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Quantification of toxic hazard from fires in buildings

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ABSTRACT

Fire safe design requires a builder, architect or fire safety engineer to ensure that the available safe escape time (ASET) exceeds the required safe escape time (RSET), for which an estimate of toxic hazard from smoke is required. In Europe, the burning behaviour of construction products must be tested and labelled according to their Euroclass, based on their fire performance in a range of tests. Each Euroclass can be used to indicate a mass loss range. The yields of toxic products may be determined for each material as a function of fire condition. Reliable data has been widely reported from the steady state tube furnace (ISO TS 19700) and the fire propagation apparatus (ISO 12136) for both well-ventilated and under-ventilated flaming. By combining the toxic product yields, most easily expressed as an LC_{50}, with the mass loss range, a methodology is proposed for quantifying the volume of toxic effluent produced by burning construction materials within an enclosure. This allows a maximum safe loading of construction materials to be quantified for a given volume of enclosure. This is intended to ensure that estimates of toxic hazard are undertaken as part of any fire hazard assessment, not to replace more rigorous engineering analyses. It will allow architects and builders to ensure that their materials' selection does not compromise fire safety.

1. Introduction

Fire effluent toxicity is responsible for the majority of deaths, and the majority of injuries, from unwanted fires [1]. Fire safety engineers have been very successful in minimising structural failure in building fires, but no simple methodology exists to estimate the toxic hazard from burning building materials and/or contents. The toxic hazard is the potential for harm resulting from exposure to toxic combustion products [2]. The toxic hazard depends on two major parameters: the mass loss rate of the burning object; and the toxicity of the fire effluent it produces per unit mass of fuel, which is itself a function of both the material composition and the fire condition. Only with an estimate of toxic hazard will a builder, architect or fire safety engineer be able to ensure the fire safety of a building, by being able to demonstrate that the available safe escape time (ASET) exceeds the required safe escape time (RSET) [3].

In Europe, the Construction Products Regulations [4] require the fire performance of construction products to be tested and labelled according to their Euroclass (e.g. A1 is non-combustible; D is typical for untreated timber; F is untested etc.). This assesses fire performance in terms of established parameters such as fire growth rate (FIGRA), heat release rate (HRR) and smoke growth rate (SMOGRA). Surprisingly, fire toxicity is not part of the Euroclass system. The Euroclasses are based on performance in a room scale reference scenario, in this case the ISO 9705 room [5]. To save testing such large quantities of each product, intermediate scale tests have been developed, which are supposed to replicate behaviour in the reference scenario. Thus, the allocation of most Euroclasses is based on performance in the single burning item (SBI) test, EN 13823 [6]. This paper describes a methodology for using the Euroclass to estimate the mass loss. In the assessment of flammability, such as in the Euroclass system, the worst case scenario is the normal atmospheric oxygen concentration, 21% oxygen (by volume). In the assessment of fire toxicity, the yields of most toxicants increase by a factor of around 20 when the oxygen concentration falls to 15% (by volume) [7].

The toxic product yields may be determined for each material as a function of fire condition. Reliable data has been widely reported from the steady state tube furnace (ISO TS 19700) [8] and the fire propagation apparatus (ISO 12136) [9] for both well-ventilated and under-ventilated flaming; it has been reported from the cone calorimeter (ISO 5660) with a non-standard controlled atmosphere enclosure, but only appears to replicate the least toxic, well-ventilated flaming condition [10]. By combining the toxicity data, most easily expressed as a material-LC_{50} (the mass of material required to produce a lethal fire effluent of volume 1 m^3), for a particular fire condition, with the mass loss over a fixed time

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Nomenclature

$[CO_2]$	Carbon dioxide concentration (% by volume)
$[O_2]$	Oxygen concentration (% by volume)
[X]	Concentration of toxicant X (expressed in same units as $LC_{50,\,X}$ e.g. $\mu L\,L^{-1}$)
A	Acidosis factor (in FED equation)
b''	Fractional burn area
ΔH_c	Heat of combustion ($MJ\,kg^{-1}$)
FED	Fractional Effective Dose
$LC_{50,\,X}$	Lethal concentration of toxicant X to 50% of the exposed population (expressed in same units as [X] e.g. $\mu L\,L^{-1}$)
$L_{s,\,ha}$	Maximum safe loading, for a healthy adult population (m^2 per 100 m^{-3})
m	Mass of material (kg)
m_E''	Mass of material exposed, per unit area ($kg\,m^{-2}$)
m_L	Mass of material lost (kg)
m_L''	Mass of material lost, per unit area ($kg\,m^{-2}$)
m-LC_{50}	Material-LC_{50}-the mass of material required to generate a toxic atmosphere on burning, lethal to 50% of the population ($g\,m^{-3}$)
ρ''	Material density per unit area ($kg\,m^{-2}$)
t_b	Fractional burn thickness
THR	Total heat release (kJ)
THR_{600}	Total heat release in first 600 s of SBI test (kJ)
V	Volume of enclosure containing fire effluent (m^3)
V_{CO_2}	Hyperventilation Correction Factor
$V_{LC_{50}}$	Lethal volume (of toxic fire effluent) (m^3)
Y_v	Volatile fraction

(10 min in the current work), a methodology is proposed for quantifying the volume of toxic effluent produced by burning construction materials within an enclosure. This allows a maximum safe loading of construction materials to be quantified for a given volume of enclosure. This is intended to ensure that estimates of toxic hazard are undertaken as part of any fire hazard assessment, not to replace more rigorous engineering analyses. It will allow architects and builders to ensure that their materials' selection does not compromise fire safety.

National building codes stipulate the levels of safety for different types of building and use. They will normally specify a minimum Euroclass for a particular application. The focus of these government regulations and guidance is the hazard to life from fire. In addition, insurers often specify the materials of construction for particular industrial buildings in order to protect their risk from property loss, for which fire toxicity is a lesser concern. In the UK, Approved Document B provides guidance for building specifiers to select appropriate construction materials using their Euroclass, for the level of hazard associated with the particular type of construction (e.g. multi-storey, multi occupancy dwelling, school, hospital etc.). As an alternative to following the guidance in Approved Document B, a performance-based approach may be adopted using techniques of fire safety engineering to ensure the fire safety of building occupants. On completion of the construction, the Regulatory Reform (Fire Safety) Order (2005) puts the onus on building occupiers to ensure the fire safety of the buildings in their control. This means that individuals with no formal expertise in fire safety are responsible for ensuring the ongoing fire safety of buildings. Thus simple tools, like the approach described here, are essential for them to ensure the safety of the people using their buildings.

2. Estimation of fire toxicity

Toxic fire hazard may be predicted by using two parameters:

- The toxic product yields (a function of material and fire condition [11]).
- The mass loss of fuel (a function of flammability, fire conditions and time).

The burning of an organic material, such as a polymer, produces a cocktail of products. These range from the relatively harmless fully-oxidised products, such as carbon dioxide (CO_2) and water, to products of incomplete combustion, including carbon monoxide (CO), hydrogen cyanide (HCN), organoirritants etc. Significant differences in toxic product yields arise between flaming and non-flaming combustion, and between well-ventilated and under-ventilated flaming.

In addition to water, CO_2, CO, and HCN, fire gases contain a mixture of partially oxidised products, such as aldehydes; fuel or fuel degradation products, such as aliphatic or aromatic hydrocarbons; and other stable gas molecules, such as nitrogen, nitrogen oxides and hydrogen halides. CO is one of the most toxicologically significant components in fire gases, preventing oxygen transport by the formation of carboxyhaemoglobin, and acting as a marker for other toxic products of incomplete combustion, such as HCN and oxygenated organics. HCN is important because it is over 20 times more toxic than CO, preventing uptake of oxygen by the body's cells. The combined effect of these toxicants has been expressed as a fractional effective dose (FED) using Purser's model (Eq. (1)) (ISO 13344). The gas-LC_{50} values were obtained from rat lethality experiments. In essence the ratio of the concentration of the individual toxicants to their lethal concentration is summed for each toxicant. These are multiplied by the factor V_{CO_2}, because CO_2 stimulates an increase in the respiration rate. In addition, an acidosis factor and an oxygen depletion factor are included in the overall summation. An FED equal to 1 would be lethal to 50% of the exposed population.

$$FED = \left\{ \frac{[CO]}{LC_{50,\,CO}} + \frac{[HCN]}{LC_{50,\,HCN}} + \frac{[HCl]}{LC_{50,\,HCl}} + \ldots \right\} \times V_{CO_2} + A + \frac{21 - [O_2]}{21 - 5.4}$$

$$V_{CO_2} = 1 + \frac{\exp(0.14[CO_2]) - 1}{2}$$

$$\text{A is an acidosis factor equal to } [CO_2] \times 0.05. \qquad (1)$$

The lethality as FED can be conveniently expressed as a material-LC_{50} (Eq. (2)). This is the mass of material (grams of fuel) needed to produce 1 m^3 of lethal effluent (FED=1).

$$\text{material–}LC_{50} = \frac{M}{FED \times V} \qquad (2)$$

Comparing the toxic potencies of different materials, the lower the LC_{50} (the smaller the amount of materials necessary to reach the toxic potency) the more toxic the material is. LC_{50} values should be referenced to the fire condition under which they were measured.

3. Measurement of toxic product yields

The steady state tube furnace, ISO TS 19700 [7] has been