concentrations exceeding 30%COHb. When I carried out experiments in which non-human primates were exposed to carbon monoxide while being kept active performing a behavioural task, I found that there were no effects on their activity or ability to perform the task until they achieved around 30%COHb, at which point they went through a brief period of severe intoxication (similar to the effects of severe alcohol intoxication) before collapsing and becoming unconscious. There is some evidence that somewhat higher concentrations of COHb can be tolerated in the presence of elevated CO2 concentrations, as for example during fires, but for some degree of additive interaction between the effects of alcohol and CO. For resting primates, similar effects were obtained at around 40%COHb. For human CO exposures, the average level measured in the blood of fatalities is around 75%COHb, but as stated, survival and recovery is rare once a level of 50%COHb is exceeded. Cigarette smokers develop an increased tolerance to CO, with an increased blood haemoglobin concentration.
Table A1: Classical relationship between carboxyhaemoglobin concentration and signs exhibited in humans and non-human primates (see Purser and McAllister Table 63.8)

<table>
<thead>
<tr>
<th>Blood saturation %COHb</th>
<th>After Stewart</th>
<th>After Sayers and Davenport</th>
<th>After Purser (non-human primates)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.3 - 0.7</td>
<td>Normal range due to endogenous production</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 - 5</td>
<td>Increase in cardiac output to compensate for reduction in oxygen carrying capacity of blood (heart patient may lack sufficient cardiac reserve)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5 - 9</td>
<td>Exercise tolerance reduced, visual light threshold increased, less exercise required to induce chest pains in angina patients</td>
<td>Minimal symptoms &lt; 10%</td>
<td></td>
</tr>
<tr>
<td>16 – 20</td>
<td>Headache, abnormal visual evoked response, may be lethal for patients with compromised cardiac function</td>
<td>Tightness across forehead and headache experienced 10 – 20%</td>
<td></td>
</tr>
<tr>
<td>20-30</td>
<td>Throbbing headache; nausea; abnormal fine motor dexterity</td>
<td>Throbbing headache</td>
<td></td>
</tr>
<tr>
<td>30-40</td>
<td>Severe headache; nausea and vomiting; syncope (fainting)</td>
<td>Severe headache; generalized weakness, visual changes, dizziness, nausea, vomiting, and ultimate collapse</td>
<td>30% caused confusion, collapse and coma in active animals during 30 minute exposures with nausea after</td>
</tr>
<tr>
<td>40 - 50</td>
<td>Syncope, tachycardia (rapid heartbeat) and tachypnoea (rapid breathing)</td>
<td>40% caused coma, bradycardia (slow heartbeat), arrhythmias, EEG changes, in resting animals during 30-minute exposures</td>
<td></td>
</tr>
<tr>
<td>50+</td>
<td>Coma; convulsions</td>
<td>Coma and convulsions</td>
<td></td>
</tr>
<tr>
<td>60-70</td>
<td>Lethal if not treated</td>
<td>Death from cardiac depression and respiratory failure</td>
<td></td>
</tr>
</tbody>
</table>

Prediction of time to skin pain and full thickness (third degree) burns

A28 Apart from exposure to toxic smoke, a major cause of incapacitation and death in fires is exposure to heat resulting in skin pain and burns. During the early stages of exposure to a fire in a flat, as the heat gradually increased, occupants would first experience a sensation of heat leading to pain, especially to unprotected or poorly protected areas of her skin (especially the face and hands). As the intensity and duration of the exposure increased the would then begin to suffer burns.

A29 The two main sources of heat are radiant heat, especially from the heated upper layer, and by convected heat due direct contact with hot smoke. During the early stages of a flat fire the main source of radiant heat is the hot upper layer, while the air at bed height would be relatively cool.
Causes of incapacitation and death at Grenfell fire from exposure to toxic fire products

Once the fire developed and the smoke layer descended to near bed height, flat occupants would then be exposed to both increased heat radiation from the heated upper layer effluent and a convected heat component from direct contact with hot gases. Flat occupants trapped in a flat would be able to shelter for some time from the heat by taking refuge in closed rooms within the flat away from the fire (for example in the flat hall/corridor or bathroom).

A30 The effects of heat exposure depend upon the intensity of the exposure and the exposure time, so in similar way to the asphyxiant gases it is possible to consider "doses" of heat exposure over a period of time leading to different effects.

A31 For exposure to radiant heat fluxes in excess of 2.5 kW/m², time (minutes) to different endpoints for effects of exposure to radiant heat $t_{rad}$, at a given radiant flux of $q$ kW/m², is given by Equation 132.133 using the appropriate exposure dose endpoints (values of $r$) as the numerator.

$$t_{rad} = \frac{r}{q^{1.33}}$$

where $r$ is the radiant heat exposure dose (($kW.m^{-2})^{1.33}.min$) required for any given endpoint

<table>
<thead>
<tr>
<th>Values of $r$ for different heat effect endpoints</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.33 (kW.m$^{-2}$)$^{1.33}.min (tolerance limit/pain/first degree burns)</td>
</tr>
<tr>
<td>10 (kW.m$^{-2}$)$^{1.33}.min (severe incapacitation and second degree burns)</td>
</tr>
<tr>
<td>16.7 (kW.m$^{-2}$)$^{1.33}.min (fatal exposure with third degree burns).</td>
</tr>
</tbody>
</table>

A32 The fractional dose of heat acquired per minute is the reciprocal of the time to incapacitation$^{87,88}$. The fractional heat doses each unit of time are summed until the FED for any particular heat endpoint reaches unity at which time incapacitation due to pain is predicted.

In order to include the effects of both radiant and convected heat it is possible to calculate the total incident heat flux as follows:

$$q = \varepsilon \sigma (T_i^4 - T_m^4) + h_c (T_i - T_m)/1000$$

Where:

- $q$ = heat flux kW/m²
- $T_i$ = heat source temperature °K
- $T_m$ = material surface temperature °K
- $\varepsilon$ = emissivity (0.05 for a gas to 1 for a black body, perhaps 0.5 for smoke)
- $\sigma$ = Stefan Bolzmann constant (5.67 x $10^{-8}$ Wm⁻²K⁻⁴)
- $h_c$ = convective heat transfer factor. For air this depends upon the flow rate past the object. It will be approximately 5-8 for slow moving air.

A33 The first term in the equation represents the radiant component of heat flux and the second term the convected component of heat flux. Using this equation it is therefore possible to calculate total heat flux from the ambient surroundings at body height. The radiant component is relatively small at low temperatures, and is negligible for hot air due to its low emissivity. However, for smoke the emissivity is likely to be much higher (around 0.5) so that at higher temperatures both components should be considered in order to calculate the total heat flux to the skin. In addition to the heat flux from the fire effluent enveloping a subject there is likely to be additional heat radiation from hot upper layers and/or directly from the fire. If the subject is in air (with a low

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Causes of incapacitation and death at Grenfell fire from exposure to toxic fire products

Below a hot smoke layer, the only significant radiative heat flux sources are likely to be the upper layer, the fire or hot surfaces.

At Grenfell the fires in the majority of flats in which occupants died burned for many hours, so that their bodies were largely consumed by the fire, although some remains were sufficient to obtain blood samples for %COHb analysis. The main issue I am addressing is the extent to which flat occupants were overcome and rendered unconscious or died, before they were exposed to sufficient heat to cause pain and burns. In order to make this assessment I am relying on the analysis I have made of the comparative calculated times to incapacitation from toxic smoke or pain and burns during the experimental BRE fires, reports from Grenfell occupants during the fire (mainly 999 calls), and data from other fire incidents for which the extent smoke inhalation (in terms of %COHb), and the extent of burns, have been measured.

Explanation of the basis of FED hazard assessment methodology

The effects of exposure to asphyxiant gases such as carbon monoxide (CO) in a fire depend upon an "exposure dose" inhaled over a period of time. As long as a subject is inhaling CO at a particular concentration in air, the dose of CO in their body increases with time. The size of the dose inhaled after any period of time depends upon the concentration of CO in the air and the time for which has been inhaled. Eventually a dose will be inhaled that is capable of causing a serious toxic effect (an effective dose), such as incapacitation due to loss of consciousness.

The concentration of CO is usually expressed as parts per million in air (ppm) or per cent in air. (1000 ppm CO is 0.1% by volume). The exposure dose can therefore be represented in terms of ppm x minutes.

For example, if an active subject is exposed to 5000 ppm for around 5 minutes (representing an exposure dose of 25,000 ppm.minutes), they are in danger of becoming incapacitated.
Causes of incapacitation and death at Grenfell fire from exposure to toxic fire products

A38 The same situation applies if the CO concentration is different (for example 10,000 ppm) in which case the incapacitating exposure dose of 25,000 ppm.minutes is reached after 2.5 minutes.

During fires the CO concentration is not constant but usually increases considerably over a period of time.

The total exposure dose can then be calculated by measuring the average CO concentration over short periods of time (for example one minute intervals), calculating the exposure doses for each period and summing them. When the total exposure dose reaches 25,000 ppm.minutes, incapacitation is predicted.

<table>
<thead>
<tr>
<th>Average CO concentrations (ppm)</th>
<th>Exposure dose when CO concentration changes with time</th>
</tr>
</thead>
<tbody>
<tr>
<td>14000</td>
<td></td>
</tr>
<tr>
<td>12000</td>
<td></td>
</tr>
<tr>
<td>10000</td>
<td></td>
</tr>
<tr>
<td>8000</td>
<td></td>
</tr>
<tr>
<td>6000</td>
<td></td>
</tr>
<tr>
<td>4000</td>
<td></td>
</tr>
<tr>
<td>2000</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>

Exposure dose for each time period is expressed as a fraction of the dose required to cause a

<table>
<thead>
<tr>
<th>Time during fire (minutes)</th>
<th>Average CO concentration</th>
<th>Exposure dose Concentration x 1 minute</th>
<th>Fractional exposure dose</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>800</td>
<td>800</td>
<td>0.032</td>
</tr>
<tr>
<td>2</td>
<td>1600</td>
<td>1600</td>
<td>0.064</td>
</tr>
<tr>
<td>3</td>
<td>3300</td>
<td>3300</td>
<td>0.132</td>
</tr>
<tr>
<td>4</td>
<td>6450</td>
<td>6450</td>
<td>0.258</td>
</tr>
<tr>
<td>5</td>
<td>12850</td>
<td>12850</td>
<td>0.514</td>
</tr>
<tr>
<td>Total Exposure dose</td>
<td></td>
<td>25000</td>
<td>1.000</td>
</tr>
</tbody>
</table>
Causes of incapacitation and death at Grenfell fire from exposure to toxic fire products

toxic effect such as incapacitation. This is the Fractional Effective Dose (FED). \( \text{FED}_{\text{CO}} = \text{FED} \) carbon monoxide.
Appendix B: Developing fire conditions in BRE house fire tests CDT16 and CDT18

B1 The house ground floor consisted of a hall and stairs, separate dining room and lounge, and a kitchen, while the first floor consisted of front and rear bedrooms and a bathroom. The 10 experimental fire tests all involved flaming ignition of upholstered furniture (single armchairs) eight of which were constructed to be compliant with the current furniture regulations (with fire-retarded covers and cushions), while two were constructed of materials that would no longer be compliant. For each test a chair was placed in the lounge in the corner near the front window. For one test the lounge door was closed and for 9 of the tests the lounge door was left fully open. On the ground floor the kitchen and dining room doors were closed, while on the first floor the door to the main front bedroom (bedroom 2 above the lounge) was left open, while the bathroom and rear bedroom (bedroom 1) doors were closed. All windows and doors to the exterior were closed throughout the tests.

B2 The interior volume of the lounge in which the fires were conducted was 31.2 m$^3$ and the volume of the open areas (lounge, hall-stairs-landing and bedroom 2) was 98.4 m$^3$.

B3 The fires were started by a flaming ignition source (no 7 crib) placed on the rear of the cushion of a chair. This ignition source is approximately equivalent to four sheets of crumpled newspaper and is sufficient to overcome the ignition resistance of the chairs and lead to a flaming, growing, armchair fire.

B4 For each fire experiment the test conditions (fire scenario) therefore consisted of a flaming ignition fire in a closed or open lounge. For the closed lounge scenario the fire and fire effluents were confined to the lounge, apart from some smoke and gases leaking around gaps between the lounge door and frame. The leaked smoke and gases produced some gradual smoke contamination of the ground floor hallway, the first floor landing and the open first floor bedroom.

B5 For the open lounge door scenario large volumes of fire effluent flowed out of the fire room, into the hallway, up into the first floor landing area and into the open first floor front bedroom.

B6 During these tests detailed measurements were made at different locations throughout the building, including the lounge, hallway, stairs, landing and the open and closed first floor bedrooms. The measurements included temperature, smoke density, particulates, toxic gas concentrations (CO, CO$_2$, HCN, O$_2$, and acid gases). The results of these experiments have been published. 89

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Causes of incapacitation and death at Grenfell fire from exposure to toxic fire products

Plate 1: The BRE Cardington house during a fire test

Relevance of BRE tests to the early stages of a Grenfell flat fire

B7 It is my opinion that the BRE (British Research Establishment) house fire tests provide a good indication of the generic conditions and time course of fire development that would have occurred during the early stages of a Grenfell flat fire, before the windows failed. The carbon-nitrogen content of the upholstered furniture is somewhat similar to that of the PIR exterior cladding and widow assembly materials, and similar to that of soft furnishings likely to be present in a Grenfell flat. In the BRE tests the fires consumed approximately six kilograms of armchair covers, foam interior material, and wood framing. The fire behaviour of the fuel materials during the early stages of a Grenfell flat fires and those BRE test chairs should be reasonably similar. However, from the extent of the fire damage, all the Grenfell flats in which occupant died were essentially burned out during the prolonged period over which the fires burned. Once the windows failed at Grenfell the flat fire would have rapidly progressed to post-flashover conditions, resulting in almost complete destruction of the combustible contents of the flats. This is especially the case for flats in the half of the Tower. At lower floor levels the fire damage was lower for some of the flats.
Causes of incapacitation and death at Grenfell fire from exposure to toxic fire products

Plate 2: Remains of armchair following BRE house fire test CDT18

Plate 3: Wall damage following BRE house fire test CDT18

Test programme and selection of CDT16 and CDT18

B9 The CDT series of lounge furniture house fire tests included a total of 10 fire experiments conducted in the two-storey house at the BRE Cardington laboratory. For all these tests a single armchair was placed in front left hand corner of the lounge (looking towards the window from outside). Three different chairs were tested, involving different materials for the covers and cushions. Two chair types were constructed in accordance with the current furniture regulations, while one was constructed to represent a chair type typical of materials used before the regulations were changed. Of the two compliant chairs both had the same CMHR polyurethane foam, but one was constructed with FR cotton covers and one with FR-backed Dralon® acrylic covers. The first two tests involved a smouldering ignition scenario, the remainder used a flaming ignition source (No 7 crib - a flaming ignition source approximately equivalent to 4 sheets of crumpled newspaper). For the third test (CDT16) the lounge door was closed. The remaining tests all involved flaming ignition of a single armchair with the lounge door open and one first floor bedroom door open. Additional fuels such as cushions were added in the later tests, the final test being of a fully furnished room.

B10 The closed door (CDT16) test is a fire scenario likely to have been generically similar to that occurring during the early stages of a fire in a Grenfell flat in which the fire room door is closed and before the (closed) windows failed, in that initially the combustion products are evolved into an enclosed room volume.

B11 The open door tests (CDT17-23) are considered to be fire scenarios generically similar to that occurring during a Grenfell flat fire in which the internal flat doors are open.

B12 Three of these experiments (CDT17, 18 and 20) involved a single armchair with no other fuels, and two of these (CDT17 and CDT20) were carried out using chairs with FR-cotton covers while CDT18 involved a chair with FR-backed Dralon acrylic covers. Other tests involved fully furnished rooms. Any of these three tests could be used to demonstrate the development of the generic fire conditions, and they all produced generically similar fires and fire conditions. Test CDT18 has been selected because I have studied it in detail previously. However, in coming to an opinion I have also considered the overall results of the other tests, but in less detail than CDT18.
Causes of incapacitation and death at Grenfell fire from exposure to toxic fire products

General description of fire development for closed room test CDT16

B13 House fire test CDT16 was carried out on 5th December 1995 in the two-storey house at the BRE's Cardington Laboratory. The fuel consisted of an armchair weighing 23.8 kg with a wooden frame, fire-retarded cotton covers and combustion modified polyether foam cushioning. The armchair was placed in the front left hand corner of the lounge near the front window (viewed from outside the house). The lounge door to the hallway was closed, but the door to the first floor front bedroom was open (BRE bedroom 2). All windows, doors to the exterior and other interior doors were closed. The fire was started by a flaming ignition source consisting of a No.7 wood crib placed on the horizontal seat cushion against the centre of the vertical back cushion.

B14 The general pattern of fire development for furniture fires in this type of scenario, including this one, is illustrated in Figure B1, which shows the temperature at different heights above the floor near the lounge doorway. Following ignition of the cushion the fire grew fairly slowly during the first three minutes, and then very rapidly, providing a peak temperature after 5.3 minutes in the upper layer at ceiling height of around 279°C and 227°C at 1.69m above floor level (approximately nose height for a standing person). At 0.74m (approximately the height of a person lying in bed), the temperature peaked briefly at 115°C after 6 minutes, a temperature too low to cause skin pain or burns. As shown in Fig B1 the fire then decreased in size as the combustion became restricted by the lack of oxygen, so that the temperature at head height decreased to 100°C after 10 minutes. This was followed by a second brief increase and period of flaming before the fire self-extinguished after approximately 14 minutes. Although the temperature of the air at bed height did not reach very high levels, persons and objects both in and under the hot smoke layer would be subject to considerable heat radiation from the hot gases at higher levels in the room.

B15 Because the combustion was ventilation controlled (vitiated) the yields and concentrations of carbon monoxide were high. Figure B2 shows the upper layer gas concentrations, with the CO concentration increasing to 13780 ppm after 8 minutes and 16960 ppm after 11.8 minutes.

Uptake of carbon monoxide and effects on a fire room occupant

B16 From these gas concentrations it is possible to calculate the rate of uptake of CO for a person exposed to the upper layer gases, and their blood carboxyhaemoglobin concentration (%COHb) with time. This is presented in Figure B3. A blood level capable of causing loss of consciousness (~40%COHb) is achieved after 8 minutes and a lethal level (50%COHb) after 11.5 minutes. It is estimated that a person standing in the room would become unconscious after approximately 8 minutes when their blood carboxyhaemoglobin exceeded 40%COHb, from which time their respiration decreases by approximately half, so that the rate of increase in blood carboxyhaemoglobin then becomes slower.

Time to skin pain and burns for a fire room occupant

B17 Using the upper layer temperature data it is also possible to estimate the severity of heat exposure for a subject near the fire room door in test CDT16. For this analysis I have estimated the time to pain from heat exposure and the time at which 3rd degree (serious full thickness burns) would be predicted for exposed naked skin. I have carried out the analysis for a person standing in the room and for a person lying down at bed height. The results show that for a person standing, skin pain is predicted after 5 minutes and 3rd degree burns after approximately 18 minutes. For a person lying on a bed throughout (or on the floor), skin pain is also predicted from just after 5 minutes. It is likely that burns would occur, but that they would be less severe than for a standing person. For a person lying in one position (for example on their back), then burns would occur only to the exposed skin (such as the face) but not to protected areas such as the back. Clothing or covers would be expected to provide some degree of protection. For
Causes of incapacitation and death at Grenfell fire from exposure to toxic fire products

...example for a person in bed and covered by a duvet, the areas under the duvet would not be severely burned if at all.

B18 Another important consideration is the spread of smoke. During a fire in an enclosed room a positive pressure develops, especially at higher levels above the floor, so that some leakage of smoke is likely around the edges of the room door, especially if it is a normal domestic interior door. The distribution of smoke during this closed-door fire experiment is shown in Figure B4. During this experiment the smoke inside the fire room quickly became very dense, reaching an OD/m of 1.0 at head height after 4 minutes and at 0.5 m above the floor after 5 minutes. The difference in timing for the two heights is because the upper layer containing the smoke descends progressively during the fire, so it descends to head height 1.69 m first and then continues to descend to reach 0.5 m 1 minute later. An optical density per metre (OD/m) of 1 represents a visibility distance of approximately 1 metre, while and OD/m of 0.5 represents a visibility distance of approximately 2 metres.

B19 An OD/m of 1 therefore represents very dense smoke, which would not only be visually obscure but irritant to the eyes and nose. A person exposed to such conditions would be expected to behave as if in total darkness, and therefore experience some difficulty finding their way around a room. However if they were familiar with the room (for example in their own bedroom), then it is to be expected that they would be able to find the room door.

Effect of smoke on a person in the closed fire room or on the first floor landing

B20 Figure B4 also shows the smoke density in locations outside the fire room and in particular at head height in the hall on the landing of the floor above. There is also a video taken from the landing during this fire. The data in Figure B4 show that smoke first started to appear in the hall after approximately 4 minutes, with a brief dense "pulse" which then thinned as the smoke mixed into the stairwell. The density on the stairs and upstairs landing became dense after around 7 minutes, and

![Figure B1](image-url)

Figure B1: Temperature (°C) at different heights above the floor at the lounge doorway during flaming ignition armchair fire in enclosed lounge (Test CDT16)
Causes of incapacitation and death at Grenfell fire from exposure to toxic fire products

Figure B2: Fire gases at 1.69 m above the floor in the centre of the during flaming ignition armchair fire in enclosed lounge (Test CDT16)

Figure B3: Fractional Effective Doses for heat (pain and 3rd degree burns) and %carboxyhaemoglobin (%COHb) Temperature (°C) for a person standing or lying down at the lounge doorway during flaming ignition armchair fire in enclosed lounge (Test CDT16).
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Figure B4: Smoke density (OD/m) at different locations during for flaming ignition armchair fire in closed lounge (Test CDT16)
from the video it is my opinion that from around 7.5 minutes it is likely that a person opening a bedroom door and finding smoke of this density on the landing might well decide that the smoke was too thick for them to attempt escape down the stairs. During this experiment there was only a small increase in temperature on the first floor landing, so that heat would not have been an obstacle to escape via the stairs. There is very little penetration of smoke into the closed bedroom over a 25-minute period. This is important in relation to Grenfell because it demonstrates the degree of protection from heat exposure provided by a closed interior fire room door. A Grenfell occupant closing the door of a burning lounge, bedroom or kitchen (rooms with windows penetrated by the exterior fire), would be protected for some time from heat exposure before the door burned through, and would limit toxic smoke exposure, but to a limited extent.

**General description of fire development for open room test CDT18**

B21 House fire test CDT18 was carried out on 13th February 1996 in the two-storey house at the BRE's Cardington Laboratory. The fuel consisted of an armchair weighing 23.8 kg with a wooden frame, fire-retarded cotton backed Drailon® acrylic covers and combustion modified polyether foam cushioning. The armchair was placed in the front left hand corner of the lounge near the front window (viewed from outside the house). The lounge door was open to the hallway, as was the door to the first floor front bedroom (BRE bedroom 2). All windows, doors to the exterior and other interior doors were closed. The fire was started by a flaming ignition source consisting of a No.7 wood crib placed on the horizontal seat cushion against the centre of the vertical back cushion.

B22 The general pattern of fire development for furniture fires in this type of scenario, including this one, is illustrated in Figure B5, which shows the temperature at different heights above the floor in the centre of the ground floor lounge (fire room), which is close to the fire. After ignition there is a period of relatively

![Figure B5: BRE test CDT18: Temperatures at different heights above the floor in the centre of the lounge](image-url)
slow fire growth as the fire takes hold, with a slowly increasing temperature in the fire room. The heated fire gases rise to the ceiling and form a smoke layer under the room ceiling which gradually deepens (fills down) as the fire develops. In the room there is a well-defined demarcation between the upper hot smoke layer and the lower layer containing cool clear air, although some degree of mixing and some smoke contamination of the lower layer gradually develops. As the fire grows, fresh air from the room is drawn into the fire from below. The rate of fire growth is not linear, but grows increasingly rapidly, being represented fire engineering calculations as a “t²” fire growth curve, whereby the size of the fire (rate of burning or rate of heat release) increases as a function of the time from ignition squared. This point is important to understand since while conditions in the fire deteriorate relatively slowly at first, after a few minutes the conditions change from relatively benign to extremely hazardous within a period of a minute or less. Thus in this case the temperature in the lounge near ceiling height (2.34 metres), required a period of 4.5 minutes to change from room temperature to 100°C, it then increased rapidly to 350°C within a further 2 minutes.

B23 As the hot smoke layer fills down from the lounge ceiling to depth below the soffit of the doorway between the lounge and the hall, some of the hot smoke (fire effluent) begins to flow out into the hallway and spread out under the hall ceiling. Once it reaches the void over the stairs the smoke flows up into the first floor landing area. A characteristic of a vertically rising smoke plume is that it entrains (mixes with) larger quantities of air than does a horizontally flowing smoke plume. The result is that the smoke at first floor level is more diluted with air than that in the upper layer inside the lounge and flowing out though the lounge doorway. The smoke density and temperatures are therefore lower. Figure B6 shows that the temperatures in the hallway near the lounge door, although lower at ceiling height, are similar at head height (1.69 m) to those in the centre of the lounge, but Figure B7 shows that on the first floor landing the temperatures are considerably lower, with a maximum at head height of 100°C. This is important because for a person standing on the first floor landing, although the smoke would feel hot — somewhat similar to that in a sauna for example — it would not feel painfully hot, since...
the minimum air temperature required to induce skin pain is 121°C maintained for approximately eight minutes\textsuperscript{90}.

B24 Figure B4 shows the temperatures on the stairs up to a height of 3.21 metres, which is just less than 1 metre above floor level on the first floor. This shows that although the maximum temperature on the landing was around 100°C, a person attempting to descend the stairs would experience gradually increasing higher temperatures as they descended, passing through a region at around 150-160°C at face level about halfway down the stairs. This temperature would be experienced as very hot to unprotected skin, such as that of the head and especially the face, but should be tolerable for a minute or so before severe pain would be experienced.

Figure B7: BRE test CDT18: Temperatures at different heights above the floor on the first floor landing

\textsuperscript{90} See Purser and McAllister 2016
Causes of incapacitation and death at Grenfell fire from exposure to toxic fire products

Figure B8: BRE test CDT18: Temperatures at different heights above the floor on the stairs

B25 As the upper layer fire effluent flows out of the lounge, fresh, cool air from the open areas of the hall, landing and upstairs bedroom flow into the lounge at low level, providing ventilation to support combustion of the fire. As the effluent mixes in these areas and the smoke fills them, the oxygen concentration in the air entrained into the fire gradually decreases. Also, as the smoke layer in the lounge descends, the flames begin burning in the oxygen-depleted upper layer. During the early stages of fire growth, when the fire is small and the there is ample fresh air to support it, the fire is said to be fuel controlled, which means that the rate of increase of the fire size depends mainly on the nature of the burning fuel (the chair) and the way the fire spreads and develops over the burning item. Once the air entrained into the flames starts to become depleted in oxygen and as the upper layer descends closer to the burning fuel, then the fire becomes ventilation controlled, so that the fire size depends upon the rate of air entrainment and the oxygen concentration in the air. The result of these processes is that as the ventilation and oxygen becomes limited the fire stops growing and reaches a maximum size, corresponding to the peak temperature in Figure B1, in this case at around 7 minutes after ignition. As these processes continue the fire then begins to decrease in size, and may eventually self-extinguish, or settle to a small fire if there is sufficient leakage of air into the building.

B26 In addition to the smoke filling the ground and first floor areas, and its effects on visibility, the fire effluent contains toxic fire gases. As the fire grows and then becomes ventilation controlled the yields and concentrations to toxic gases increase (Figure B9). The upper layer fire gas concentrations in the lounge reach a maximum (and the oxygen concentration a minimum) at the peak of the fire at around 9 minutes and then decrease as the fire self-extinguishes and the gases spread and mix evenly throughout the open volume of the house.
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Figure B9: BRE test CDT18: Fire gases at head height (1.7m) above the floor in the lounge

B27 The main hazards to first floor occupants are therefore firstly the impairment of escape capability from exposure to the dense, irritant, smoke, and then incapacitation with loss of consciousness due to the inhalation of the toxic fire gases.

Smoke spread to the first floor and effects on occupants in different locations

B28 Figure B10 shows the smoke density (optical density per metre [OD/m]) at different locations and heights above floor level, and the timings of activation of the smoke alarms. For a person in the fire room the smoke at head height becomes very dense after around 2.5 minutes, which is similar to, but slightly less than that in the closed room test. However, because the smoke then starts to flow out of the upper part of the doorway, severe obscuration at bed height does not occur until around 5 minutes. A person in the fire room would therefore be able to see and remain under the smoke layer up to around this time.

B29 A person outside the room at the time of ignition, for example on the stairs or landing on the floor above, would have a period of around 3-4 minutes from ignition during which the smoke density on the stairs would be low enough for them to descend the stairs to the fire floor. Once on the fire floor they would be able to see under the smoke layer for up to around 5 minutes.

B30 The first traces of smoke penetration into the closed bedroom occurred after 4.5 minutes, so a person awake in a closed bedroom would be able to see and smell smoke from around this time.

B31 The first limitation on a person attempting to escape from a first floor bedroom is visual obscuration by smoke on the landing and this smoke is also likely to be irritant. As stated, it is difficult to predict with certainty at what smoke density any particular individual will decide that they will not attempt escape down a smoke contaminated stair. As an indication, approximately a third of subjects in two studies indicated that they would turn back rather then enter smoke with a density exceeding approximately OD/m 0.3 (around 4 metres visibility) and at a OD/m above approximately 0.5 (2-2.3 metres visibility) persons attempting to move through non-irritant smoke behave as if in total darkness, feeling their way along the walls, and this behaviour occurs at a
somewhat lower density for irritant smoke such as would be expected from a furniture fire. Having viewed the landing video of house fire test CDT18 (Table B1), I felt that from around 4 minutes the smoke density was such that I would be reluctant to attempt escape through it. By this time the smoke density at 1.5m height on the landing was approximately 0.7, representing around 1.5 metres visibility. Also, a person attempting to descend the stairs would experience increasing temperatures, although the temperature did not reach 100°C until 6 minutes.

B32 A person opening a bedroom door to the landing would encounter some smoke obscuration from around 2 minutes after ignition and would therefore be faced with a choice as to whether they felt able to descend the stairs and escape via the front door, or whether to retreat into a bedroom, close the door and either await rescue of escape via an alternative route such as the first floor window.

B33 From 4 minutes, on entering the landing a person would find the smoke very dense and acrid, so that they would be effectively as if in darkness. If the landing lights were on they may be able to see the glowing light through the smoke, but would be unable to see their surroundings such as the walls, banisters and stairs.

![Figure B10: BRE test CDT18: Smoke OD/m at different locations and heights above floor level](image)

B34 It is therefore considered that from around 4 minutes they would be reluctant to attempt escape down the stairs due to the smoke density and irradiancy, while after around 6 minutes the temperature of the smoke on the stairs would become increasingly uncomfortable, further inhibiting escape attempts via that route.

B35 A person remaining in the closed bedroom in test CDT18 would experience significant smoke penetration from around 6-7 minutes, with dense smoke from around 8 minutes if the window remained closed.

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See Purser and McAllister 2016
### Table B1. BRE House fire test CDT18: Notes from video files taken from various locations

<table>
<thead>
<tr>
<th>Time from ignition</th>
<th>Camera time</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>14:41:56</td>
<td>Lounge Camera angle from outside quite high up looking down towards chair</td>
</tr>
<tr>
<td>2</td>
<td>14:43:56</td>
<td>Flaming ignition</td>
</tr>
<tr>
<td>2.5</td>
<td>14:44:26</td>
<td>Flames 0.8m slight smoke</td>
</tr>
<tr>
<td>3</td>
<td>14:44:56</td>
<td>Flames to top of chair + 10 cm light smoke</td>
</tr>
<tr>
<td>3.5</td>
<td>14:45:26</td>
<td>Smoke swirling flames .3 m above back</td>
</tr>
<tr>
<td>4</td>
<td>14:45:56</td>
<td>Can see chair but thick grey smoke everywhere</td>
</tr>
<tr>
<td>4.5</td>
<td>14:46:26</td>
<td>Flames to 1 m above top of chair back – dense smoke</td>
</tr>
<tr>
<td>5</td>
<td>14:46:56</td>
<td>Can just see flames but very dense smoke</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cannot see anything – all black</td>
</tr>
<tr>
<td>2-2.5</td>
<td>14:43:56</td>
<td>Hall from outside –</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Flames standing up to just above chair back</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Flames lying against chair back</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Lounge layer about mid window line</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Flames to around 0.5 m above chair burning in smoke layer, but a lot of smoke swirling around to floor level</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Smoke layer down to top of chair back, flames to ceiling</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Smoke suddenly goes from grey to very black, layer 2/3 down window and smoke from floor to ceiling</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Layer 2/3 – ¾ down window, flames about to ceiling</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Smoke below window base – room fully smoke logged, glass cracked</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Second crack,</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Flames subsiding?</td>
</tr>
<tr>
<td>1.5</td>
<td>14:43:26</td>
<td>Smoke appearing in hall downstairs flowing under ceiling near front door</td>
</tr>
<tr>
<td>2</td>
<td>14:43:56</td>
<td>Grey smoke filling hall downstairs</td>
</tr>
<tr>
<td>2.5</td>
<td>14:44:26</td>
<td>Light smoke apparent on landing</td>
</tr>
<tr>
<td>3</td>
<td>14:44:56</td>
<td>Smoke on landing thickening, but I would still try to escape through it</td>
</tr>
<tr>
<td>3.5</td>
<td>14:45:26</td>
<td>Thicker but could still escape</td>
</tr>
<tr>
<td>4</td>
<td>14:45:56</td>
<td>Landing smoke very thick, I don’t believe I would try to escape through it</td>
</tr>
<tr>
<td>4.5</td>
<td>14:46:26</td>
<td>Landing smoke very thick, can just see white of post at top of stairs</td>
</tr>
<tr>
<td>5</td>
<td>14:46:56</td>
<td>Pitch black, cannot see anything.</td>
</tr>
</tbody>
</table>

### Uptake of carbon monoxide and effects on a fire room occupant

B36 The rate of uptake of CO for a person exposed in the fire room to the upper layer gases, and their blood carboxyhaemoglobin concentration (%COHb) for is presented in Figure B11. A blood level capable of causing loss of consciousness (~40%COHb) is achieved after 10 minutes while a lethal level (50%COHb) is not predicted. It is estimated that a person standing in the room would become unconscious after 10 minutes when their blood carboxyhaemoglobin reached approximately 40%COHb, from which time their respiration decreases by approximately half, and...
Causes of incapacitation and death at Grenfell fire from exposure to toxic fire products

the CO concentration decreases, so that the rate of increase in blood carboxyhaemoglobin becomes slower.

![Fractional Effective Doses for heat (pain and 3rd degree burns) and %carboxyhaemoglobin (%COHb) Temperature (°C) for a person standing or lying down at the lounge doorway during flaming ignition armchair fire in an open lounge (Test CDT18).](image)

Figure B11: Fractional Effective Doses for heat (pain and 3rd degree burns) and %carboxyhaemoglobin (%COHb) Temperature (°C) for a person standing or lying down at the lounge doorway during flaming ignition armchair fire in an open lounge (Test CDT18).

Time to skin pain and burns for a fire room occupant

B37 Using the upper layer temperature data and temperatures at head height (1.69 m) and nearer the floor at 0.73 m it is also possible to estimate the severity of heat exposure for a subject near the fire room door in test CDT18. For this analysis I have estimated the time to pain from heat exposure and the time at which 3rd degree (serious full thickness burns) would be predicted for exposed naked skin. I have carried out the analysis for a person standing in the room and for a person lying down at bed height.

B38 The results show that for a person standing skin pain is predicted after 7.5 minutes and 3rd degree burns after approximately 18 minutes. For a person lying on a bed throughout (or on the floor), skin pain is predicted from just after 8 minutes and 3rd degree burns after 11 minutes. The hazard from pain and burns due to heat is therefore greater than for the closed door fire (CDT16).

B39 It is likely that burns would be less severe for a lying person than for a standing person. For a person lying in one position (for example on their back), then burns would occur only to the exposed skin (such as the face) but not to protected areas such as the back. Clothing or covers would be expected to provide some degree of protection.

Appearance of smoke stains on outer side of a closed fire room door

B40 Figure B12 shows the appearance of smoke stains on the hall side of the fire room door after the closed door test CDT16. Note that the pressure at the upper levels of the fire room has caused
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smoke to flow out around the edges of the door forming soot deposits along the edges of the outer door surface.

Figure B12 CDT16 showing appearance of closed lounge door from hallway after test
Causes of incapacitation and death at Grenfell fire from exposure to toxic fire products

APPENDIX C

Curriculum Vitae for David Purser

NAME
Professor DAVID ANTHONY PURSER CBE

DATE OF BIRTH
11 August 1944

NATIONALITY
British

PROFESSION
Toxicologist/Fire and human factors risk science and engineering

KEY QUALIFICATIONS
BSc (Hons) First Class (Zoology, Comparative Physiology) 1966 (University of Birmingham, UK)
PhD (Neurophysiology) 1969 (University of Birmingham, UK)
Dip R C Path (Toxicology) 1984 (Royal College of Pathologists)

POSITION LAST ORGANISATION
Technical Development Director, Fire Division, BRE Ltd. 1991 – 10th May 2006 (retired)

CURRENT SITUATION
Consultancy business: Hartford Environmental Research, 1 Lowlands, Hatfield, Herts. AL9 5DY, UK.
Consultancy, academic teaching and research in fields related to toxicology, environmental hazards and human behaviour in emergencies, especially fires, combustion chemistry and hazard modelling, particularly in relation to fires and combustion products.

Current appointments:
Visiting Professor: University of Central Lancashire UK (Centre for Fire and Hazards Science, School of Forensic and Investigative Sciences). 2010-

Recent appointments:
Adjunct Faculty (Fire Engineering) University of Maryland (USA) (2002-2014)
External Examiner MSc Fire Engineering University of Ulster (2010-2014)
External Examiner MSc Fire Engineering University of Leeds (2010-2014)
Visiting Professor in Fire Safety and Toxicology at the University of Greenwich (School of Computing and Mathematical Sciences), UK, (Appointed 1998)
Guest lecturer, Fire Safety Engineering, University of Lund (Sweden). 2011-2015
Visiting Tutor: Fire Service College, Moreton UK. 2009-2011
Visiting lecturer University of Lund, Sweden. 2009, 2010
Guest Lecturer University of Leeds, School of Chemical and Process Engineering. Fire and Explosion Investigation Courses. 1997-
Visiting Professor. Combustion Chemistry and Toxicology, Centre for Materials Research and Innovation, University of Bolton 2007-2011
Guest lecturer Forensic Toxicology. University of Surrey (2006-2011).
National Association of State Fire Marshals NASFM (USA) Member of Scientific Advisory Committee (2009-2013)

Standards Committees:
Chairman of BSI FSH/16 Hazards to life from fires (1992 - 2010), UK expert and leader of UK delegation to TC92, SC3 and working groups. Currently member of these committees.
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SPECIALISATION 1991 – 2006 Retired from Building Research Establishment 10th May 2006, continued as BRE Associate

Director of research programmes in the Fire and Risk Sciences Division, Building Research Establishment Ltd. (a former UK government research institute now a private foundation), leading a team conducting research and consultancy on all aspects of fire and fire engineering involving people. This ranged from the psychology of human behaviour in fires and the design of means of escape to fire chemistry, the toxicological and behavioural aspects of human fire exposures, protection of buildings from fire hazards and CBRN incidents, in the context of the work of the Division on all aspects of fires and related hazards.

PROFESSIONAL EXPERIENCE

1989-present: Private consultancy: Hartford Environmental Research: Set up to pursue specific areas, principally of academic interest, national and international standards work and some commercial and legal consultancy work in relation to toxic and environmental hazards, particularly involving combustion.

A significant part of this work involves participation in international scientific conferences including membership of conference scientific committees, reviewing and presenting papers, and acting as external examiner for UK and international post graduate students in fire science and engineering.

1991-2006: In September 1991 joined the Building Research Establishment, Fire Research Station (Now BRE Ltd.), where I continued to work on toxicological and behavioural aspects of human fire exposures. Research related particularly to: occupant behaviour in relation to means of escape, the chemical yields of toxic products in fires and evaluation of fire hazard development (and environmental hazards) from experimental full-scale compartment fires and fire incidents. The work involved consultancy and experimental studies for a variety of government and private clients, a major function being research underpinning the continuing development of the UK Building Code in relation to fire safety.

Other projects at BRE and during current self-employment have included providing advice to Communities and Local Government (CLG) on protection of buildings from chemical, biological, radiological and nuclear incidents, an EU funded project for the University of Cambridge on analysis of the vulnerability of communities to fires induced by volcanic pyroclastic flows, CLG projects on use of elevators and escalators for evacuation during fires and other emergencies, effects of sprinklers and water mist suppression systems on rescue from prison cells, and a study of motor vehicle fire hazards sponsored by the Motor Vehicle Fire Research Institute on behalf of the US National Highway Traffic Safety Administration.

I have been an active member of a number of British and International Standards committees relating to fire hazards, fire safety engineering, fire toxicity and means of escape during the last 30 years, acting as chairman of 2 committees (FSH/16, FSH 24/3). I have also served on several UK government scientific advisory committees (see below).

1974-1991: Joined the Department of Inhalation Toxicology at Huntingdon Research Centre (at that time the largest independent toxicology research company in Europe) and during the next 17 years conducted research and directed studies in environmental and inhalation toxicology, particularly on industrial chemicals and pharmaceutical substances affecting the nervous, cardiovascular and respiratory systems. Much of this work consisted of research projects in the field of combustion toxicology, involving detailed studies of the effects of fire gases and other combustion products on central nervous system function, lung function and behaviour, in order to evaluate the mechanisms whereby fire products cause incapacitation and death. This led to the development of calculation models for the assessment of toxic and other life hazards in fires, with application to forensic investigation of fire incidents.
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1966-1973: Engaged in doctoral and post-doctoral research into mammalian central nervous system physiology at the University of Birmingham and pre-clinical teaching of medical and dental students  
1963-1966: Undergraduate student Department of Zoology and comparative physiology, University of Birmingham

1953-1963: Bedford School, Bedford

Membership of professional bodies:

Royal College of Pathologists  
British Association for Lung Research (to 2017)  
International Association of Fire Safety Science (to 2018)

Honours

Commander of the Order of the British Empire (CBE) for services to fire safety.  
New Year Honours List 2015

Awards

2013 Institution of Fire Engineers: Rasbash Medal for outstanding contribution to the advancement of knowledge in fire behaviour.

Continuing professional development:

International scientific conferences attended from 2010:

2010
- Sixth Fire and Explosion Hazards Seminar, University of Leeds, Sunday 11 – Friday 16 April 2010  
- National Association of State Fire Marshals Annual Conference, Intercontinental Hotel Chicago.  
  July 22-24th 2010

2011
- 2011 Annual UK review meeting on outdoor and indoor air pollution research. Institute of Environment and Health. Cranfield University 10-11 May 2011  
- 13th European meeting on fire retardant polymers. Alessandria, Italy 26-30th June 2011  
- The Rosepark care home fire: investigation, research and finding the lessons to be learned. Tuesday 6 December 2011.  

2012

2013

2015

2016
- FIRETOX2016 COST MP1105 Fire Toxicity Conference 21-26th March 2016

2018
- 8th International symposium on tunnel safety and security (ISTSS) Boras, Sweden, 16-18th March 2018

Expert Committee Memberships

130
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British Standards and International Standards Committees

Chairman of BSI FSH/16 Hazards to life from fires (1992 - 2010), UK expert and leader of UK delegation to TC92, SC3 and working groups. Currently member of these committees.


Previously: PRI/26 Member of Project Steering Committee - Guidance on Environmental Impact of Burning Plastics and Rubbers

Halon Advisory Group - Committee involved in the evaluation of halon fire suppression systems, particularly in relation to safety and toxicity aspects.

Department of Health Expert Committees providing advice to the Chief Medical Officer on particular issues of national concern. This includes advice on scientific issues, setting of research priorities and assessing research applications. The committees are as follows:

- Committee on the medical effects of air pollution (membership term ended June 2000)
- Scientific committee on tobacco and health - Technical Advisory Group (to 2006)
- Health advisory group on chemical contamination incidents - working subgroup on environmental hazards from smoke toxins (now changed to National Focus on Chemical Incidents)

University work

Lecturing in human behaviour and means of escape, fire chemistry and toxicology, fire investigation and forensic toxicology to undergraduate and post-graduate courses at the following universities:

- University of Greenwich
- University of Leeds
- University of Surrey.
- University of Salford
- University of Ulster
- University of Central Lancashire
- University of Lund, Sweden
- University of Maryland USA: (Presenting and assessing Masters Course module)
- University of Canterbury, Christchurch NZ: (Presenting and assessing Masters Course module)
- Collaboration on research projects: Universities of Salford (as visiting Fellow), Central Lancashire, Ulster, Lund, Cambridge, Santander.

Postgraduate MSc and PhD project supervision: University of East Anglia, University of Ulster, and University of Maryland.

Postgraduate External examiner, lecturer (November 2009-

External examiner MSc and PhD students: University of Greenwich, University of Leeds, Southbank University, University of Maryland, University of Canterbury NZ, Lund University, University of Ulster, Manchester Metropolitan University.
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Postgraduate lecturing in Toxicology at St. Bartholomew’s hospital Toxicology Research Department, London and King’s College London.
Development and presentation of Fire Engineering Course to City of Birmingham, Building Control Department 2004.

Legal expert work:
Involvement with a number of cases in the UK, USA, Egypt and France in relation to Legal and court work (testimony and depositions) as expert in fire toxicity and human behaviour in fire, including:

Appointed expert to US Federal Court: San Juan Puerto Rico, Dupont Plaza Hotel Fire


Since retirement from BRE in 2006 acting as expert in UK on two incidents involving deaths of fire officers during fire incidents (one advising defence), five cases involving deliberate or accidental fire deaths – one advising defence four advising prosecution.


Design Project Experience

Experience of design and peer review work relating to a variety of major design projects involving stadiums and large places of assembly including the following:

• Theatres on the Bay Singapore: large complex including concert hall and theatre, shopping mall, interior and exterior circulation areas.
• Indoor leisure park – Singapore
• Means of escape design for a number of airport projects including Brussels Airport - new “finger” and terminal connections
• Advisor regarding means of escape provision for new sports stadiums in Germany 2006.
• Means of escape provision design for modification of retail outlets in Hatfield Galleria 2005
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PUBLICATIONS AND SCIENTIFIC CONFERENCE PRESENTATIONS

A total of 152 publications and conference presentations over the period 1969-2018
A full set of publications is listed on Researchgate https://www.researchgate.net

A selection of recent publications and some particularly relevant to the Grenfell Inquiry is listed below. The selection includes publications relating to evacuation behaviour and effects of smoke in fires, assessment of toxic and heat hazards in fires, combustion chemistry and the yields of toxic combustion products from materials involved in fires.

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