David Purser

Grenfell Tower Inquiry
Phase 1 Report Presentation

Exposure of Grenfell occupants to toxic fire products – effects on escape and survival

Part 1

Production of toxic smoke and gases and effects in generic domestic fire scenarios similar to those occurring at Grenfell

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Instructions

To prepare an expert report for Phases 1 and 2 of the Grenfell Inquiry addressing:

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 for those whose bodies were consumed by the fire
3. The possible toxicity performance of materials present at Grenfell Tower

This Phase 1 report is intended to be a general report which does not make reference to specific detailed evidence regarding individual Grenfell occupants.

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Instructions

- For Phase 2 the report will be updated and expanded as necessary in relation to the continuing inquiry evidence and the results of ongoing and any future investigations.
- This will include an examination of:
    - witness statements and oral evidence of Tower occupants
    - the transcripts of calls made by Grenfell occupants to the emergency services.
    - Firefighter evidence

Main purpose:

- to obtain a detailed understanding of the conditions to which each person inside the Tower was exposed and how their behaviour, escape capabilities and survival were affected.

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Generic versus specific evidence

Why the Phase 1 report is based on mainly on generic evidence on fire hazards rather than specifically on Grenfell evidence

- Because we have detailed information from previous incidents and investigations
- Due to the limitations of available evidence from Grenfell
- Some detailed aspects of Grenfell still under investigation

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Presentation

Presentation in three parts:

- ***Part 1 - Production of toxic smoke and gases and effects in generic domestic fire scenarios similar to those occurring at Grenfell***
- ***Part 2 - Fire hazard scenario development and effects on occupants during the Grenfell incident***
- ***Part 3 - Possible Toxicity Performance of Materials Present at Grenfell Tower***

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Performance-based fire safety design principle

Performance-based design principle:

Fire hazards depends on two parallel processes:

- The time from ignition to when the fire become dangerous
- The time needed for occupants to escape

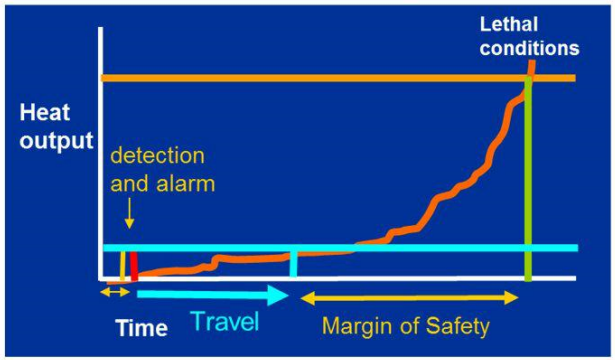
(or the time they can stay put in a place of safety)

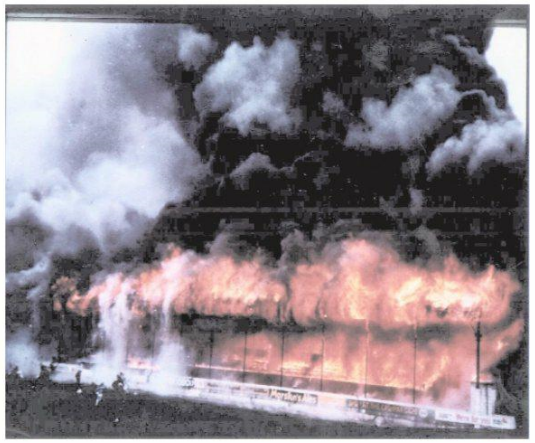
In any fire incident in a any building:

Available Safe Escape Time > Required Safe Escape Time by an appropriate safety margin

ASET = time from ignition to loss of tenability

RSET = time from ignition to escape





Bradford stadium 1985

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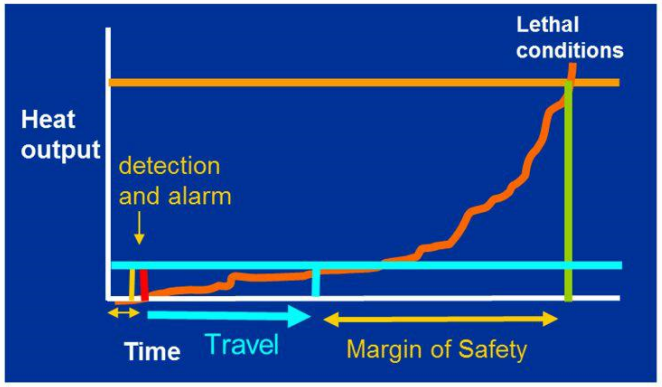
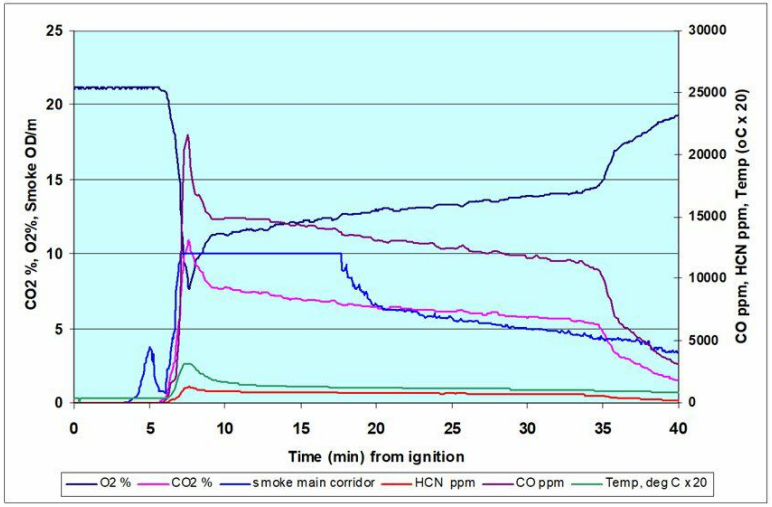
Performance-based fire safety design principle

To investigate an incident:

The time from ignition to when the fire become dangerous:

- Determine the time-concentration curves for fire hazards occupants were exposed to:
  - smoke - effects on visibility and irritancy
  - toxic (asphyxiant) gases - cause collapse, coma and death when sufficient doses have been inhaled
  - Heat - cause pain then burns after a sufficient exposure ("dose")
- Determine the time at which escape capability was affected by each hazard, when collapse and death occurred
- Effects on occupants escape behaviour and survival





Rosepark care home fire reconstruction

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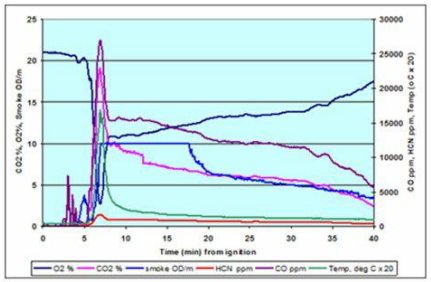
Three main methods – powerful when used in combination:

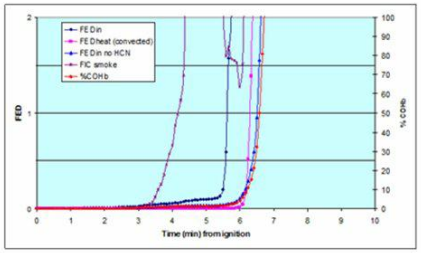
- Detailed fire incident investigation:
  - ➢In depth information on interactions between building, fire and effects on occupants – survivor interviews - detailed experiences
  - ➢Pathology studies (burns, COHb) extent of exposure to fire, mixed smoke and gases and effects
  - ➢But: no detailed information on conditions during fire and no detailed information on effects of individual hazards
- Full scale fire tests and incident reconstruction or incident fire modelling
  - ➢Measured or calculated time-concentration curves for smoke, toxic gases and heat
  - ➢But: test conditions not always identical to those during the actual incident and no information on effects on occupants
- Human physiological data on exposures to individual fire gases and mixtures
  - ➢Development and application of physiological (FED) models to predict timing and effects of smoke, irritants, asphyxiant gases and heat – and calculate %COHb
  - ➢But: need to validate against real human exposures in actual fire incidents

Example:

- *Carry out reconstruction fire test, measure CO and calculate %COHb in exposed occupant*
- *Measure %COHb in blood of occupants exposed in the actual incident*

  If the two measures agree this provides validation that the fire test was a good recreation of conditions in the actual incident and explains how and when occupants were affected





Rosepark care home fire reconstruction

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Example of previous fire incident: Rosepark care home

Purpose: to understand how flames and smoke developed and spread through a building and how and when occupants were exposed to heat and toxic smoke, why they were unable to escape and how they died.

Grenfell can be considered as ~100 domestic fires with four main occupant exposure scenarios:

- Occupants alerted early during the fire and evacuated (or remained) with no or minimal exposure to toxic smoke or heat
- Occupants in smoke-free flats who were exposed to dense smoke in lobbies when they opened their flat doors – then either remained or evacuated through smoke
- Occupants remaining in flats for an hour or more and exposed to slowly increasing toxic smoke leaking into the flat
- Occupants remaining in flats then exposed to rapid fire growth and exposure after fire penetration from outside

Also at Grenfell a range of different fire development scenarios in different flats and other locations.

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Rosepark Nursing Home

Fire at 04:28 on 31st January 2004 resulting in 14 deaths

- On behalf of Scottish Office and Procurator Fiscal at BRE toxic hazards in:
  - Full-scale reconstruction of actual incident
  - Full-scale reconstruction with sprinklers
  - Full-scale reconstruction with closed ½ hour fire doors on rooms
- For Procurator Fiscal investigated fire time-line and effects on decedents and exposed survivors

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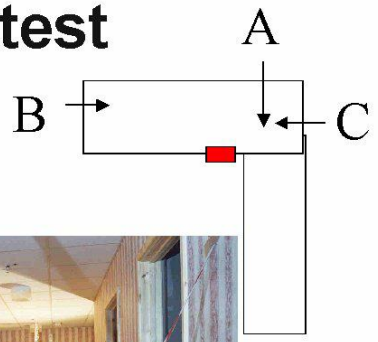
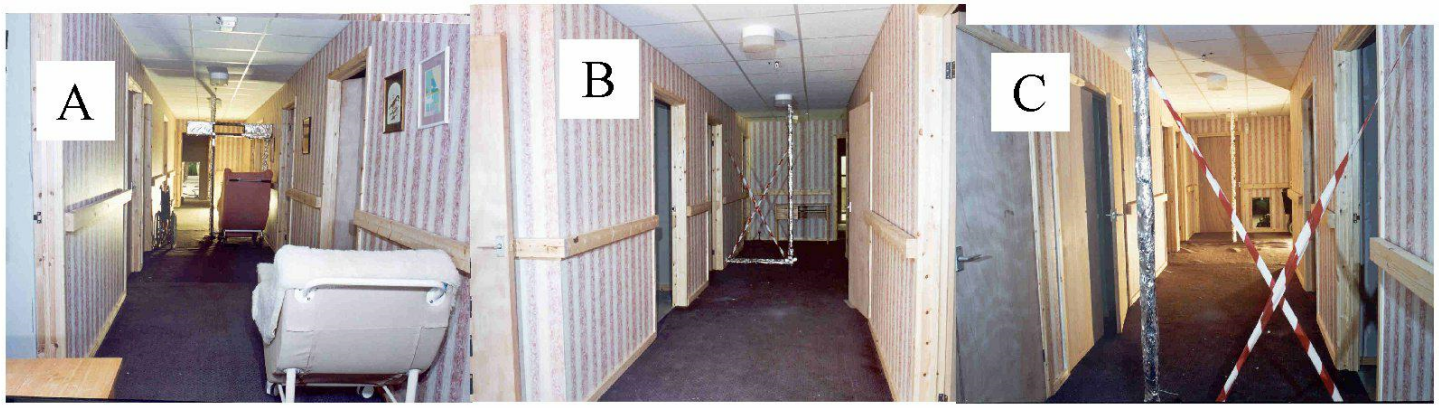
BRE Rosepark reconstruction test

Full-scale reconstruction of fire using original materials





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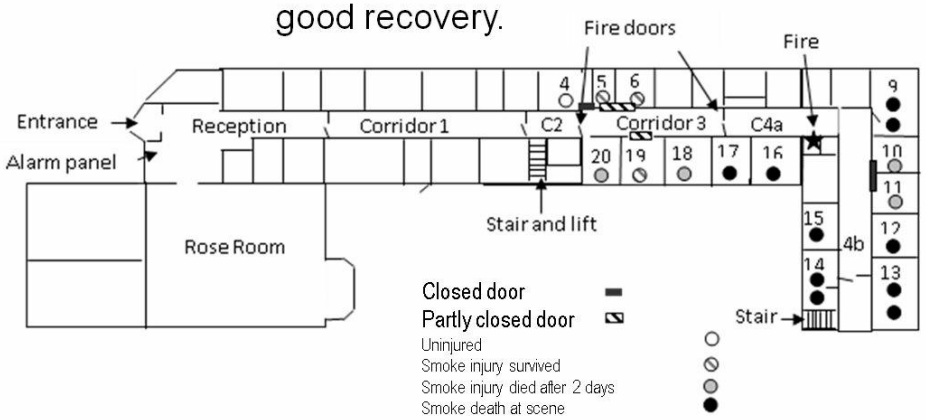
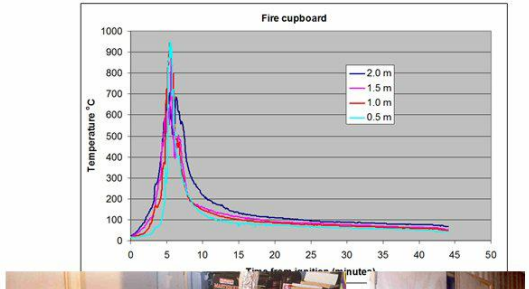
Rosepark care home fire 14 deaths

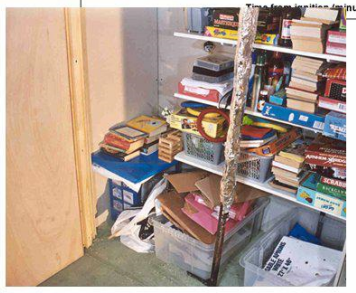
Short violent fire in a cupboard open to a corridor:

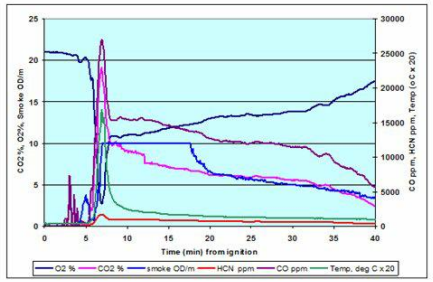
Exposure of 18 elderly persons to the smoke and gases but at different levels of severity and exposure time depending on their location.

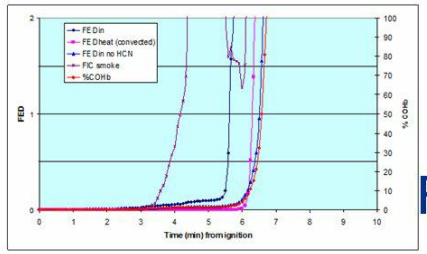
1. Corridor and open rooms filled with dense lethal smoke within a few minutes: 10 persons exposed and dead in bed within 8-9 minutes of ignition
2. 4 persons in more protected locations (in closed rooms or open rooms off corridor beyond fire doors) exposed to lower smoke concentrations for long periods of 33-58 minutes. Rescued alive (2 semi-conscious, 2 comatose and never recovered consciousness: all 4 died after a few days in hospital from bronchopneumonia)
3. 4 persons in even more protected locations (2 barrier doors between them and the fire) exposed to lower smoke than group 2 for around 33 minutes before rescue. One unconscious, one semi-conscious, all made a good recovery.











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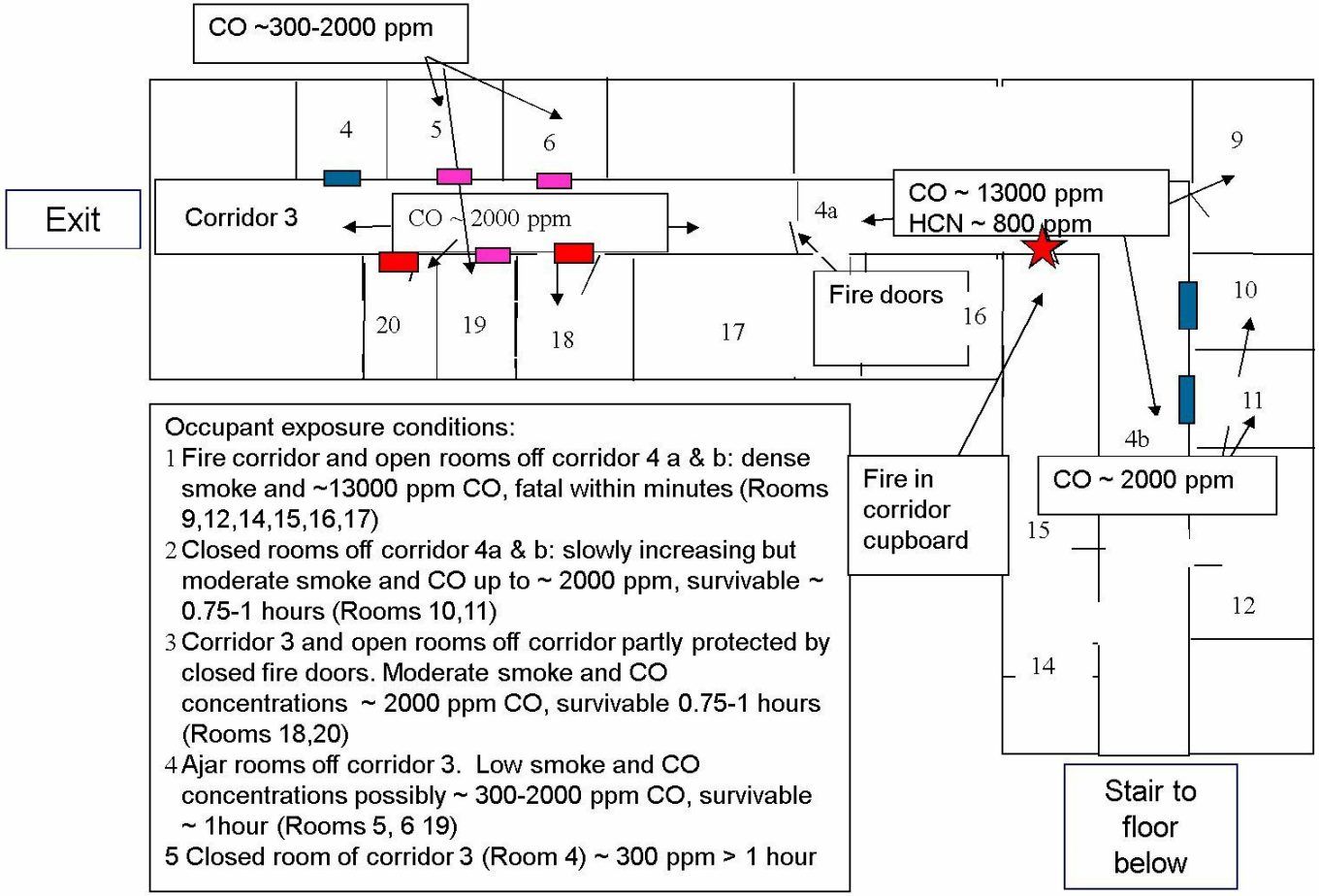
Nursing home fire – 14 deaths

Fire in open cupboard in corridor 4a. Effluent spread into open and closed rooms and through fire door into corridor 3 and adjoining rooms



Occupant exposure conditions:

1 Fire corridor and open rooms off corridor 4 a & b: dense smoke and ~13000 ppm CO, fatal within minutes (Rooms 9,12,14,15,16,17)

2 Closed rooms off corridor 4a & b: slowly increasing but moderate smoke and CO up to ~ 2000 ppm, survivable ~ 0.75-1 hours (Rooms 10,11)

3 Corridor 3 and open rooms off corridor partly protected by closed fire doors. Moderate smoke and CO concentrations ~ 2000 ppm CO, survivable 0.75-1 hours (Rooms 18,20)

4 Ajar rooms off corridor 3. Low smoke and CO concentrations possibly ~ 300-2000 ppm CO, survivable ~ 1hour (Rooms 5, 6 19)

5 Closed room of corridor 3 (Room 4) ~ 300 ppm > 1 hour

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Fractional Toxic Effects

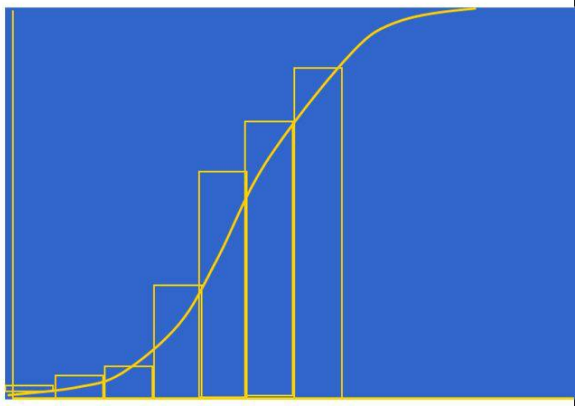
In order to assess effects of each toxic gas in a fire at any time use Fractional Effective Concentration (FEC) and Fractional Effective Dose (FED) methods:

$$\int C \times \Delta t / Ct = FED$$

FEC is used for those hazards for which immediate concentration is important (smoke and irritant gases).

FED is used for those hazards for which a certain dose level acquired over a period of time is important (asphyxiant gases and the effects of heat)

$$FED = \int_{t1}^{t2} \sum_{i=1}^{n} \frac{C_i}{(Ct)_i} \Delta t$$



When either FEC or FED crosses or reaches 1 on the y-axis on the graphs in successive slides, it represents an end-point.

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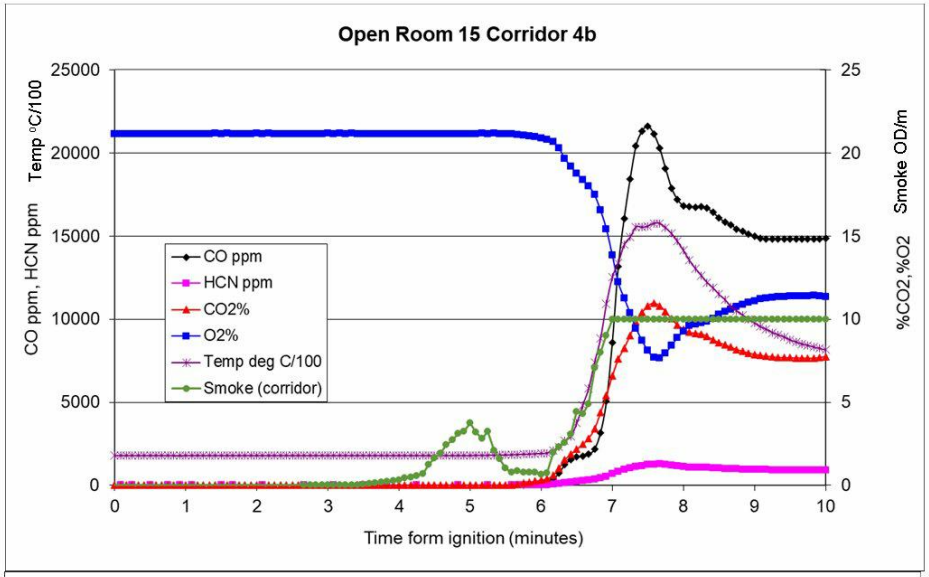

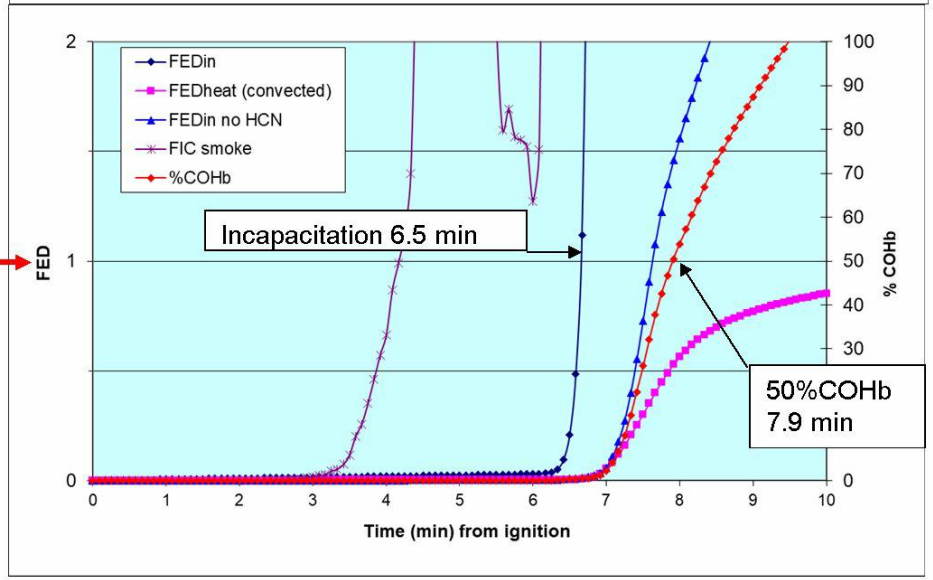

Incapacitating effect FED= 1

Reconstruction fire results

Open room (15) off fire corridor 4b

Fractional Effective Dose (FED) analysis of effects on occupants.
Escape impairment or incapacitation when FED or FEC is >1

FED analysis:
unconscious 6.5 minutes
Toxicity: Lethal 50% COHb 7.9 minutes
Heat: minor discomfort up to 10 minutes
Post mortem: no or very minor burns predicted depending on room

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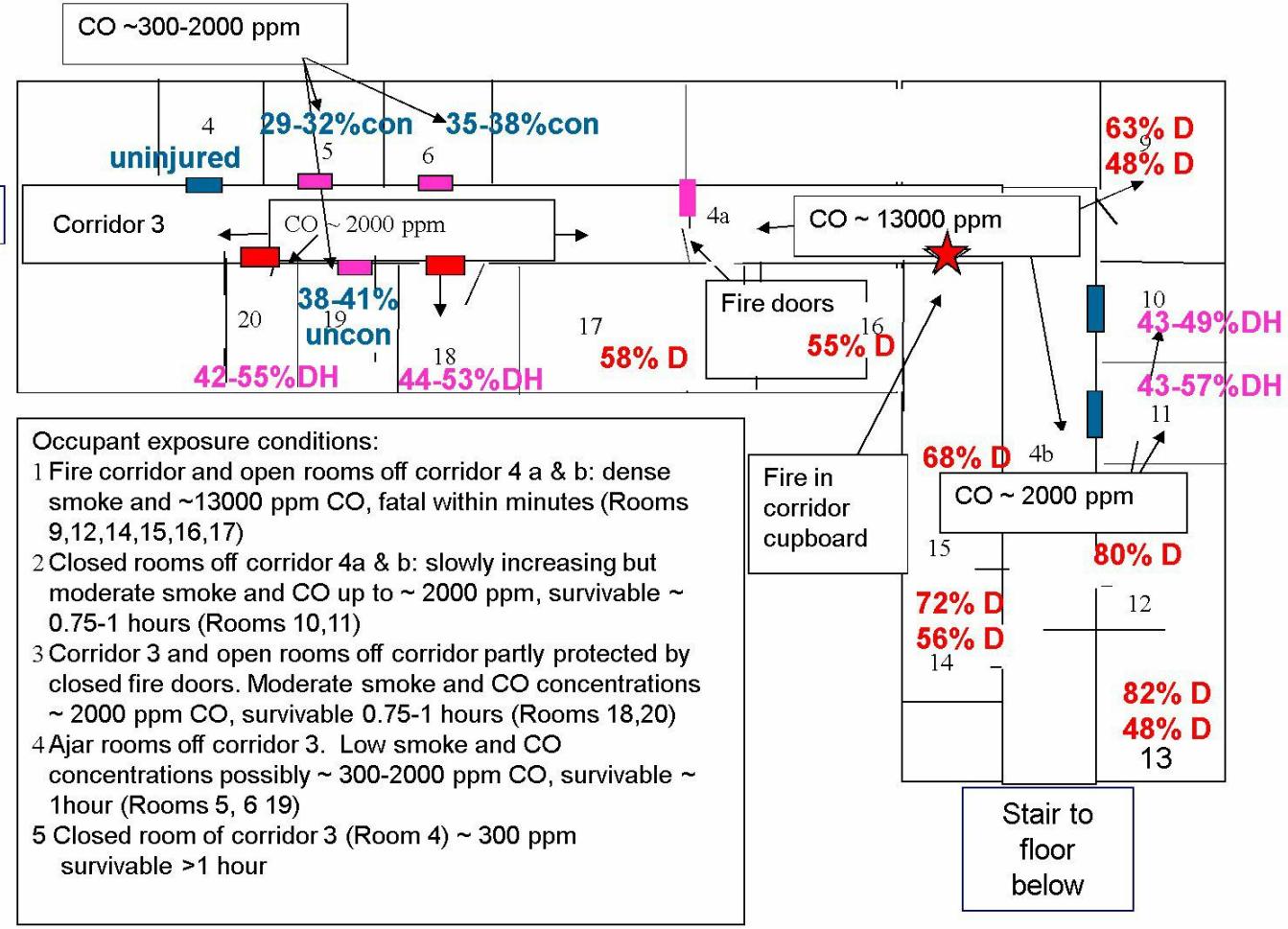
Nursing home fire

Reconstruction fire test: measured CO and incident actual %COHB at time of rescue in different locations



For fatalities:
All bodies intact after fire, full autopsy, burns and blood %COHb toxicology data

For survivors:
Hospital records of injuries and blood %COHb data

Occupant exposure conditions:

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5 Closed room of corridor 3 (Room 4) ~ 300 ppm survivable >1 hour

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Example of previous fire incident: Rosepark care home

- Detailed fire incident investigation: examination of the fire scene, detailed interviews with survivors and other witnesses
- Full-scale reconstruction fire test of the parts of the building affected by the fire, including the same materials and contents as in the actual incident
- Replication of the original fire with measurement of the time-concentration curves for smoke, heat and toxic gases in different locations.
- Calculation of time to incapacitating effects of exposure to irritant smoke and asphyxiant gases (carbon monoxide and hydrogen cyanide) using physiological (FED) models
- Calculation of predicted extent of burns and uptake of carbon monoxide as %Carboxyhaemoglobin (%COHb) in blood of fire survivors and fatalities
- Forensic data on actual burns and %COHb in fatalities and survivors
- Comparison of predicted effects from reconstruction fire with actual data from fatalities and survivors provided validation that reconstruction fire was similar to actual incident and enabled good evaluation of causes and timing of incapacitation and death.

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Information available for Grenfell

For Grenfell incident:

- Very large and complex fire with differing development in individual flats so full reconstruction not feasible.
- Fire burned for a very long period (~24 hours) so that the building and its contents were very different after the fire than they were during the early stages when most occupants were exposed to heat and toxic smoke. Combustible contents of many flats almost completely burned out.
- Bodies of many fatalities were almost completely consumed during this extended fire so it is difficult to establish the conditions they were exposed to during the fire before they died.
- Pattern of fire development and smoke spread into and through the Tower very complex, involving penetration into flats of a proportion of combustion products from exterior cladding and insulation materials, from the structural materials around windows and then successive involvement of fires in the contents of different flats.

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What can be done for Grenfell

- It is possible to identify a set of different exposure scenarios for Grenfell occupants similar to those common in domestic fire incidents (fires in houses and flats) for which there is detailed information on the developing fire conditions and the effects on occupants (Rosepark is one example)
- From the information we do have on the development of the Grenfell fire and this data, from previous incidents and experimental fires, it is possible to estimate the likely effects on Grenfell occupants
- From information on the fire performance, smoke and toxic gas yields of generic versions of the exterior and interior structural materials at Grenfell, and of typical house and flat contents (furnishings and appliances), the possible contributions to the development and spread of toxic smoke into and through the Tower with time can be estimated approximately.
- I have used the above sources to estimate the likely general effects on Grenfell occupants

Valuable data from the actual Grenfell incident

- In order to validate these estimates for individual Grenfell occupants I am making a detailed examination of:
  - witness statements, oral evidence
  - transcripts of emergency telephone calls from occupants during the incident.
- I am finding these extremely valuable and effective in understanding the experiences of occupants during the fire and the effects of exposure to toxic smoke, both for those who survived and many of those who subsequently died during the fire.
- Witness descriptions of how smoke and flames penetrated different flats, the lobbies and the stair are also providing me with a good understanding of these aspects, which I am using to validate my generic predictions of likely smoke development, spread and composition.

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What can be done for Grenfell

For the Grenfell incident:

- Blood toxicology data including %COHb concentrations for 15 fatalities, who died in some flats, lobbies or on the stair.
- Photographs of the remains of these fatalities (I am awaiting the full autopsy reports).
- This information, taken together with the witness accounts and emergency call transcripts, considered in the context of data from previous incidents, is providing me with a good basis for assessment of causes of incapacitation and death for Grenfell fatalities.

Were Grenfell fatalities affected by heat or burns before they died?

- From my review of the Grenfell-specific evidence so far, and data from previous incidents, it is a strong possibility that those who died did so from smoke inhalation rather than being burned.
- I place particular emphasis on the available %COHb data.

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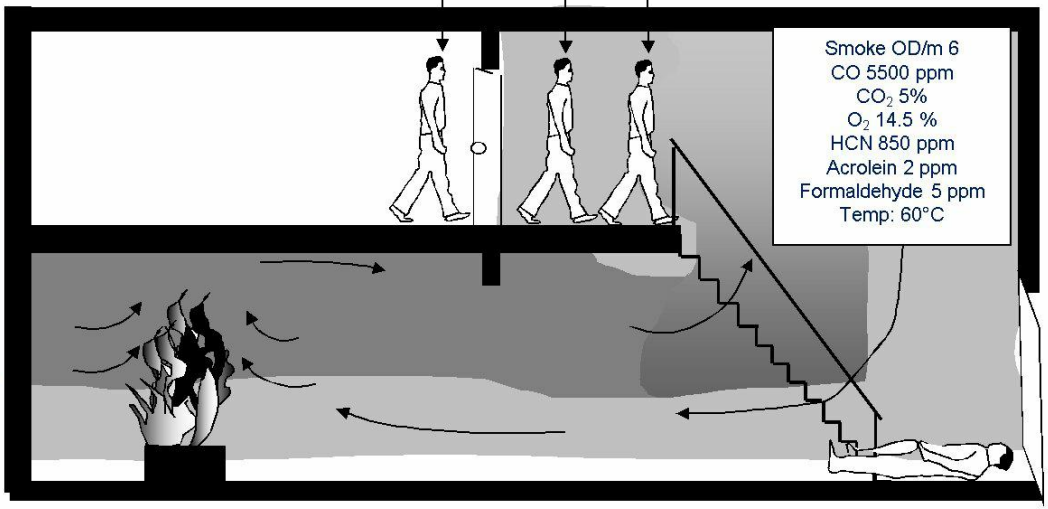
Sequence of fire hazards



Before entering

0

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

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

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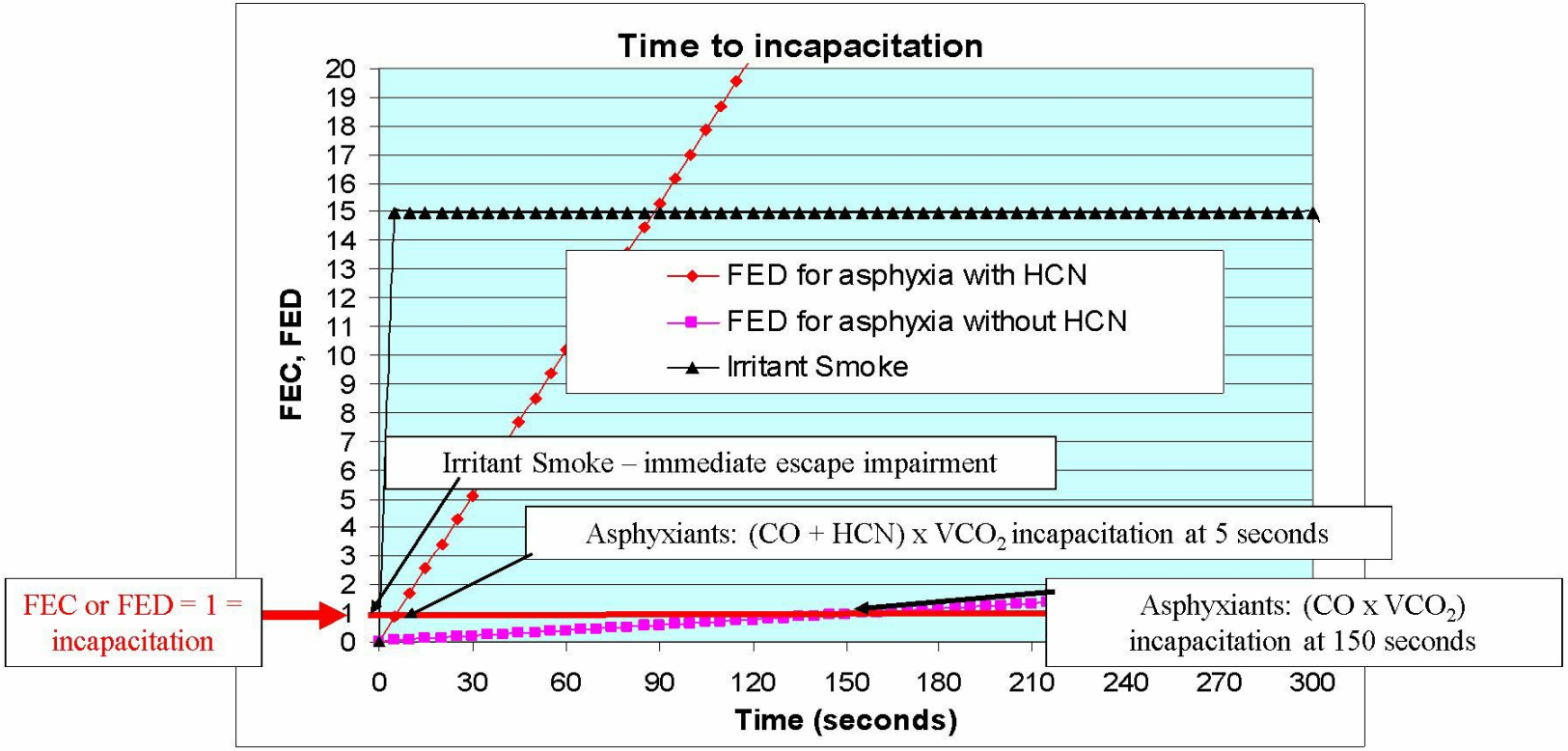
Fractional Physiological Effects

FED (Fractional Effective Dose) analysis for the lounge/bedroom fire scenario: FED = Dose inhaled/Dose required for incapacitation

Incapacitation is predicted when any of the terms FED or FEC > 1



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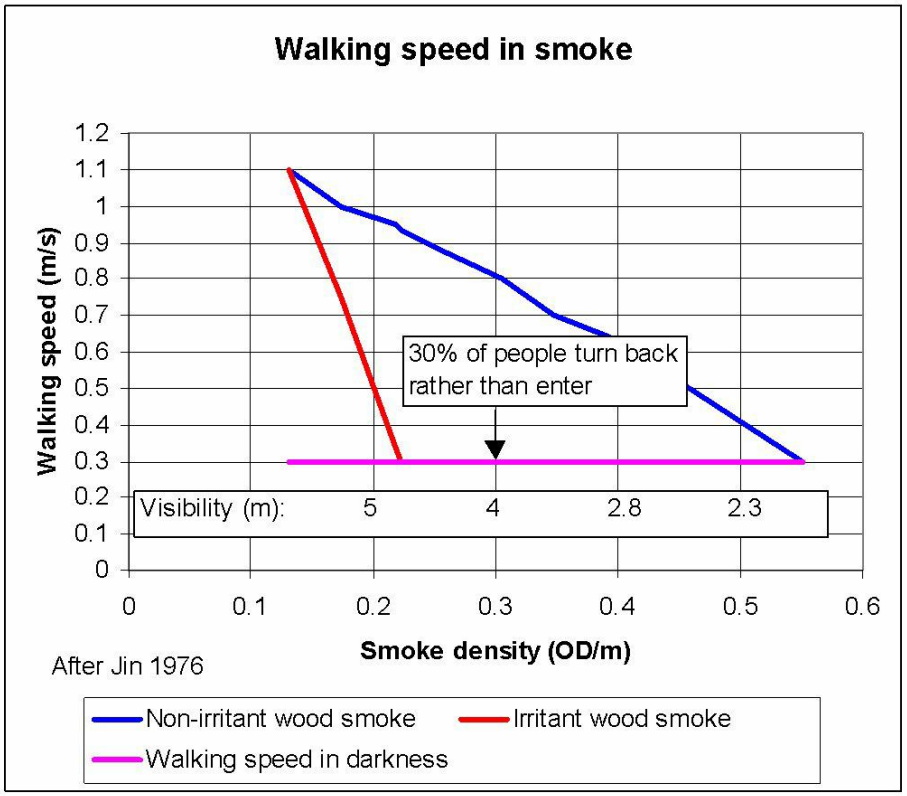
Hazards from smoke

Effects of acid gases and organic irritants on escape capability

- Bonfire smoke or side-stream cigarette smoke: eye pain, blepharospasm, breathing difficulties and chest pain
- Incident reports of escape difficulties due to irritancy



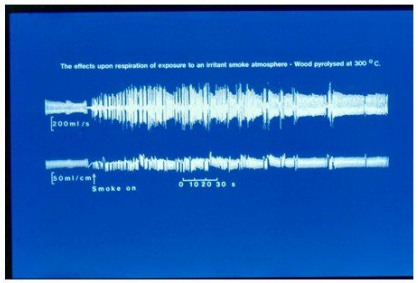
Smoke = carbon particles +

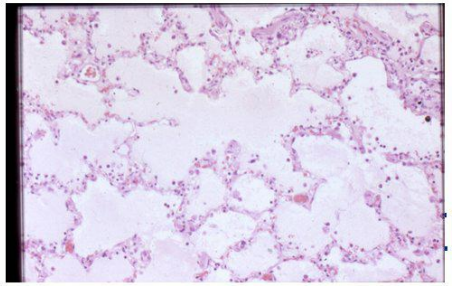
Irritants in smoke::

- Acid gases: HCl, HBr, NOx,
- Organic irritants: acrolein, formaldehyde, isocyanates

Effects:

- Impaired vision, eye pain, eye closure and tears
- Pain to nose, throat and chest
- Bronchoconstriction
- At low-moderate concentrations slow movement and turning back
- At high concentrations incapacitation
- Lung oedema and inflammation after exposure





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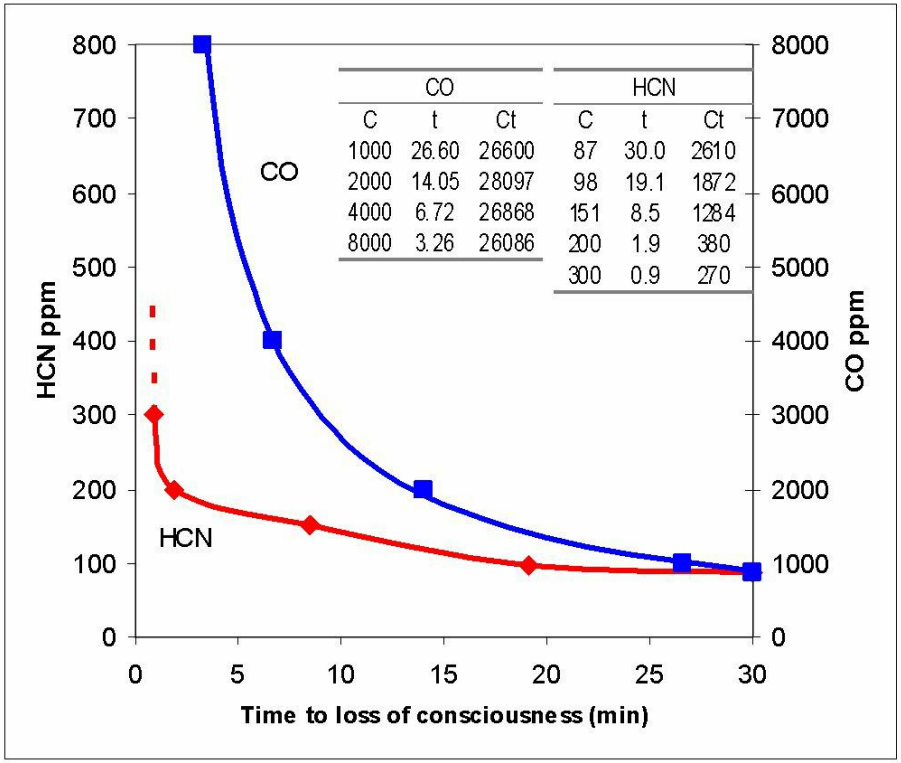
Time to incapacitation for HCN, CO and CO_2 exposure

- HCN present at 1000 ppm in domestic fires causes rapid incapacitation but dynamics of uptake and dispersal in blood result in low post-exposure blood CN, and CN unstable in blood, whereas COHb very stable
- CO is probably the main ultimate cause of death by asphyxiants but HCN may be a major cause of incapacitation
- CO_2 increases rate of uptake of CO and HCN, causes breathlessness and incapacitation above 5%.



CO		
C	t	Ct
1000	26.60	26600
2000	14.05	28097
4000	6.72	26868
8000	3.26	26086

HCN		
C	t	Ct
87	30.0	2610
98	19.1	1872
151	8.5	1284
200	1.9	380
300	0.9	270

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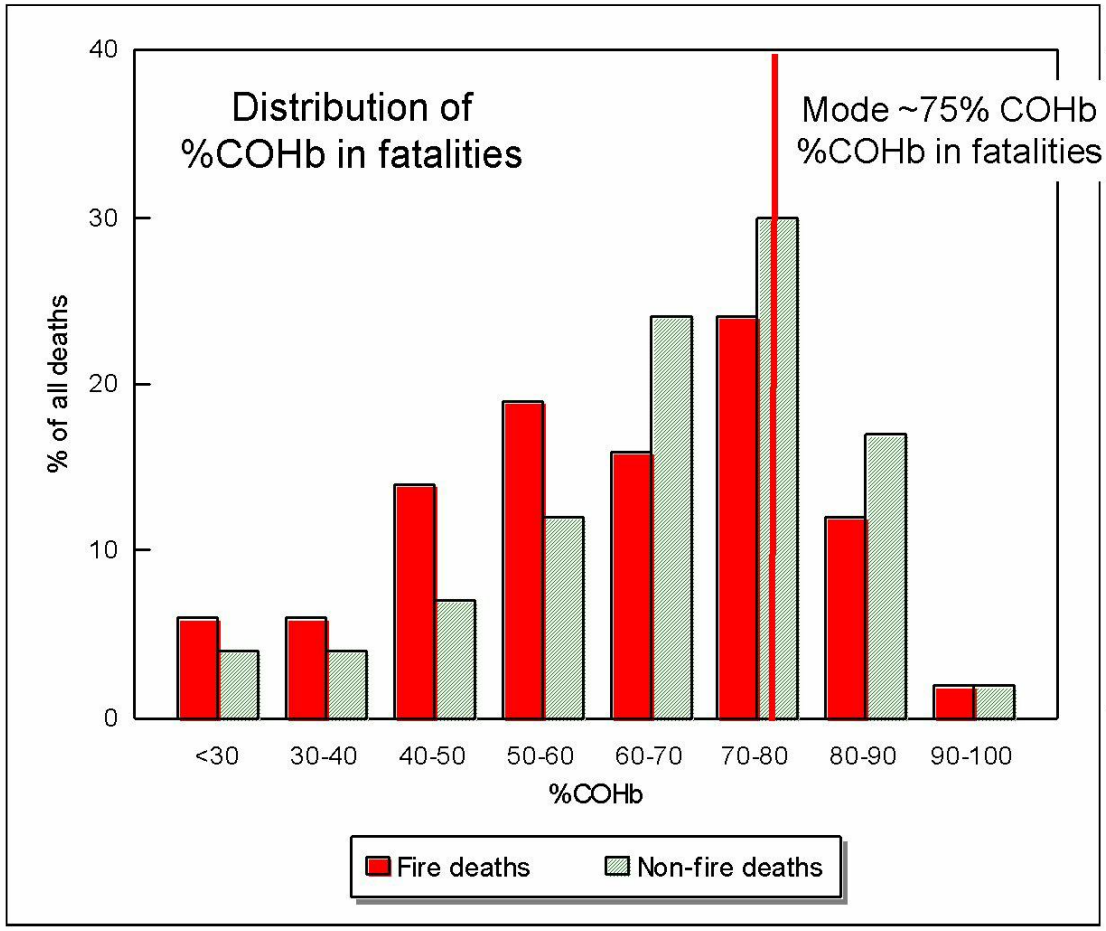
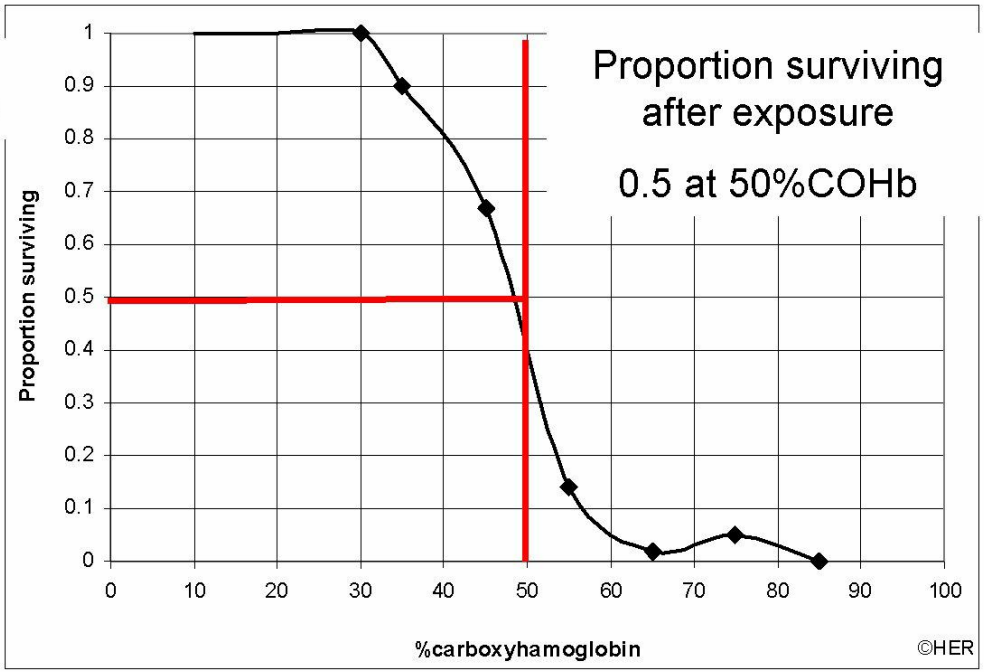
COHb post-mortem fire and non-fire





After Nelson and Pach

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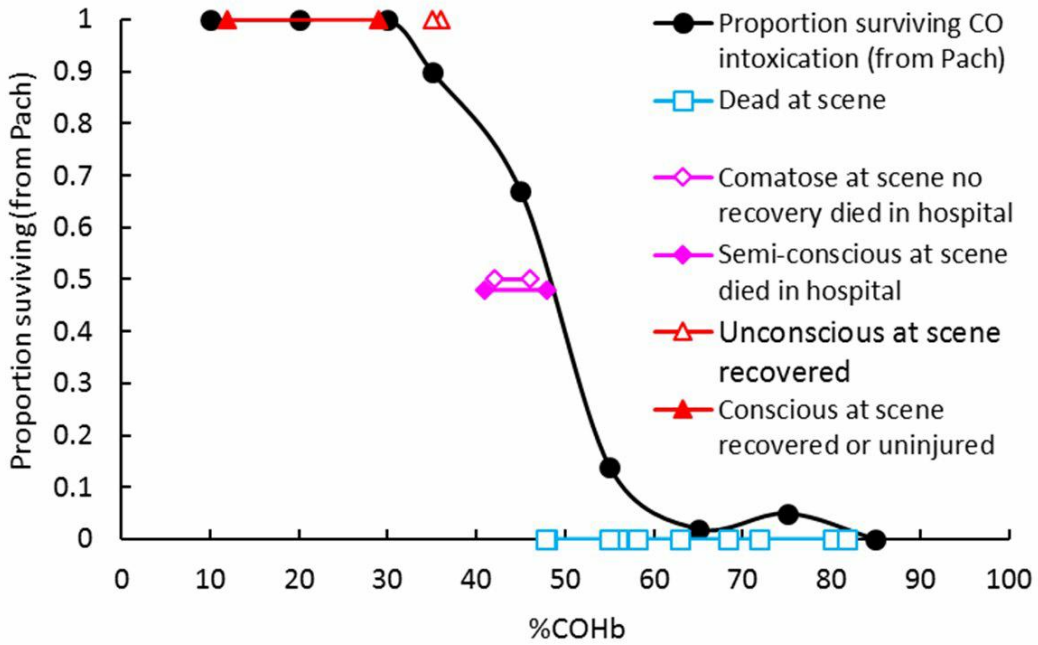
Comparison with Pach survival data



- Black curve shows proportion of 260 CO cases all ages surviving after rescue
- Full recovery up to 30%COHb – as at Rosepark
- 35% COHb: almost all recover – Rosepark 2 unconscious but full recovery
- 40-55% COHb steep decrease in survival – Rosepark 2 ~dead at scene 2~ recovered.
- 50%+ COHb almost always fatal: Rosepark all died

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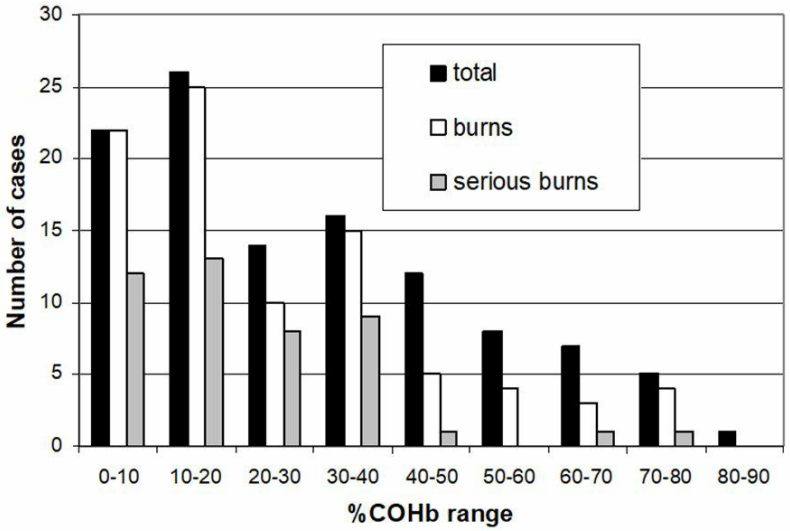
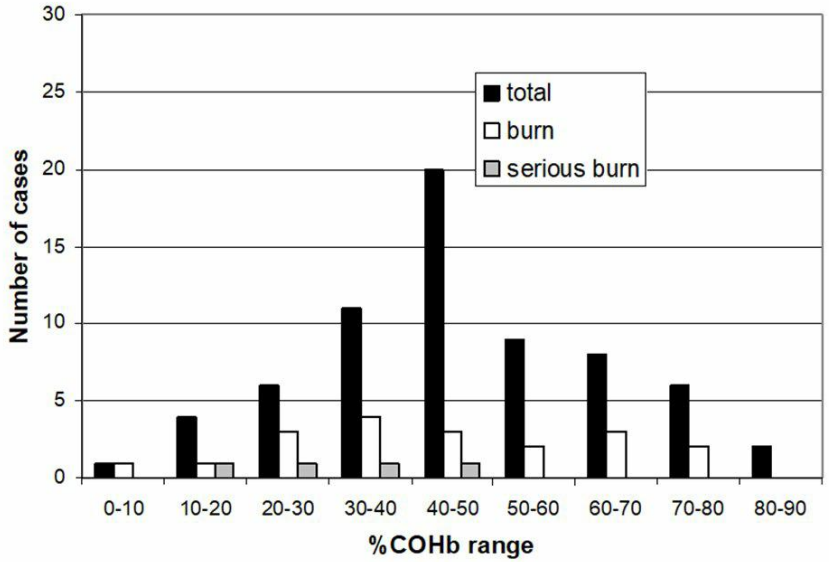
%COHb London Cases and Rosepark

Occupant in room of fire origin



Occupant remote from room of fire origin



"serious burns" = burns mentioned as a cause of death 10% COHb added to hospital cases to allow for reduction during treatment before death
In room of origin all with sub-lethal %COHb (<~40%) have burns and a many have lethal burns.
33 cases have lethal %COHb and less burns
In remote locations beyond room of origin few have burns and the most have lethal %COHb

Almost all dwellings. 111 room of origin 67 remote location (includes 14 Rosepark care home deaths)

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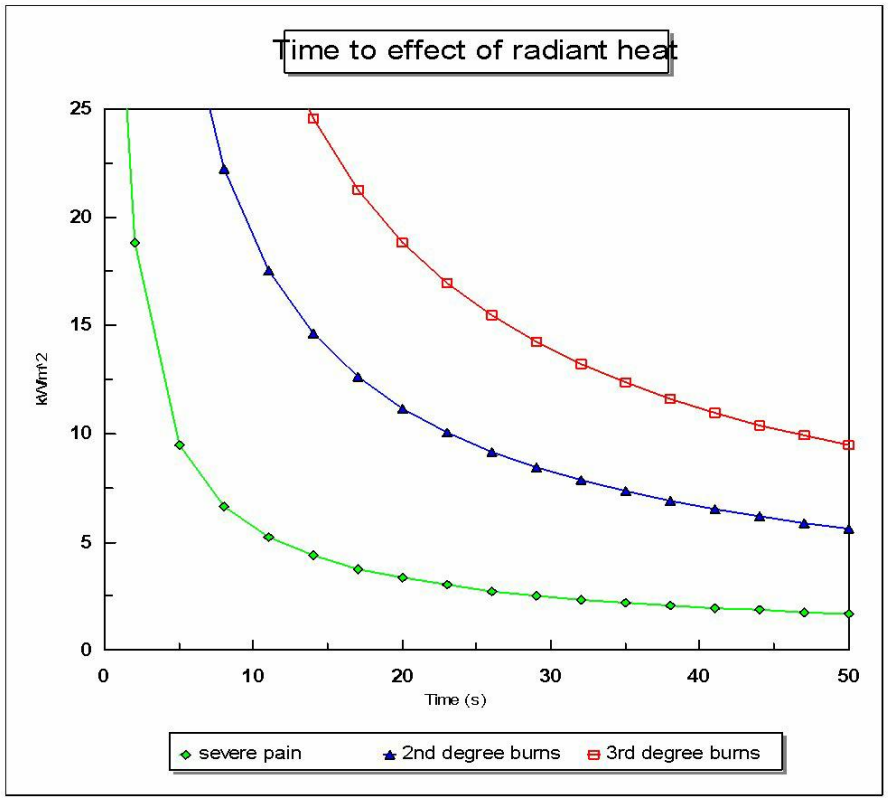
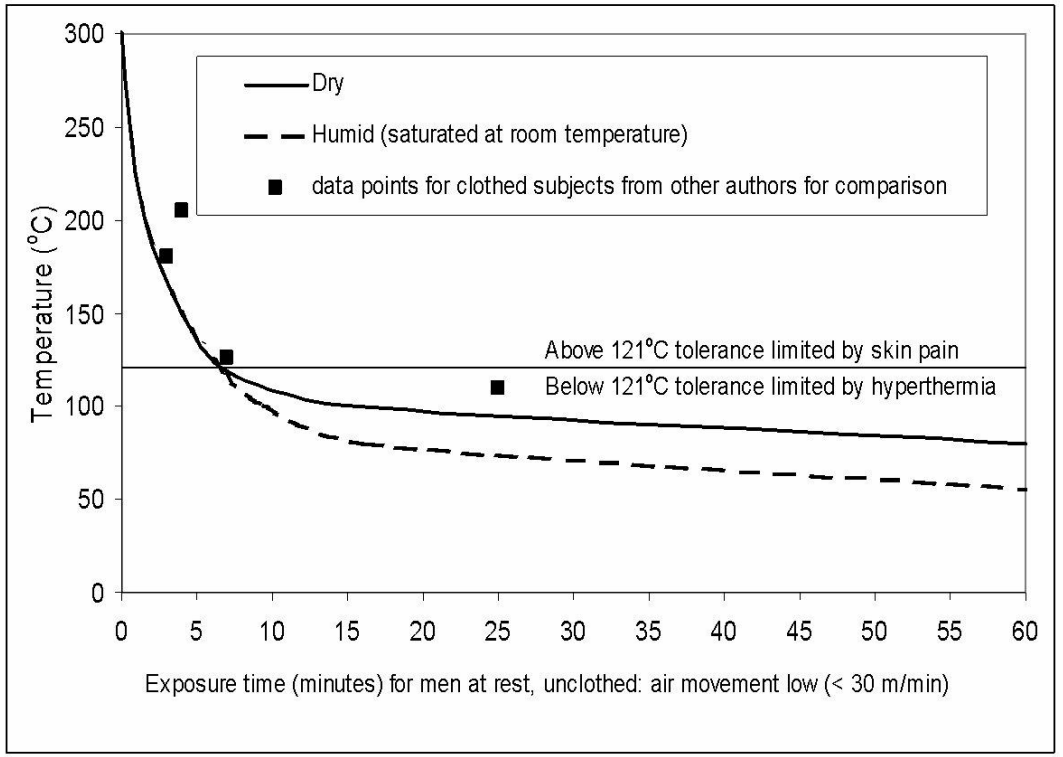
Hazards from radiant heat

$$t_{Irad} = \frac{80}{q^{1.33}} \quad (1)$$



Tolerance time for exposure to convected heat



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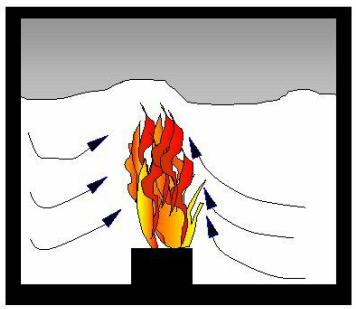
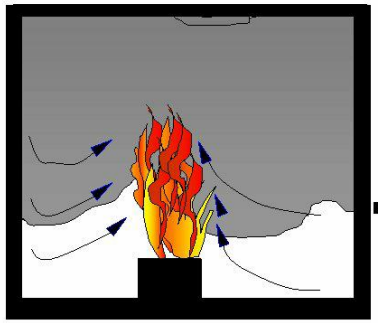
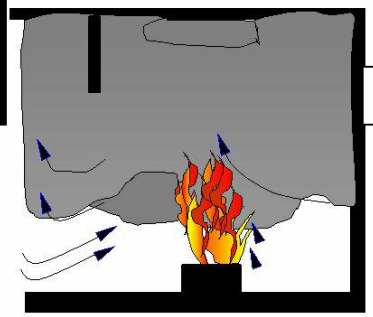
Main fires types and hazard scenarios

1. **Non-flaming/smouldering fires**
2. **Early/well ventilated flaming fires**
3. **Ventilation controlled fires**
   - **pre-flashover under-ventilated flaming fires**
   - **post-flashover under-ventilated flaming fires**



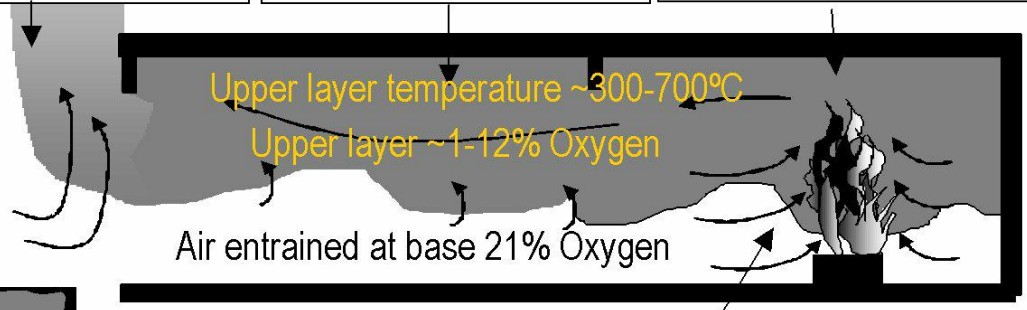




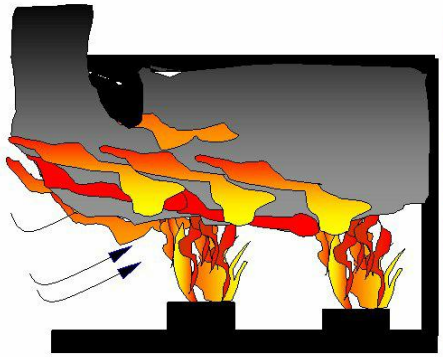
Fuel rich plume may show some flaming as entrained with fresh air if hot enough

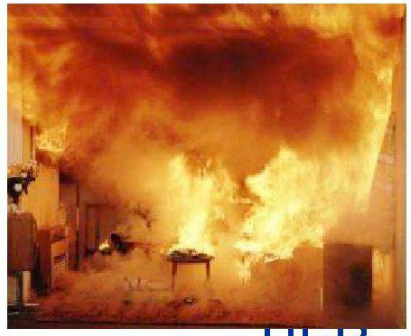
Upper layer oxygen concentration lower than in enclosed fire (down to 1-2%), with higher CO and HCN concentrations

Fire grows initially using enclosure air, then settles to a maintained size depending on ventilation until fuel consumed



Continued burning maintained by fresh air supply to lower part of fire plume





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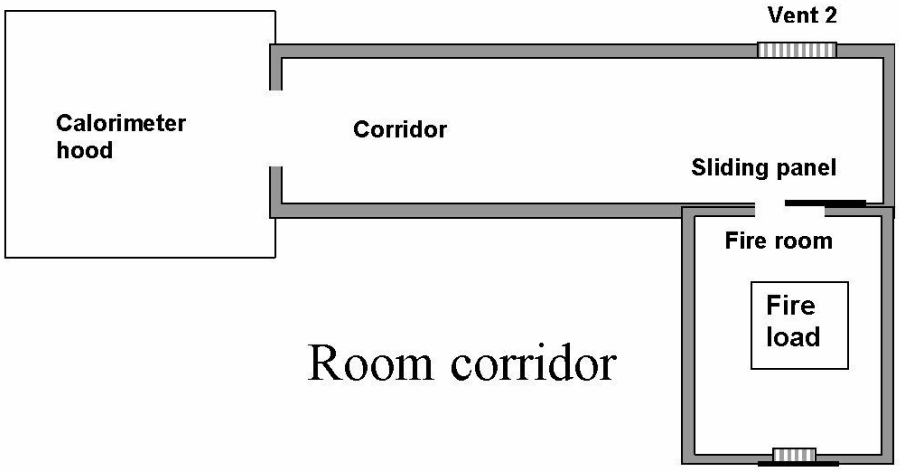
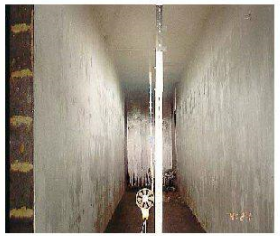
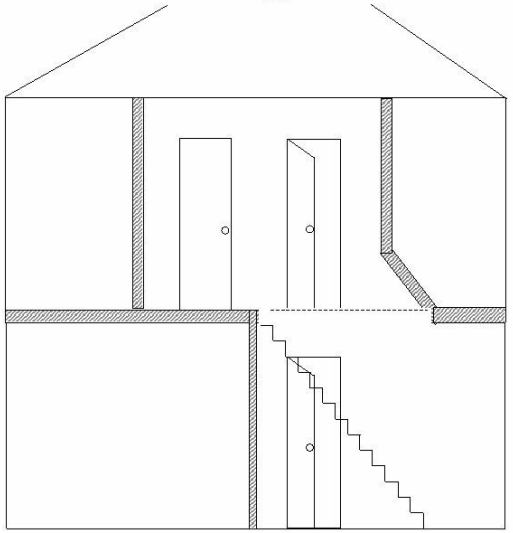
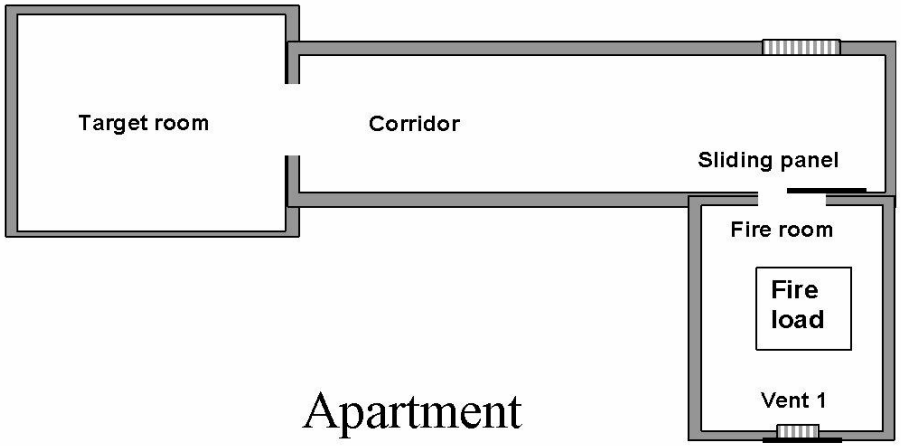
Fire test rigs



Room corridor







Apartment

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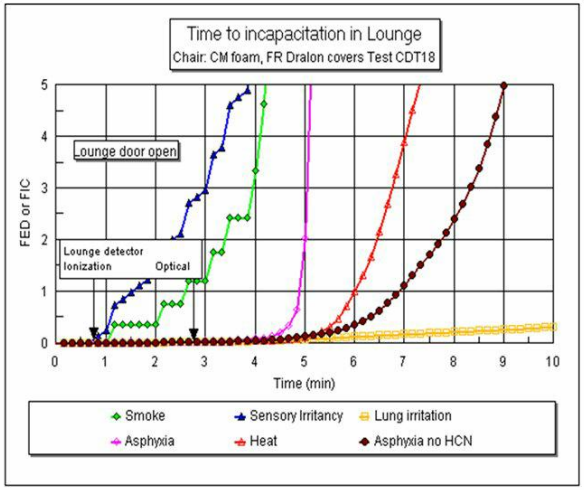

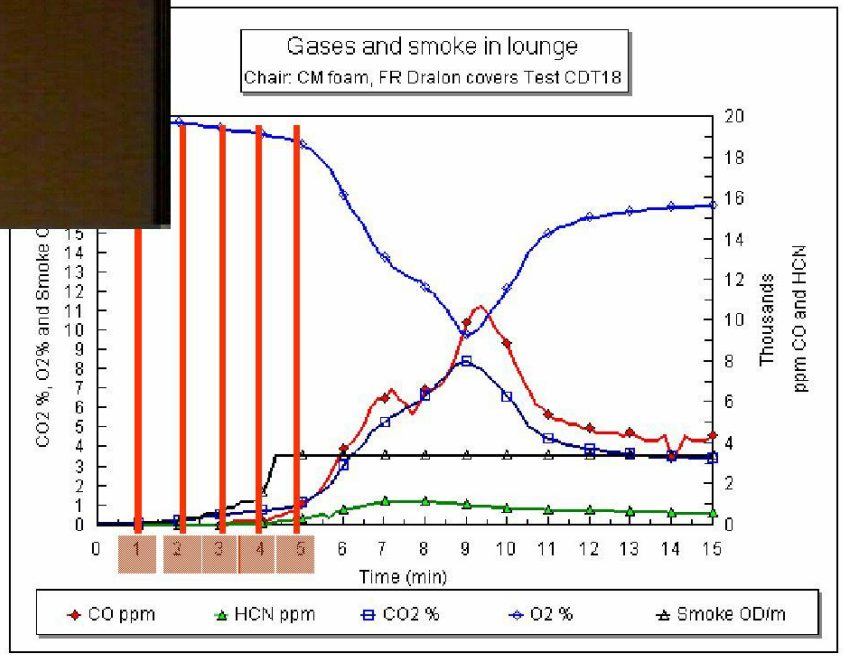

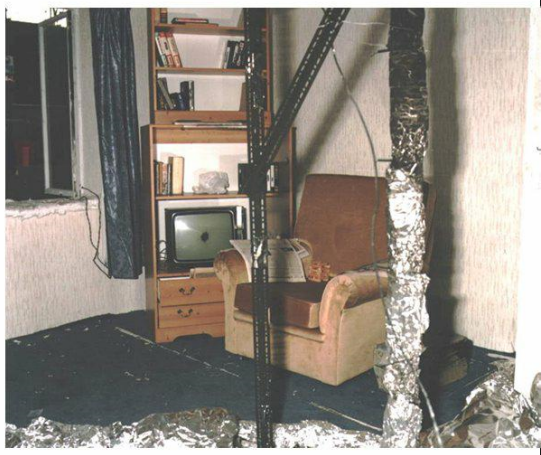

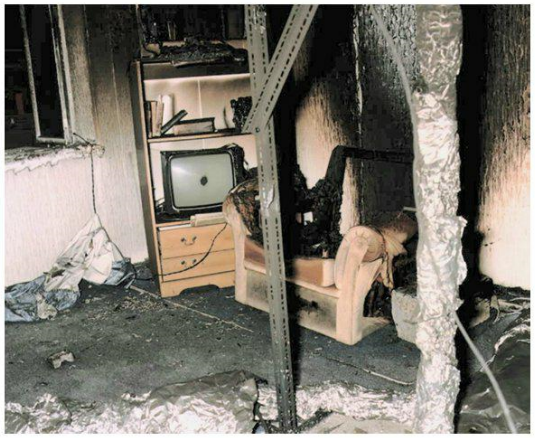

BRE furniture house fire test

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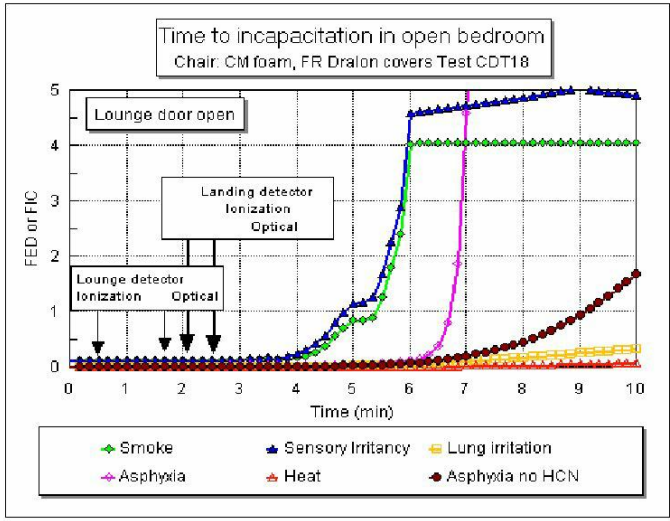

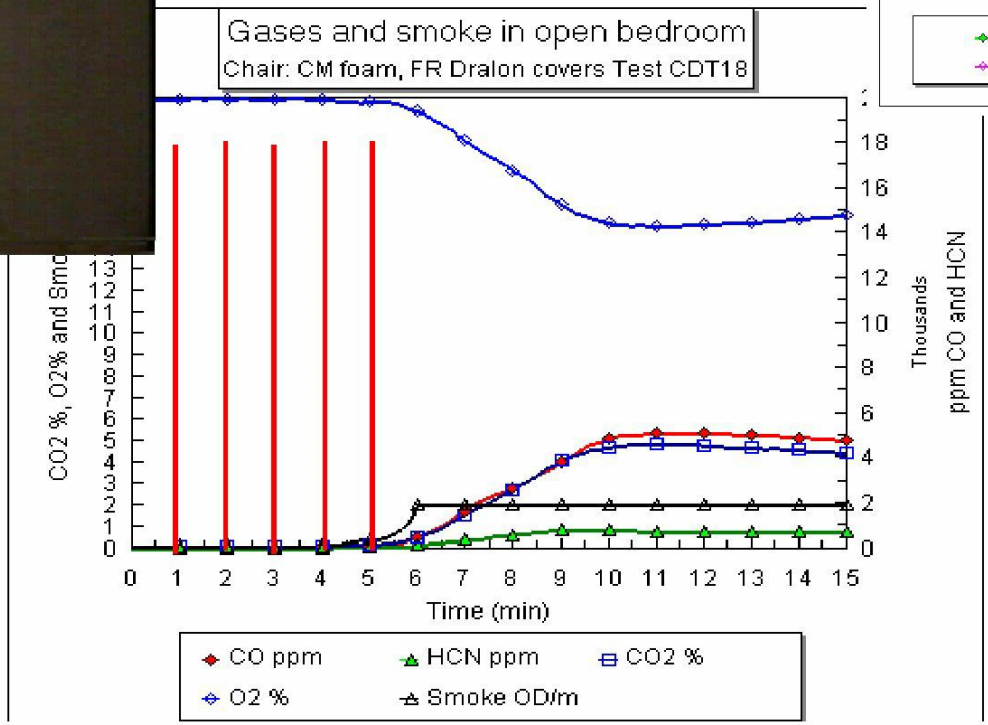

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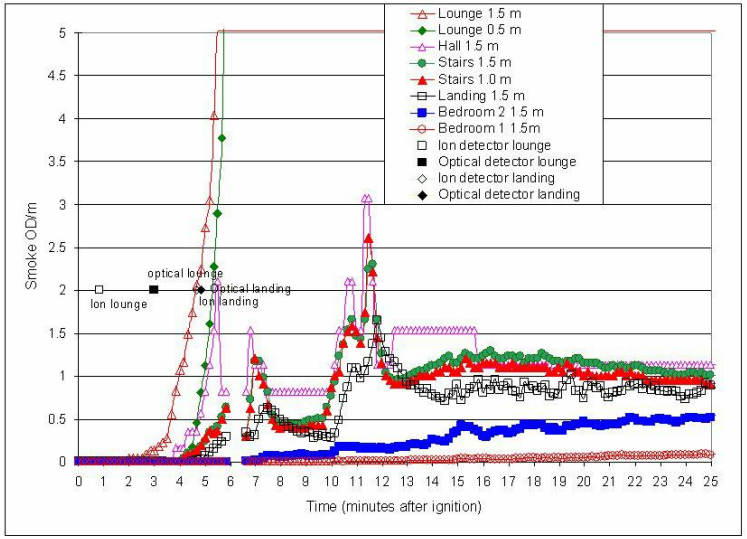
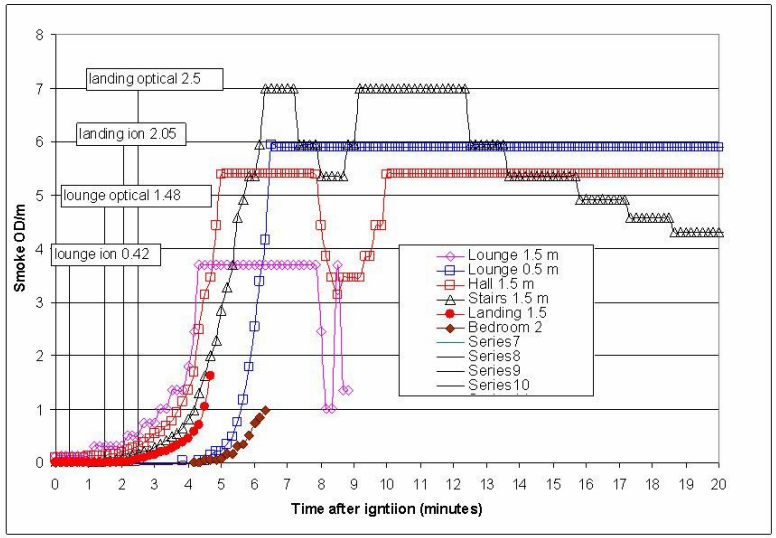
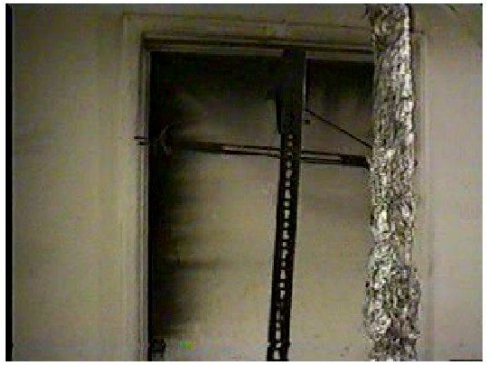
CDT16 and 18 house fires smoke





CDT16 smoke: fire room door closed

CDT18 smoke: fire room door open



Overpressure in lounge pushes smoke out into hallway – leaking around the edges of the door
Also reported by Grenfell flat occupants

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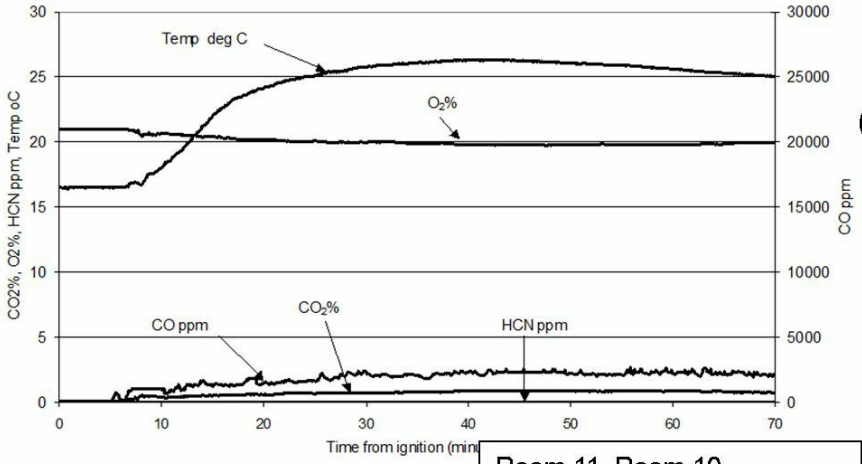
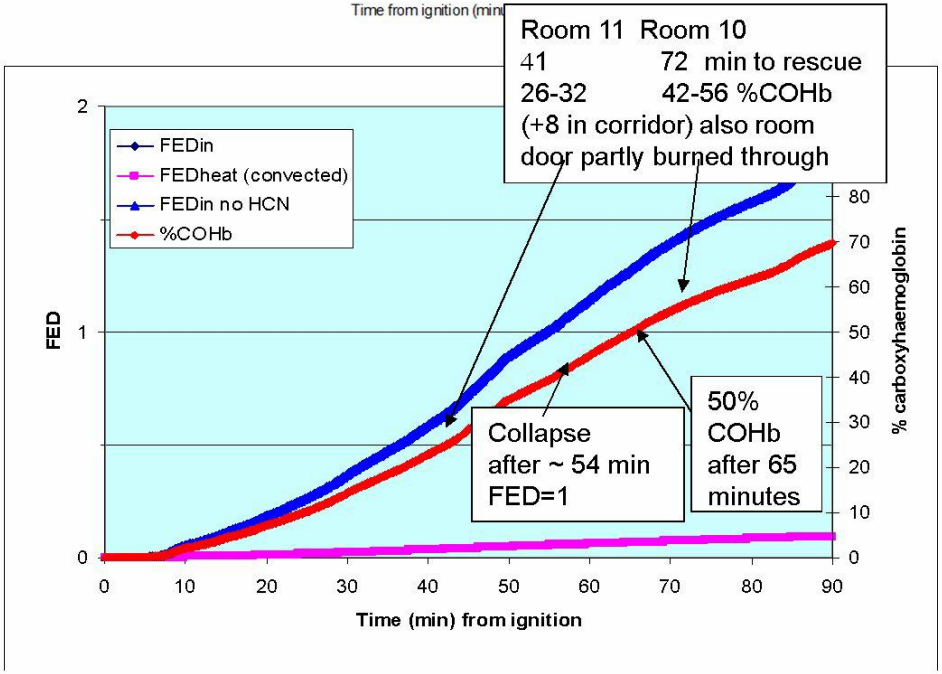
Reconstruction fire results



Closed room (11) off fire corridor 4b

But did actual doors have similar leakiness to reconstruction doors?



FED analysis:
unconscious ~ 54 minutes
Toxicity: Lethal 50% COHb ~ 65 minutes
Heat: no effect
Prognosis: minor effects in closed room up to ~ 40 min. fatal from ~ 65 min. But up to around 1 minute additional exposure in corridor during rescue
Both receive significant toxic dose before rescue, may be incapacitated

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FED tenability as a function of visibility

For any given smoke visibility how far can people go before they collapse from asphyxia (FED=1) ?

- These examples of different domestic fire scenarios and effects on occupants can be useful to estimate the likely experiences and effects on Grenfell occupants exposed in similar situations including:
  - Staying in flats during rapid dense smoke and flame penetration into flats
  - Staying put in flats as smoke penetrates over an extended period
  - Entering dense smoke in lobbies and stair to attempt escape
- But because the time-concentration curves for smoke and toxic gases throughout the flats, landing and stair at Grenfell are unknown, estimates of effects can only be approximate
- One set of information we do have for Grenfell is descriptions of the smoke density and toxicity at different times and locations from occupant witness statements and transcripts of emergency 999 calls.
- Because the ratio of smoke density to the concentrations of toxic gases in the smoke remains constant as smoke moves through the building it is possible to estimate the toxic hazard at any location from the smoke density and the yields of smoke and toxic gases formed during combustion.

- If smoke density is low so that visibility is good, for example > 10 metres, then the concentrations of asphyxiant gases in the smoke are so low that exposure can be tolerated for more than 60 minutes without serious effects
- If smoke density is so high that “you cannot see your hand in front of your face” then the concentrations of asphyxiant gases are likely to be high enough to cause collapse within a few minutes if inhaled
- The ratio of visibility to toxicity (time to collapse) depends on the yields of toxic gases in the smoke which in turn depend on the composition of the fuels burned to generate the smoke and the conditions they are burned under.

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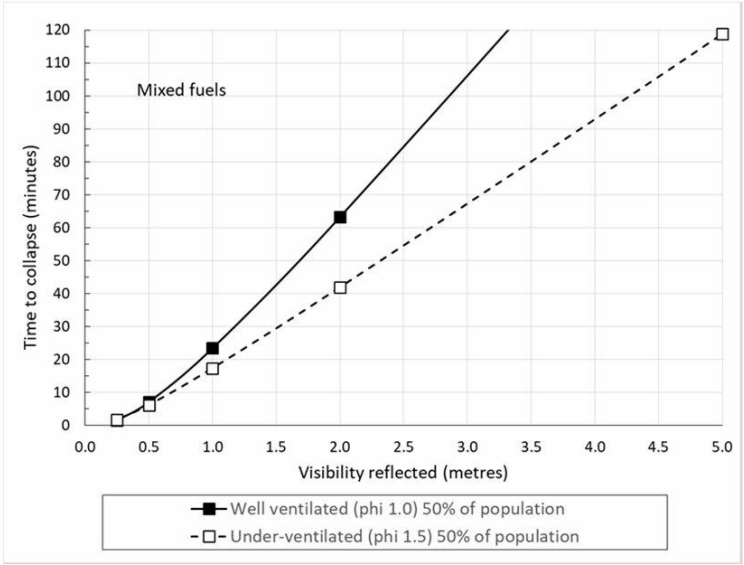
FED tenability as a function of visibility

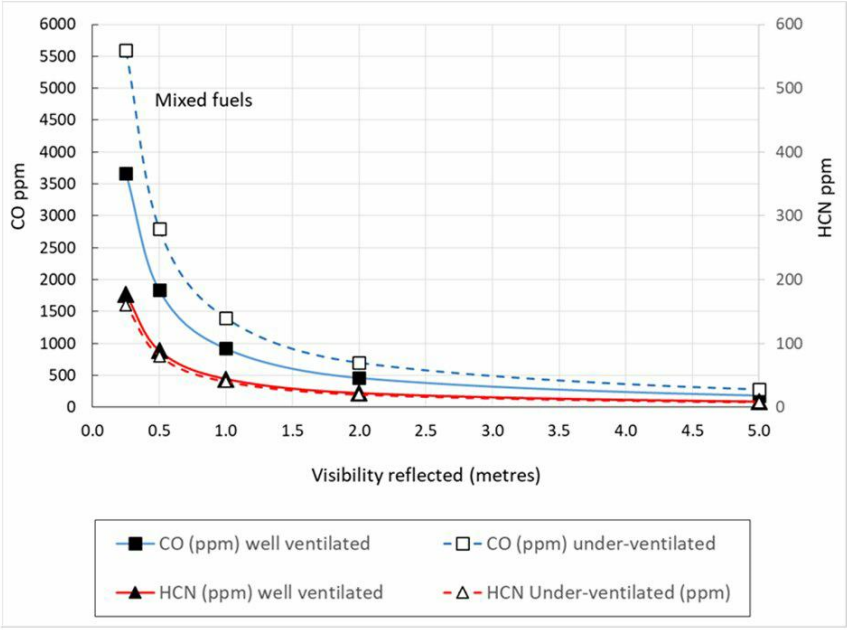
For any given smoke visibility how far can people go before they collapse from asphyxia (FED=1) ?

Time to incapacitation calculated from CO, HCN, CO_2 and O_2 concentrations and FED expressions

Can express tenability time as a function of smoke density (or visibility) since toxic gas/smoke ratio is constant

- From data for different fuels time to incapacitation can be calculated as a function of smoke density.
- Simple limit value for any flaming fuel: at 10 metres visibility no toxicity for up to 60 minutes even in sensitive subjects
- Time to collapse at a particular smoke visibility depends on fuel mix, combustion conditions and individual susceptibility.
- For mixed fuels well ventilated combustion conditions ($\varphi<1$) at 2 m visibility average person could walk for up to 1 hour before collapse, reducing to 40 minutes for under-ventilated combustion.
- For most sensitive subjects (1% of population) these times reduce to 19 and 13 minutes.





- Even under worst case toxicity conditions tenability time at 2 m visibility is at least 13 minutes.
- A subject walking at 0.3 metres/second could cover ~ 250 metres in this time
- This can be used to assess the hazards to Grenfell occupants at different times and locations

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Summary for generic hazard analysis

- Using data from past fire incidents and full-scale experimental fires coupled with FED physiological methods for calculating time to incapacitation and death it is possible to identify a set of fire exposure scenarios occurring at Grenfell and likely effects on occupants.
- By expressing FED tenability as a function of visibility it is possible to estimate hazards from irritant smoke and asphyxiant gases at different times and locations at Grenfell from witness accounts of visibility and reported toxicity symptoms
- %COHb measured in the blood of some Grenfell fatalities, related to that from previous incidents can be used to determine the extent of exposure of these fatalities to toxic smoke or heat and burns.

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