*Ph. D. Anna A. Stec**

Combustion hazards from building materials

Abstract. Fire smoke has a highly variable composition which is dependent on several factors, including oxygen supply, heating rate, temperature and the chemical structure of the materials that are burning. One area that is particularly important is the determination of volatiles that can have a negative effect on the environment as well as posing a serious hazard to human health. Prediction of toxic fire hazard depends on two parameters: time-concentration profiles for major products. These depend on the fire growth curve and the yields of toxic products; toxicity of the products, based on estimates of doses likely to impair escape efficiency, cause incapacitation, or death. Toxic product yields depend on the material composition, and the fire conditions. The most significant differences in fire conditions arise between flaming and non-flaming combustion. The burning of an organic material, such as a polymer, is a complex process, in which volatile breakdown products react, to a greater or lesser extent, with oxygen, producing a cocktail of products. These range from the relatively harmless carbon dioxide (CO_2) and water, to products of incomplete combustion, including carbon monoxide (CO), hydrogen cyanide (HCN), organoirritants etc. In addition, depending on the other elements present, halogen acids, oxides of nitrogen, and sulphur, may be formed. The fire toxicity of building materials were investigated under a range of fire conditions, oxidative pyrolysis (smouldering) and well-ventilated flaming to under-ventilated flaming. The yields of the major toxic products, carbon monoxide, hydrogen cyanide and irritant gases nitrogen dioxide, hydrogen chloride and hydrogen bromide together with polycyclic aromatic hydrocarbons are presented as a function of fire condition. The toxicities of the effluents, showing the contribution of individual toxic components, are compared using the fractional effective dose (FED) model and LC_{50}, (the mass required per unit volume to generate a lethal atmosphere under specified conditions).
Keywords: fire smoke, toxicity, fire hazard.

Performance-based life-safety design depends on a comparison between the time required for escape (Required Safe Escape Time – RSET) and the time to loss of tenability (Available Safe Escape Time – ASET). For the RSET time line, most emphasis is usually placed upon the travel time component, representing the physical movement of occupants into and through the escape routes [1]. It is the process by which occupants escape depends upon key features such as occupant characteristics (psychological and physiological), occupancy type, warnings, building complexity and fire safety management strategy (Figure 1). ASET calculates interval between the time of ignition and the time after which conditions become untenable such that occupants are unable to take effective action to accomplish their own escape to a place of safe refuge [2]. Figure 1 shows a schematic relationship between the factors required to assess the fire hazard. Toxic fire effluents are the main determinants of ASET, but they can also affect RSET. Exposure to fire effluent may affect escape behaviour, reduce movement speed in smoke. The estimated time available for escape depends on the nature both of the fire (e.g. quantity and types of combustibles, fuel chemistry) and of the enclosure (e.g. ventilation). The temperature and oxygen concentration vary significantly during a fire and between different fires, and as a consequence the gases produced in different stages of a fire may vary significantly [2].

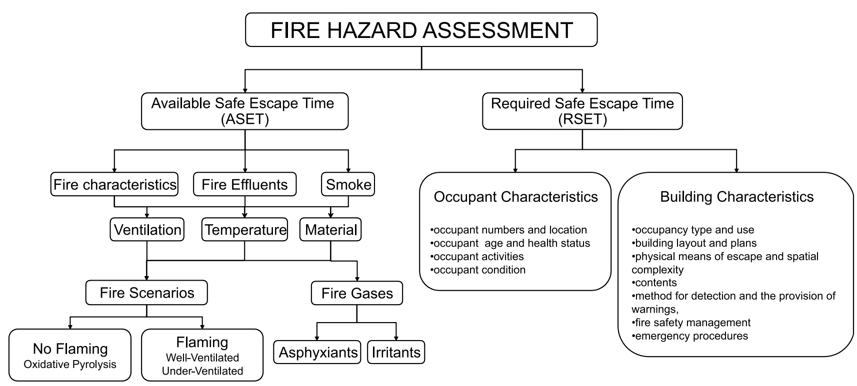

Fig. 1. Fire Hazard Assessment [2]

Fire scenarios

The transition, from non-flaming, to well-ventilated flaming, and finally to under-ventilated flaming, have been classified by ISO 19706 (Table 1) in terms of heat flux, temperature, oxygen concentration (to the fire, and in the fire effluent), and CO_2 to CO ratio, equivalence ratio ϕ and combustion efficiency (the % conversion of fuel to fully oxygenated products, such as CO_2 and water) [3]. The products of non-flaming decomposition tend to be rich in partly decomposed organic molecules (many of which are irritants), carbon monoxide and smoke particulates [4]. This scenario presents a particular hazard to a sleeping subject in a small enclosure such as a closed bedroom which can reach a lethal dose over a number of hours. High yields of smoke, toxic and irritants

* Centre for Fire and Hazard Sciences, University of Central Lancashire, Preston, Wielka Brytania

Table 1. ISO classification of fire stages, based on ISO 19706

Fire Stage	Heat [kW/m²]	Max temp [°C]		Oxygen [%]		Equivalence ratio ϕ	$\frac{V_{CO}}{V_{CO_2}}$	Combustion efficiency [%]
		fuel	smoke	in	out			
Non-flaming								
1a. Self sustained smouldering	n.a.	450 – 800	25 – 85	20	0 – 20	–	0,1 – 1	50 – 90
1b. Oxidative, external radiation	–	300 – 600		20	20	< 1		
1c. Anaerobic external radiation	–	100 – 500		0	0	>> 1		
Well – ventilated flaming								
2. Well ventilated flaming	0 to 60	350 – 650	50 – 500	~ 20	0 – 20	< 1	< 0,05	> 95
Under – ventilated Flaming								
3a. Low vent. room fire (Small Under – ventilated)	0 to 30	300 – 600	50 – 500	15 – 20	5 – 10	> 1	0,2 – 0.4	70 – 80
3b. Post Flashover (Large Under ventilated)	50 to 150	350 – 650	> 600	< 15	< 5	> 1	0.1 – 0.4	70 – 90

are generated, in flaming fires, at temperatures around 600 °C. Under well-ventilated conditions (ϕ between 0,4 and 1,0), a room occupant is exposed to a highly toxic effluent mixture capable of causing incapacitation and death from asphyxiation within a few minutes. They will also suffer from exposure to heat, with a possibility of burns [5].

The final category of flaming fire scenario in enclosures is under-ventilated flaming fire. Flashover can occur when the upper-layer temperature is sufficiently high (around 800 °C or above) to cause ignition of combustible materials. The effluent plume is similar in composition to that from a pre-flashover under-ventilated fire, fuel-rich (ϕ between 1,5 and 5) combustion conditions, with very low oxygen concentrations, and high concentrations of asphyxiant gases (CO, HCN), organic irritants and smoke particles. Since the temperatures are higher and the conditions somewhat more extreme, the yields of toxic products may be somewhat higher than for pre-flashover under-ventilated fires [5]. The heat release rate, and therefore the rate of effluent production, is very high. Post-flashover fires are therefore extremely hazardous because a large amount of hot toxic effluent plume material can rapidly fill extensive building spaces remote from the seat of the fire. In the UK, and probably across Europe, where rooms and buildings tend to be smaller with less open layouts, most fire deaths (55% in 2012 in the UK) result from small fires when the victim is in the room of fire origin [6].

Exposure effects from fire effluents

Behavioural Effects. There are both behavioural and physiological effects associated with exposure to fire effluents that can impact significantly upon occupants' taking effective action to accomplish their own escape. Behavioural effects impacting escape are human factors commonly contributing to estimation of the time required for escape, examined in detail in ISO/TR 16738 [7]. However, for escape from fire, it is also necessary to consider the ways in which human behaviour would be modified by exposure to fire and its combustion products. The behavioural consequences of such exposure could lead to escape being aborted or even prevented by reduced visibility, hyperthermia, impaired breathing due to upper-respiratory tract sensory irritation, etc. [1, 8].

Physiological Effects. There are a number of primary physiological effects of exposure to fire and its combustion products. These can include visual obscuration due to smoke optical density, reflex blinking of the eyes, pain in the eyes, nose, throat and chest, coughing, laryngeal spasms, and various types of hypoxia due to lack of oxygen supplied to body organs. Hypoxia results in central nervous system depression, the effects of which are manifest by varying degrees of impaired judgement, disorientation, loss of motor co-ordination, unconsciousness and, ultimately, death [2].

In order to ensure safe evacuation, ISO 13571 [9] subdivides the hazards to people escaping from a fire into:

- *Asphyxia* from the inhalation of toxic gases, resulting in confusion and loss of consciousness;
- respiratory tract pain and breathing difficulties or even respiratory tract injury resulting from the inhalation of *irritant smoke*;
- impaired vision resulting from the optical *opacity of smoke* and from the painful effects of irritant smoke products and heat on the eyes;
- pain to exposed skin and the upper respiratory tract followed by burns, or hyperthermia, due to the effects of *heat* preventing escape, which can lead to collapse.

It treats each of the four components separately, defining untenability when any of the four reach a level which would prevent a potential victim effecting their own escape. The effect of asphyxiants and deep lung irritants depend on the accumulated doses, the sum of each of the concentrations multiplied by the exposure time, for each product; upper respiratory tract irritants are believed to depend on the concentration alone [2]. As this process is dynamic time-based, it depends upon the time-concentration curves (the exposure concentration (kg·m^{-3}), or exposure dose (kg·m^{-3}·min), requiring inputs on smoke and toxic product yields under different fire conditions. List of main asphyxiant and irritant gases is given in Table 2.

Table 2. List of main asphyxiant and irritant gases

Asphyxiant gases	Irritant gases
Carbon monoxide (CO) Hydrogen cyanide (HCN)	Hydrogen chloride (HCl) Hydrogen bromide (HBr) Nitrogen dioxide (NO_2) Sulphur dioxide (SO_2)

Fire effluents present two hazards to human life, as toxicants causing collapse and death directly, or as incapacitating irritants, impairing the function of the lungs and eyes, preventing escape [10, 11]. Carbon monoxide (CO), and hydrogen cyanide (HCN), (interacting synergistically with the hyperventilatory effect of carbon dioxide) are recognized as some of the most immediately life-threatening products.

Asphyxiants. Carbon monoxide binds to the haemoglobin in red blood