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The assessment of fire hazards, tenability and human evacuation behaviour for fire safety engineering design
Erasmus Mundus Programme

Assessment of physiological and toxic hazards in fires

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Aspect of combustion toxicology

In this lecture I plan to cover some aspects of:

- The nature of fire hazards
- Acute toxic effects of fires and methods for assessment

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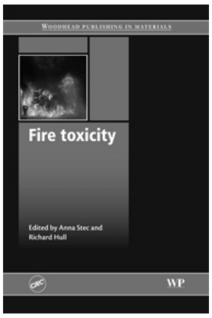
Book



Fire toxicity

Edited by A A Stec and T R Hull, University of Central Lancashire, UK

March 2010

Woodhead Publishing/CRC

ISO TC 92/SC 3 "FIRE THREAT TO PEOPLE AND THE ENVIRONMENT"

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Life safety objectives of Fire Safety Engineering Design:

- **Fundamental issue: Determination of the life safety objectives of a design:**

  ISO/TR 13387-8 Fire safety engineering Part 8: Life Safety - Occupant behaviour, location and condition

  "Should a fire occur in which occupants are exposed to fire effluent and/or heat, the objective of the fire safety engineering strategy is to ensure that such exposure does not significantly impede or prevent the safe escape (if required) of essentially all occupants, without their experiencing or developing serious health effects".

  Design to ensure as far as possible that no exposure occurs during the majority of envisaged scenarios. Where exposure is likely during more extreme scenarios need is to consider effects during a fire and potential effects on long term survival and health afterwards.

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Life-safety objective of design

- Occupants should be able to reach a place of safety without exposure to conditions likely to endanger life or health
- For most envisaged scenarios this should mean escape without any exposure to toxic smoke or heat
- For "defend in place" design need to ensure that occupants are protected from unacceptable levels of exposure to fire effluent
- For more extreme low probability scenarios some exposure is likely to occur, toxic hazard assessment enables prediction of likely consequences

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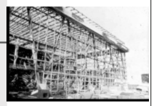
How fire safety is achieved by the Building Regulations

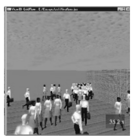
Approved Document B - Building Regulations 2000

Requirement

Means of warning and escape

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





Main aims of enclosure and structural performance:

- Safe environment for occupants for as long as they need to remain in the building
- Safe means of escape with sufficient capacity for all occupants to evacuate in a reasonable time

Regulatory Basis

NFPA 101 Life Safety Code: Scope

1.2.1 Danger to Life from Fire: Construction, protection and occupancy features necessary to minimize danger to life from fire, including smoke, fumes or panic.

1.2.2 Egress facilities: Establishes minimum criteria for the design of egress facilities so as to permit prompt escape of occupants from buildings or, where desirable, into safe areas within buildings

Goals : 4.1.1 ….to provide an environment for the occupants that is reasonably safe from fire and similar emergencies by the following means:

1. Protection of occupants not intimite with the initial fire development
2. Improvement of the survivability of occupants intimite with the initial fire development

Performance-based fire safety design principle

Performance-based design principle (which also applies to prescriptive design):

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
"defend in place" is a special case where both must be effectively very long


Bradford Soccer stadium

Toxic fire hazards

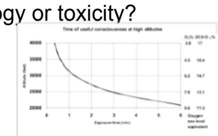
Depend upon two major parameters:

1. Time-concentration curves for major products (gases, smoke and heat)
- **Fire growth curve (mass loss rate of fuel [kg/s] and dispersal volume)**
- **Yield of toxic products (eg kg CO/kg material burned)**

2. Toxic potency of the products

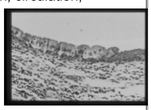
exposure concentration [$kg.m^{-3}$] or exposure dose [$kg.m^{-3}.min$] required to cause toxic effects in terms of :
- **concentrations or doses likely to impair escape efficiency**
- **incapacitating exposure concentrations or doses**
- **lethal exposure concentrations or doses**

Fire physiology or toxicity?



Toxicity = physiology + pathology

Physiological effects:
- Rapidly developing (seconds-minutes)
- Affect immediate vital functions: vision, pain, respiration, circulation, brain (movement ability, consciousness, death)



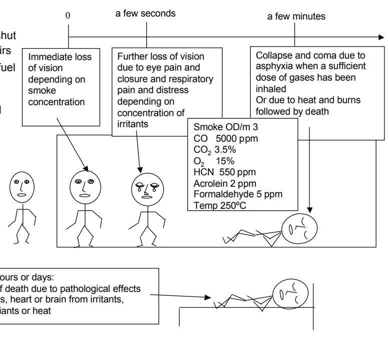
Pathological effects:
- Slow to develop (hours-days-years)
- Affect longer term functions of organ systems, leading to adverse health effects and death due to failure of vital functions

Physiological incapacitating effects are the most important aspects of toxicity (toxic hazard) in fires:
- Determine whether occupants escape or not
- Nearly all fires are fatal due to heat or asphyxia if you remain long enough

Physiological effects in fires

Fire toxicity involves a set of different physiological effects occurring over different time scales

Scenario:
- In bedroom with door shut
- Fire in lounge downstairs
- Fire burns a few kg of fuel then self-extinguishes after 10 minutes
- House filled with mixed toxic smoke
- Occupant awakes and opens bedroom door
- What is effect on occupant?



Fractional Toxic Effects

In order to assess effects of each toxic gas in a fire at any time:

For those where concentration is most important:

Fractional Effective Concentration (FEC):

FIC = $\frac{\text{concentration of gas present}}{\text{concentration causing irritant effect}}$ e.g $\frac{100 \text{ ppm HCl}}{200 \text{ ppm HCl}}$

For those where exposure dose is most important:

Fractional Effective Dose (FED)

= $\frac{\text{conc. gas present x time}}{\text{conc x time for endpoint}}$

Fractional Lethal dose (FLD)

= $\frac{\text{conc. gas present x time}}{\text{conc x time for lethal exposure}}$ e.g. $\frac{1900 \text{ ppm HCl x 30 min}}{114{,}000 \text{ ppm x min}}$

In both cases the exposure would be half that required for the given effect

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Fractional Physiological Effects

The FICs for individual irritant gases are summed to obtain the overall FIC for an irritant mixture as follows:

$$FIC_{total} = FIC_{HCl} + FIC_{HBr} + FIC_{HF} + FIC_{SO2} + FIC_{NO2} + FIC_{CH2CHO} + FIC_{CH2O} + \Sigma FICx$$

Where $\Sigma FICx$ = FICs for any other irritants present.

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Asphyxiant equations

Fractional Effective Dose (FED) basic concept:

$$= \frac{\text{conc. gas present x exposure time}}{\text{conc x time for incapacitation}}$$

Asphyxiants:

$$FED_{IN} = (FED_{Ico} + FED_{Icn}) \times VCO_2 + FED_{Io}$$

FED for incapacitation for CO, HCN and low oxygen:

$$FED_{Ico} = (8.2925 \times 10^{-4} \times \text{ppm } CO^{1.036}) \times t/30$$

$$FED_{Icn} = (\exp([CN]/43))t/220$$

$$FED_{Io} = t/\exp[8.13 - 0.54(20.9 - \%O_2)]$$

Ventilatory stimulation by CO_2:

$$VCO_2 = \exp([CO_2]/5)$$

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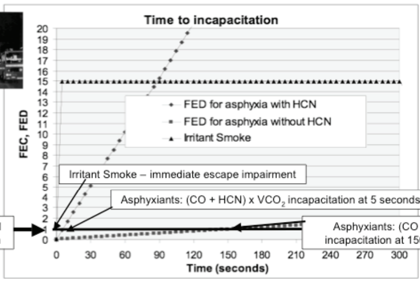
Fractional Physiological Effects

FED analysis for the lounge/bedroom fire scenario:

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



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Toxic fire hazards

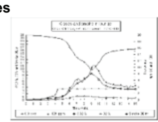
Dynamic time-based process depending upon two major parameters:

1. Time-concentration curves for major products which depends on:
- **Fire growth curve (mass loss rate of fuel [kg/s] and dispersal volume)**
- **Yields of toxic products (e.g. kg CO/kg material burned)**
  Change with changing combustion conditions throughout the fire

2. Physiological effects of the products

exposure concentration [$kg.m^{-3}$] or exposure dose [$kg.m^{-3}.min$] required to cause toxic effects in terms of :
- **concentrations or doses likely to impair escape efficiency**
- **incapacitating exposure concentrations or doses**
- **lethal exposure concentrations or doses**

Timing and severity depends upon the changing concentrations and doses of each different type of toxicant and their physiological effects



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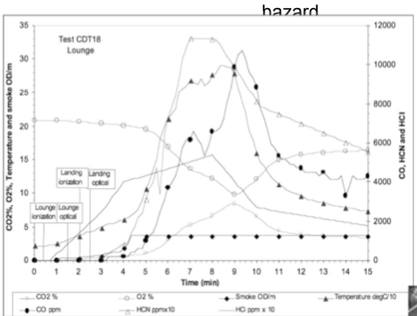
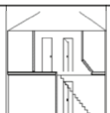
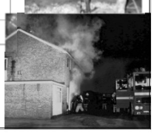
Toxicity tests and toxic hazard







Armchair: FR polyacrylonitrile covers, CM polyurethane foam burning in lounge with open doorway in enclosed house

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Toxicity tests and toxic hazard

Is it realistic to classify reaction-to-fire properties of a material or product (such as ignitability, heat release and flame spread) using small-scale tests?

Up to a point YES because these small-scale tests measure relatively fundamental properties of materials and products operating at any scale that can be used to predict full-scale fire behaviour

Is it realistic to represent "toxicity" or toxic hazard of a material or product in terms of a single number generated using a small-scale combustion toxicity test?

NO because:
- Toxic hazard is a property of a full-scale system depending upon the time-varying dynamics of fire growth and effluent spread in specific fire scenarios
- Toxicity involves a time varying set of different physiological effects
- Yields of toxic species and hence toxicity from any material or products are variables which depend upon the combustion conditions.
  (decomposition conditions in existing toxicity test methods give a poor representation of those in any full-scale fire)

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Toxic product yields in fires

Depend upon three major parameters:

1. **Elemental composition of material**
   – **Mass % C,H,O,N,P,Cl,Br,F,S,inert fillers**
2. **Organic composition of material**
   – **Aliphatic or aromatic**
   – **Char forming or decomposing into gas phase**
   – **Detailed structure, isocyanates etc**
3. **Decomposition conditions in fire**
   – **Flaming/non-flaming, ventilation, temperature**

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Toxic smoke products

IRRITANTS

•Consist of :

ACID GASES:

HYDROGEN CHLORIDE, BROMIDE AND FLUORIDE,

SULPHUR DIOXIDE,

NITRIC OXIDE AND NITROGEN DIOXIDE, PHOSPHORIC ACID

ORGANIC IRRITANTS:

ACROLEIN, CROTONALDEHYDE, FORMALDEHYDE, ACETALDEHYDE, PHENOL, ISOCYANATES

• Depending upon concentration cause painful stimulation of the eyes, nose, mouth, throat and lungs with some hypoxia due to breathing difficulties which impedes escape and can be fatal

• Depending upon dose inhaled cause lung inflammation and oedema which may be fatal usually some hours after exposure

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Toxic smoke products

Asphyxiant gases:

CARBON MONOXIDE

HYDROGEN CYANIDE

CARBON DIOXIDE

LOW OXYGEN

cause confusion and loss of consciousness followed by death from asphyxia when a sufficient dose has been inhaled

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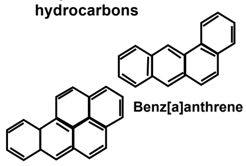
Toxic and carcinogenic compounds in fire residues and soot

Dioxins

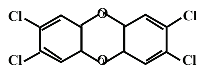
Polyaromatic hydrocarbons

Dibenzofurans



Benz[a]anthrene

Benzo[a]pyrene



2,3,7,8, Tetrachlorodibenzodioxin

Benzene

Isocyanates

acids

Formaldehyde

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Toxic smoke products

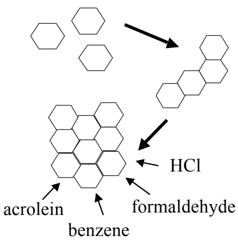
Particles:

Carbonaceous soot particles:

Organic hydrocarbon fragments undego ring cyclization, forming aromatic ring compounds which coalesce into progressively larger molecular graphite-like plates by removal of hydrogen

Volatile toxic species such including acids, organic irritants and carcinogens condense on the particles

The particles if inhaled provide a delivery system for deep lung penetration of "packets" of concentrated toxins



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SMOKE PARTICLES