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Toxicity of combustible building materials – scoping study

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Preface

This report is one output of the project QR11351 Toxicity of Combustible Building Materials in Fires – Scoping Study. The second output is a report titled *Toxicity of Building Contents in Building Fires*, which was sponsored through the Fire and Emergency New Zealand (FENZ) Tactical Research Fund.

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Toxicity of combustible building materials – scoping study

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Abstract

Inhalation of smoke and combustion products is one of the primary causes of death and injury in building fires. This hazard is heightened by the increasing use of synthetic materials and chemical additives in both modern construction materials and building contents. Although fire toxicity is a major hazard, it is not known whether it is adequately described and controlled in New Zealand. This literature review is a first step in increasing our understanding of the type and characteristics of combustion products, their effects during both building evacuation and post-fire activities and how the risk is addressed internationally. The review reflects current knowledge, both overseas and in New Zealand, and identifies knowledge gaps where further research may be beneficial.

Keywords

Toxicity, fire safety, building materials, building contents, smoke, tenability.

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1. Introduction

Smoke inhalation is one of the primary causes of death and injuries in building fires (Stec, 2017; Giebułtowicz, Rużycka, Wroczyński, Purser & Stec, 2017; Alarifi, Phylaktou & Andrews, 2016).

Health effects caused by smoke exposure can be either acute or chronic, depending on which species are present in the fire effluent. The increasing use of synthetic materials and chemical additives in building products and contents has increased the hazards related to smoke exposure during building fires (Stec, 2017).

The trend in fire deaths in New Zealand has been compared to the UK. UK fire statistics showing that, despite the number of fatal fires decreasing in the UK over the last 20 years, the number of fatalities caused by smoke inhalation has remained about the same (McKenna et al., 2018). The proportion of deaths and injuries attributed to smoke and toxic gases compared with other causes is shown in Figure 1.

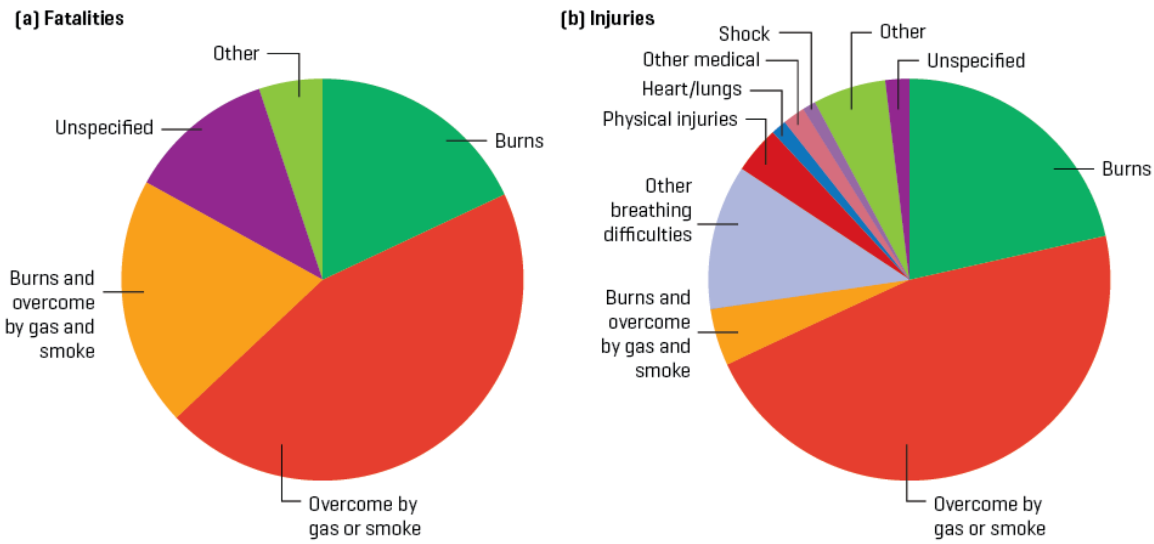

Figure 1. Cause of (a) fatalities and (b) injuries from UK dwelling fires 2018/19 (Source: Hull, 2020).

Consideration of fire toxicity is therefore an important issue in fire safety, and assessing fire toxicity of building materials has been the focus of some research internationally (Chow, Chow & Lu, 2004; Blomqvist, Hertzberg, Dalene & Skarping, 2003; Neviaser & Gann, 2004). In addition, unwanted fires make a significant contribution to atmospheric particulates, which are believed to kill 37,000 people per year in the UK.

Initial research interest in fire toxicity has been attributed to the introduction of synthetic materials as replacements to traditional materials in homes. However, early experimental work to replicate real fires at bench scale proved difficult. Reasons cited for the recent resurgence in smoke toxicity research interest are:

- replacement of prescriptive codes with performance-based approaches to fire safety
- progress in the development of tools to more accurately assess fire toxicity
- gradual recognition that toxicity has been overlooked in favour of a focus on heat release in fire safety engineering (Stec & Hull, 2010).

1.1 Factors affecting smoke toxicity

Almost all fire effluent contains carbon dioxide (CO_2) and carbon monoxide (CO), although not always in toxicologically significant quantities. Additional toxicants of greater severity can be present in the fire effluent, depending on what materials are present, the temperature and availability of oxygen (Stec, 2017). The amount of oxygen available decreases with each stage in the fire's development.

As a building fire grows, it quickly becomes ventilation controlled and consumes more oxygen, producing greater volumes of effluent that spreads through the building (Gottuck & Lattimer, 2008).

Figure 2 shows the toxicity-related factors that determine the time taken to reach untenable conditions (Stec & Hull, 2011).

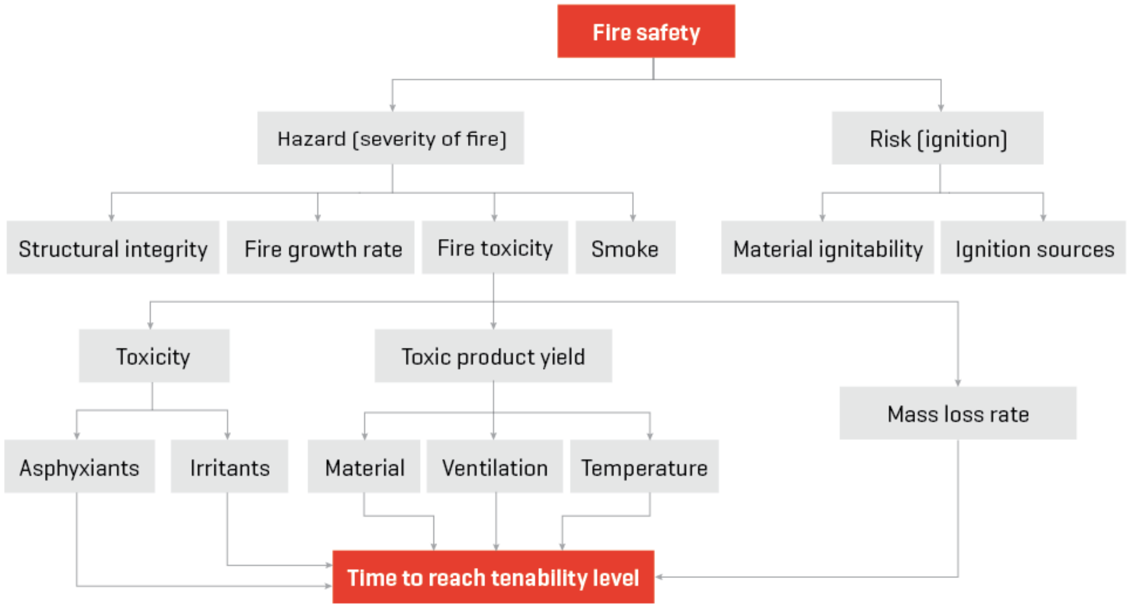

Figure 2. Schematic of factors required for fire hazard assessment relating to fire toxicity (Source: Stec & Hull, 2011).

The presence of carbon, nitrogen and halogens in the fuel materials is significant in terms of the toxicity hazard. Carbon is almost always present and is the source of soot particles, the asphyxiant CO and respiratory stimulant CO_2 (Purser, 2018). Carbon is also the source of some organic irritants, including acrolein and formaldehyde. Nitrogen-containing materials can produce the asphyxiant hydrogen cyanide (HCN) and lung irritants nitrogen oxides (NO_x). Halogens, typically either chlorine (Cl) or bromine (Br), are a source of acidic gases hydrogen chloride (HCl) and hydrogen bromide (HBr). These gases cause eye irritation and both acute and chronic breathing problems. In addition, halogen additives used as flame retardants reduce combustion efficiency, which can result in greater amounts of carbon and nitrogen fuel being released as the asphyxiant gases CO and HCN (Purser, 2018).

Examples of compounds produced in fire effluent, their fuel sources and their potential health effects are shown in Table 1.

Table 1. Selected components in fire effluent and their primary associated risks (Source: Blomqvist, 2005).

Type of component	Examples of compounds	Examples of sources	Principal risks
Inorganic gases	CO (carbon monoxide)	All fires	Acute: asphyxia
	CO_2 (carbon dioxide)	All fires	Acute: asphyxia
	HCN (hydrogen cyanide)	Nitrogen-containing fuels (e.g. nylon, polyurethane)	Acute: asphyxia
	NO_2 (nitrogen dioxide)	Nitrogen-containing fuels (e.g. nylon, polyurethane)	Acute: irritation Sublethal: lung damage
	NH_3 (ammonia)	Nitrogen-containing fuels (e.g. nylon, polyurethane)	Acute: irritation Sublethal: lung damage
	HCl (hydrogen chloride)	Chlorine-containing fuels (e.g. PVC)	Acute: irritation Sublethal: lung damage Increases yield of CO and HCN
	HBr (hydrogen bromide)	Bromine-containing fuels (e.g. brominated flame-retardant materials)	Acute: irritation Sublethal: lung damage Increases yield of CO and HCN
	HF (hydrogen fluoride)	Fluorine-containing fuels (e.g. polytetrafluoroethylene (PTFE), polyvinyl fluoride (PVDF))	Acute: irritation Sublethal: lung damage
	SO_2 (sulphur dioxide)	Sulphur-containing materials (e.g. wool)	Acute: irritation Sublethal: lung damage
Volatile organics	Organic irritants (e.g. acrolein, formaldehyde)	Cellulosic materials under non-flaming combustion	Acute: irritation
	Isocyanates	Nitrogen containing fuels (e.g. polyurethane)	Acute: irritation Sublethal: asthma, cancer
	Phenol	General for many fires	Acute: irritation
	Styrene	Polystyrene fires	Acute: irritation
	Benzene	General for all fires	Sublethal: cancer
Semi-volatile/ condensed phase organics	PAHs (polycyclic aromatic hydrocarbons e.g. benzo(a)pyrene)	General for all fires, particularly aromatic fuels	Sublethal: cancer
	Dioxins/furans	Fires with fuels containing chlorine or bromine	Sublethal: cancer, immuno-toxicity etc.
Particles	Soot particles of various sizes	All fires	Acute: visual obscuration Sublethal: deposition in the lungs

1.2 Effects of smoke toxicity

1.2.1 Acute toxicity

In a burning building, choking, blinding, and disorienting effects of smoke may hinder escape, whether that forces victims to remain in place long enough to become trapped or move more slowly. The first hazard of smoke is incapacitation (resulting in collapse or inability to breathe). If escape is not accomplished, death will result from exposure to asphyxiant gases. Since many fire victims are elderly or otherwise mobility impaired, they are more susceptible to incapacitation than a healthy adult population.

1.2.2 Chronic toxicity and carcinogenicity

Exposure to some toxicants can result in chronic effects. Several studies have shown that the increased risk of cancer to firefighters is due to occupational exposure to a range of carcinogens in fire effluent (Brandt-Rauf, Fallon, Tarantini, Idema & Andrews, 2008; Fent et al., 2019; Stec et al., 2018). During overhaul and subsequent activities at the fire site, levels of toxicants may pose a risk to firefighters, fire investigators, insurance company personnel and returning occupants.

As smoke disperses into the surrounding environment, toxicants may contaminate nearby buildings, indoor and external environments. If not adequately managed, the long-term effect of exposure to these contaminants poses a threat to nearby residents and the environment (Stec, Dickens, Barnes & Bedford, 2019).

1.2.3 Sub-incapacitating effects

In all cases, the exact effect of toxicants on an individual will depend on several factors including age and health status. Norris (2019) described the importance of considering sub-incapacitating effects of smoke and toxicants. For example, when considering what level of exposure will disable a population, the health of the population and exposure context must be considered. In the case of elderly or paediatric populations or those with compromised cardiorespiratory systems, setting a generic acceptable exposure level may not be adequate.

A key study by Jin (1997) demonstrated that visibility through smoke containing irritant toxicants was lower than through smoke with less irritants. Figure 3a shows that, past a certain smoke density (extinction coefficient), visibility decreases sharply in irritant white smoke and more gradually in less-irritant black smoke. Experiments showed that participants' eyes were affected by irritant smoke so that they could not keep their eyes open for a long enough time to see exit signs. This highlighted a hazard for evacuees who were unfamiliar with exit signs and for whom reduced visibility could impair evacuation.

In addition, irritant effects can impact on psychological state and walking speed. Figure 3b shows a similar sharp decrease in walking speed in irritant smoke as smoke density increases. The reduction in speed was reported as being due to participants' impaired vision and walking in a zigzag direction or one step at a time along a wall.

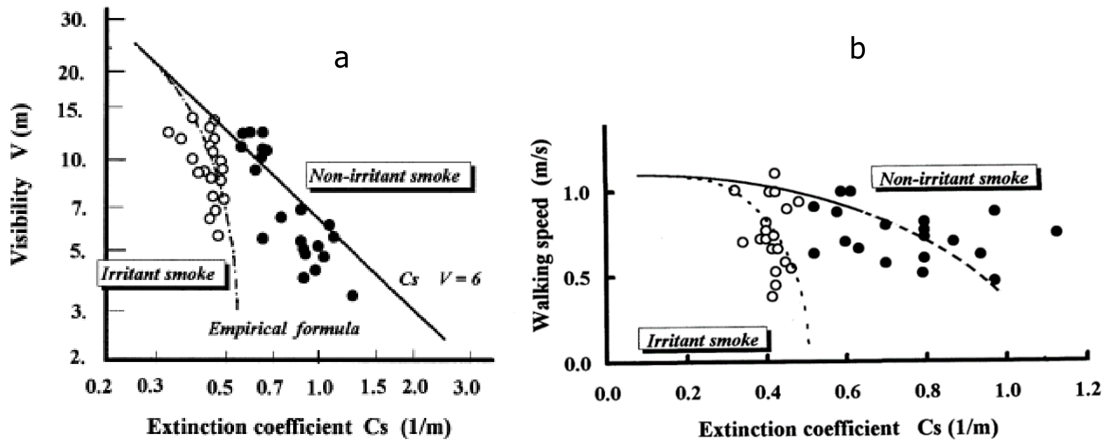

Figure 3. (a) Visibility of fire exit sign at the legible threshold of the words in irritant and non-irritant smoke and (b) walking speed through smoke (Source: Jin, 1997).

2. Assessing fire toxicity

Accurately assessing the hazard posed by toxic species is challenging and depends on several factors, including what materials are present, the type of ignition and the susceptibility of individuals to toxic hazards (Gottuck & Lattimer, 2008). Replicating the fire scenario at full scale is costly and resource intensive. Developments in fire toxicity testing have largely been focused on bench-scale assessment methods that can accurately replicate the range of fire scenarios.

This section will describe the research done on key bench-scale methods and notable full-scale toxicity experiments.

In terms of tenability loss in a fire scenario, toxicity can be expressed in several ways. Definitions of key terms used in toxicity assessment are given in ISO 13571:2007 *Life-threatening components of fire – Guidelines for the estimated of time available for escape using fire data*:

- Fractional effective dose (FED) is the ratio of the exposure dose for a given asphyxiant gas to that exposure dose of the asphyxiant expected to produce a specified effect on an exposed subject of average susceptibility.
- Fractional effective concentration (FEC) is the concentration of an irritant to a level that is expected to produce a specified effect on an exposed subject of average susceptibility.

In the case of both FED and FEC, the specified effect may be lethality or incapacitation or other endpoints. Both values may refer to either a specific toxicant or the summation of all toxicants in a given fire scenario.

An FED or FEC equal to 1 indicates that the sum of concentrations of individual species will be lethal to 50% of the population over a 30-minute exposure. An FED or FEC that does not equal 1 cannot be used to draw conclusions, except that the concentration is too dilute or concentrated to have a quantifiable effect.

In addition to FED and FEC values, other ways toxicity is described in ISO 13571:2007 and other literature include the following:

- Lethal concentration (LC_{50}), which can refer to the toxicant or the mass of a material required to produce a concentration that is lethal to 50% of the exposed population.
    - Toxicant-LC_{50} describes the concentration of a toxicant per m^3 predicted to be lethal to 50% of the test population within a specified exposure and post-exposure time. LC_{50} is inversely proportional to toxicity – the smaller the LC_{50} value, the more toxic the component.
    - Material-LC_{50} is the mass of material required to produce a lethal concentration of effluent per unit volume (McKenna et al., 2019). For example, a sample of PIR has a material-LC_{50} of 5.0 g/m^3 under given burning conditions. Therefore, under the same conditions, 500 g of PIR would fill 100 m^3 with an effluent lethal to 50% of the exposed population.
- Lethal effects (LCt_{50}). LCt_{50} is the product of LC_{50} and the exposure duration over which it was determined.

2.1 Bench-scale methods

Several small-scale methods have been developed for assessing the toxicity of materials during combustion. The toxicity assessment is typically based on either animal tests or chemical analysis or a combination of the two (Hull & Paul, 2007). Table 2 gives an overview of key bench-scale methods described in the literature that use chemical analysis for toxicity assessment. For the purposes of this study, methods involving animal subjects have been excluded.

Table 2. Bench-scale instrumentation for generating fire effluent.

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<tr><th>Instrumentation and considerations</th></tr>
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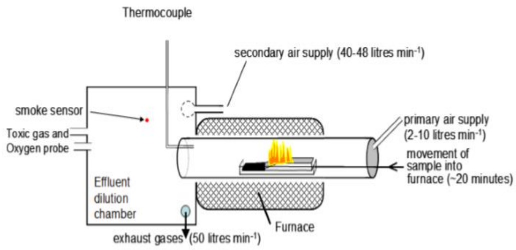
Steady state tube furnace (SSTF)



- Can replicate all fire stages.
- CO, CO_2 concentrations assessed by NDIR.
- HCl, HBr, HF, HCN, SO_2, NO_x (both NO_2 and NO), HCHO and acrolein are sampled in bags or in bubblers containing liquid reagents and determined using methods including ion chromatography, FTIR and classical analytical methods.
- Interpretation of FTIR spectra can be difficult.
- Gas yields calculated with reference to the mass loss of the sample (g/g).

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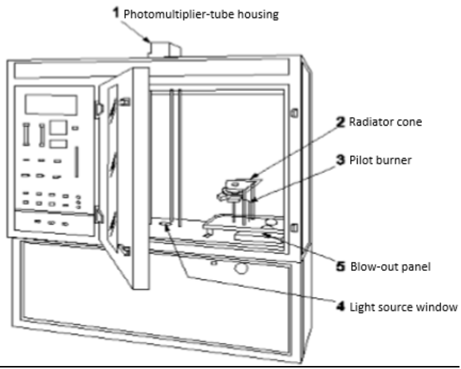
Smoke density chamber (SDC)



- Closed chamber apparatus.
- Widely used fire-test apparatus, stipulated in smoke regulations internationally that has been adapted for toxic gas generation and assessment Stec, Hull, Purser & Purser, 2014).
- Smoke density chamber standard (ISO 5659-2) specifies four test conditions to be representative of different fire scenarios.

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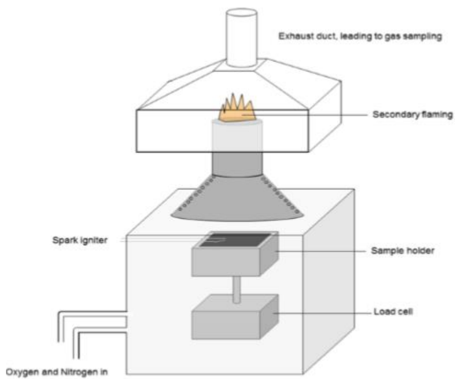
Controlled atmosphere cone calorimeter (CACC)



- Modification of cone calorimeter (ISO 5660-1) by addition of controlled atmosphere attachment for oxygen-controlled conditions.
- In some tests, the effluent may continue to burn as it emerges from the chamber giving an ultimately well-ventilated fire.
- High dilution of fire gases in and stainless-steel construction of the hood may lead to the mis-detection of some species.
- Fire gases pass through the conical heater, which may modify them.
- The CACC is not suitable for use above 50 kW m^2. At a heat flux of 50 kW m^2, the lowest that could be considered to replicate a developed fire, it is only just possible to get the gas concentration in the chamber equilibrated before so much heat has reached the load cell that it is no longer giving reliable readings.
- The gases are still reacting when in the exhaust duct. Values of CO yield closer to the 0.2 g/g found in large-scale fires and typical of under-ventilated flaming can be obtained with a longer exhaust duct.

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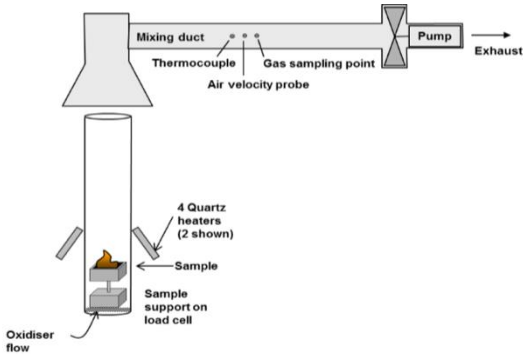
Fire propagation apparatus (FPA)

- Similar in principle to the cone calorimeter except that the fire zone is contained to silica tube (Stec et al., 2014).
- Effluent flows through a mixing duct and HRR is determined by the rate of CO_2 and CO generation.
- Effluent yields can be directly related to individual fire stages through the equivalence ratio.
- Has been used to quantify toxic products under different ventilation conditions.



Source for images: Peck (2020). Reproduced with permission.

2.2 Full-scale experiments

Replicating the toxic effects of real fires is challenging because of the range of potential variables. This typically means that it is economically unfeasible to replicate the scale of real fires in a research setting. Large-scale apparatus such as the ISO 9705 room calorimeter and full-scale fire experiments have been used to validate bench-scale methods and provide greater insight into the toxicity profile of real fire scenarios.

One aim of the TOXFIRE project was to establish whether it was possible to use results from small-scale experiments for hazard analysis of larger-scale scenarios (Månsson, Isaksson & Rosell, 2003). TOXFIRE demonstrated that it is possible to attain under-ventilated conditions at an ISO 9705 room scale. Results showed that combustion products of larger-scale fires (such as those in the storage configuration facility) are not significantly different to those from relatively smaller-scale scenarios. The ISO 9705 room scale can hence be taken as a model for real-scale fires, at least as long as modestly complex systems in space are studied.

A study by Hewitt, Christou, Dickens, Walker and Stec (2017) measured the concentrations of VOCs and SVOCs produced during experimental house fires conducted in a real house. Nine different fire conditions were investigated that differed in the location of the fire (kitchen or lounge), type of fuel (cooking oil, furnished or sofa), fire compartment door (open or closed), total ventilation to the compartment and expected ventilation condition. Samples were taken during the fire from gaseous effluent and condensed particles and analysed using GC/MS. Compounds of interest were the 16 PAHs listed by the US Environmental Protection Agency due to their potential carcinogenic effects. The PAH of greatest toxicological concern, benzo(a)pyrene, was detected in most fires. In addition to PAHs, several phosphorus-based compounds were detected in both gaseous effluent and condensed particulate samples from fires involving a sofa.

Work by Fire and Rescue NSW has investigated the effectiveness of smoke alarms at detecting untenability caused by combustion gases other than CO (Engelsman, 2017; Thai et al., 2017). The basis of this research is that building fires in homes with modern materials can reach untenable conditions in shorter times than homes with traditional furnishing materials. Test burns were conducted in fully furnished test homes across a range of fire scenarios. Variables included the type of ignition (smouldering or flaming), material first ignited, room of origin location and door open or closed. Two portable FTIR units (Gasmet DX4000) were used in the study to monitor and analyse gas levels every 5 seconds within the test compartment. Primary gases of interest were asphyxiants CO and HCN and irritants HCl, HBr, HF, SO_2, NO_2, acrolein and formaldehyde. The seven irritants have been identified as being most critical to tenability limits. One recommendation of the study by Engelsman (2017) is that gas analysis be conducted during extinguishment, post-extinguishment and during ventilation and post-ventilation to determine health risks of any toxic smoke at these periods. A way of keeping water vapour out of the analysers would need to be considered.

3. Materials

Both building contents and construction materials have the potential to contribute to the toxicity of a building fire. Building contents are typically the first items ignited in building fires, with materials in the building envelope becoming involved later as the fire develops. However, there are examples where building envelope materials have been ignited and therefore contributed to the toxicity risk early in the fire. One recent example was the Grenfell Tower fire in 2017, which started and spread through insulation material before igniting contents as flames entered apartments (Moore-Bick, 2019). The fire toxicity considerations relating to Grenfell Tower are described in more detail in section 3.3.1.

Energy efficiency targets and the need for affordability has driven the use of innovative building systems and lightweight polymer-based components in place of traditional construction materials. Polymer-based products are widely used in building components, such as piping, collars, insulation and adhesives, including in engineered wood products (EWPs).

Lockyer and Brunsdon (20190 reported trends in market share of materials for building components in New Zealand houses built between 2009 and 2018. Commonly used combustible materials on low-rise residential buildings include timber weatherboards, uPVC windows, timber framing, particleboard and strand board flooring, polyurethane wall insulation, polystyrene, fibreglass and polyester timber floor insulation. In addition, current BRANZ research on EWPs indicates that the use of these products is growing in New Zealand buildings.

3.1 Timber

3.1.1 Chemical preservatives

Timber used in New Zealand buildings must comply with preservative treatment requirements to ensure it is adequately protected from decay and insect attack. NZS 3640:2003 *Chemical preservation of round and sawn timber* sets out the range of chemical preservatives used in New Zealand to protect timber building components from different hazard conditions (Table 3).

Table 3. Preservative formulations and their applications.

Preservative	Hazard class	Applications
Copper chrome arsenate (CCA)	Can be used in all hazard classes	Interior finishing timber, wall framing, cladding, fascia, joinery, structural and decking, house piles, poles
Copper quaternary	H3.1, H3.2, H4, H5	Cladding, fascia, joinery, fence posts, landscaping timbers), house piles and poles
Copper azole (CuAz)		
Propiconazole/tebuconazole/ permethrin (PTP)	H1.2, H3.1	Wall framing, cladding, fascia, joinery
Boron compounds	H1.1, H1.2	Interior finishing timber, wall framing
Light organic solvent preservatives (LOSPs)	H3.1 (H3.2 for CuN only)	Cladding, fascia, joinery, structural and decking
Triadimefon and cyproconazole	H1.2	LVL glueline veneer treatment (when formulated as a suspension and added to phenol formaldehyde resin)

The presence of these chemicals in building fires may have implications for the combustion toxicity. Councils across New Zealand advise against or prohibit the combustion of treated timber. However, this does not mean that treated timber is not burnt.

A review of air quality in Nelson City Council's Airshed A[1] notes that arsenic contamination has been found across New Zealand in urban air and that Airshed A is no exception. Average annual arsenic concentrations in the Nelson South Airshed greatly exceeded the New Zealand ambient air quality guideline for arsenic (5.5 ng m^{-3} annual average) and were particularly high during winter (maximum 90 ng m^{-3}) (Ancelet, Davy & Trompetter, 2013). The high arsenic levels are considered to be from the burning of domestic timber that has been treated with copper chrome arsenate (CCA).

3.1.2 Engineered wood products

Engineered wood products (EWPs) are laminated products containing structural adhesives in the form of resorcinol, phenolic or polyurethane-based systems. Due to the nature of the adhesives, EWPs have the potential to introduce harmful toxicants into the fire effluent. A study compared chemical emissions from the combustion of timber with and without phenol-resorcinol-formaldehyde (PRF) adhesive (Peng, Shi & Ingram, 2011). The study showed that, compared to samples of raw timber and resin alone, PRF-bonded timber produced several additional gaseous species. The production of the additional species, which also differed by timber species, was thought to be a result of the reaction between the timber and adhesive. Polyurethane products, particularly those used in foam furniture, have been the focus of much research due to their potential to contribute to fire toxicity (McKenna & Hull, 2016; Bengtström, Salden & Stec, 2016; Blomqvist et al., 2003. Polyurethanes are a nitrogen-containing fuel that, when burned, can produce hydrogen cyanide (HCN), a major asphyxiant.

3.2 Flame-retarded materials

Flame retardants are used in some New Zealand construction products and building contents, including timber cladding, electronics items and some furniture in public buildings. As a result of growing evidence about their toxic effects, there has been debate about whether the fire safety benefits of using flame retardants outweigh the associated health risks (Shaw et al., 2010; Babich, 2006). Concerns about the use of flame retardants in household materials are related to human and environmental exposure (Lounis et al. 2019; Stapleton et al. 2010; Wenniing & Martello, 2014; Segev, Kushmaro & Brenner, 2009) and their contribution to smoke toxicity during a fire (McKenna et al., 2018). A full review of this debate is outside of the scope of this work, but the consideration of smoke toxicity during a fire is discussed below.

There has been a lot of research on furniture flammability internationally and in New Zealand, some of which has focused on whether the use of flame retardants in polyurethane foam (PUF) improves overall fire safety outcomes (McKenna et al., 2018; Chivas, Guillaume, Sainrat & Barbosa, 2009). The use of gas-phase flame retardants, which inhibit complete combustion, have been shown to increase CO and HCN yields in fire effluent (Molyneux, Stec & Hull, 2014). A UK study in 2018 compared sofas made

[1] Nelson's urban area has four airsheds defined for air quality management purposes. An airshed is a geographic area within which air pollutant concentrations tend to be similar and pollutants do not tend to mix with those in adjoining airsheds (except during windy periods). http://www.nelson.govt.nz/environment/air-quality/air-monitoring/airsheds-in-nelson/

with non-flame-retarded polyurethane foam (PUF) and one with natural materials (McKenna et al., 2018). Results showed that the flame-retarded sofa bed (meeting UK furniture fire safety criteria) burned more slowly but produced greater quantities of CO and HCN in the process.

By contrast, a review of the risks of flame retardants in European furniture (Chivas et al. 2009) concluded that flame retardants posed no additional toxic risk in fires if the furniture complied with Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) regulation[2] and cigarette and match ignition requirements. If these requirements were met, it was reported that the maximum mass loss in a fire would be low enough so as to not produce a hazardous level of toxic gas (Chivas et al. 2009). A study that was part-funded by the North American Fire Retardant Association found that flame-retarded PUF, in combination with a flame-retarded cotton barrier material, resulted in lower yields of CO and HCN than when a non-flame-retarded PUF was used (Blais & Carpenter, 2013).

3.3 Synthetic polymer components

A wide range of polymers are used for different building applications, owing to their light weight, affordability and durability (Akovali, 2005). Of these, insulation materials appear of particular interest in terms of fire toxicity and are discussed in the following section.

3.3.1 Insulation materials

In modern buildings, energy-efficiency targets have driven the replacement of traditional insulation materials with lightweight, polymer-based alternatives. Many insulation materials are more flammable and have higher combustion toxicity than traditional materials (Stec & Hull, 2011). The combustion toxicity of insulation materials has been the focus of several international studies (Stec & Hull, 2011; Liang & Ho, 2007; Blomqvist et al., 2003).

Liang and Ho (2007) studied the toxicity characteristics of insulation materials used in Taiwanese buildings. The study investigated four materials (fibreglass, rock wool, polyethylene foam and polyurethane foam) using the NES-713 test standard. Calorimetric gas reaction tubes were used to measure a range of toxic products. Of the gas tubes used, reactions were seen for CO_2, CO, acrylonitrile, nitrogen oxides and formaldehyde. The calorimetric gas reaction tube for HCN maintained its original state, indicating that no noticeable amount of HCN was produced in any of the tests. The use of NES-713 in this study was criticised by Stec and Hull (2011) because it was not intended for the assessment of construction materials.

A more recent toxicity assessment of insulation materials was done by Stec and Hull (2011). Six insulation materials – glass wool (GW), stone wool (SW), expanded polystyrene foam (EPS), phenolic foam (PHF), polyurethane foam (PUR) and polyisocyanurate foam (PIR) – were investigated under a range of fire conditions using the steady state tube furnace according to ISO TS 19700. The combustion effluents were collected and measured using bubbler solutions and high-performance ion chromatography (HPIC). Toxicities of the effluents were then compared using the FED model described in ISO 13344. Data shows that the most toxic were PUR and PIR foam and that the greatest contributor to the FED is HCN (Figure 4).

[2] https://echa.europa.eu/regulations/reach/understanding-reach

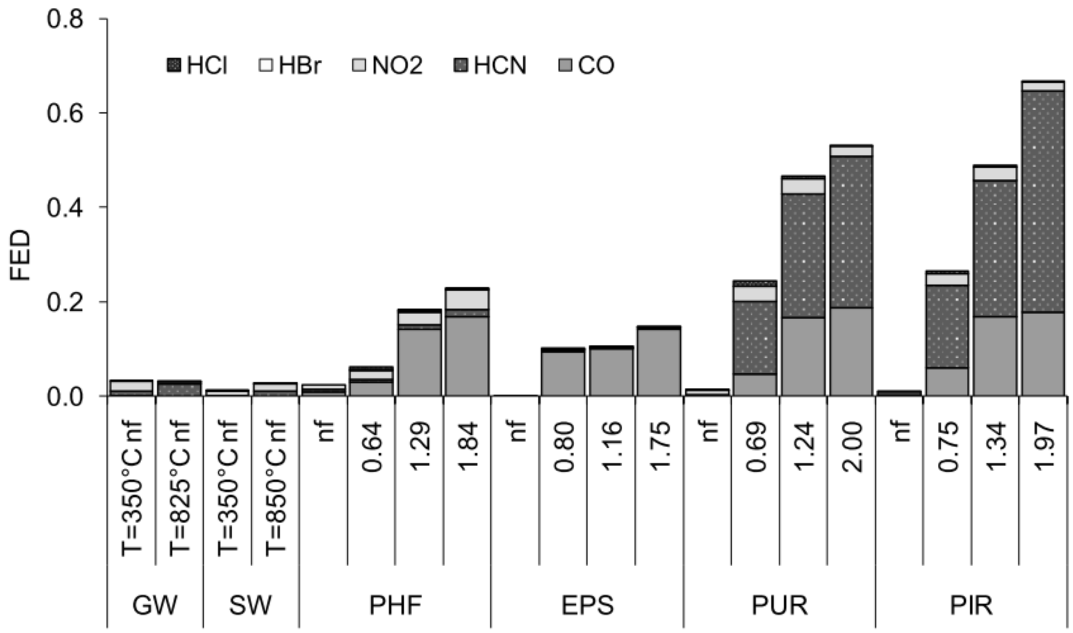


Figure 4. Contribution of different toxicants to FED for a range of insulation products as a function of equivalence ratio for flaming conditions (Source: Stec & Hull, 2011).

The key contribution of insulation products to the smoke toxicity in the Grenfell Tower fire has been reported as part of the Grenfell Tower Inquiry. The findings highlighted that the presence of polyethylene cores in the aluminium composite material (ACM) rainscreen panels was the principal reason why flames spread so rapidly up and around the building (Moore-Bick, 2019). In addition, the presence of polyisocyanurate and phenolic foam insulation boards behind the ACM panels and elsewhere on the building also contributed to the rate and extent of vertical flame spread.

Smoke inhalation has been found as the primary cause of death in the Grenfell Tower fire. Blood samples were available for only some of the decedents. Of these, "five who died in burnt-out flats showed high %COHb concentrations consistent with death due to smoke inhalation". (Purser, 2018).

The Grenfell Tower fire was notable in that the main contributor of toxic species in the initial stages of the fire was from the building materials rather than the contents. David Purser's expert report for Phase 1 of the Grenfell Tower Inquiry describes the role of the cladding and exterior insulation in producing smoke that entered the tower initially (Purser, 2018). It was estimated that, within the initial 45 minutes of the fire, the large burning mass of PIR insulation and polyethylene cladding across the exterior of the tower was the major fuel package contributing to the fire and production of smoke. As the fire developed, other combustible building materials would have also contributed to the production of toxic smoke, including rigid and flexible foams, rubberised materials, polystyrene panels between windows and uPVC window surrounds. Finally, as the fire entered the interior of the tower, building contents also contributed to the development of toxic species. Purser (2018) estimates that the mixed toxic smoke from as little as 5 kg of these materials would be sufficient to produce lethal smoke conditions in a flat or lobby area of the size of those in Grenfell Tower.

Table 4 given in Purser's expert report presents toxic gas yields for a range of polymers under well-ventilated and under-ventilated conditions. The information is relevant for this report as it can be used to estimate the approximate production of key toxic species from a given building material or contents product for a given fire scenario.

Table 4. Toxic gas yields, effective heats of combustion and oxygen consumption under well-ventilated and under-ventilated combustion conditions for a range of common polymers from the ISO TS19700 tube furnace (Source: Purser, 2018).

Polymer	Phi	Eff Ht KJ/g	CO_2 mg/g	CO mg/g	HC mg/g	O_2[9] mg/g	ε_{smoke} g/g	A_{SEA} m^2/kg	HCN mg/g	NO mg/g	NO_2 mg/g	HCl mg/g	HBr mg/g	SO_2 mg/g
Well ventilated flaming: phi 0.4-0.8														
LDPE[1]	0.49	41.5	2836	15	85	3166	0.045	268						
polystyrene	0.49	31.6	2644	61	82	2416	0.110	621						
Wood	0.51	16.9	1696	6	13	1293	0.005	12						
plywood	0.52	17.3	1774	6	11	1324	0.003	1	0	2	1			
MDF[2]	0.49	16.8	1680	7	24	1283	0.003	7	0	3	1			
PAN[3]	0.88	30.4	2339	39	54	2320	0.025	104	8	2	1			
Polyamide 6	0.51	28.4	2216	3	34	2166	0.019	147	0	11	1			
PIR[4]	0.52	24.6	2340	48	13	1874	33	75	3	2	1	69		
PMMA	0.52	24.7	2192	5	13	1881	23	148	0					
CMHR PU[5]	0.59	25.3	2156	41	48	1928	28	154	4	3	1	9		
Bouclé non-FR[6] Acrylic, wool, PE 34/38/24	0.50	24.4	2128	60	19	1861	26	103	1	7	1			12
Bouclé FR[6]	0.44	19.3	1486	130	81	1474	90	456	19	8	0	10	30	11
Velour[7] Acrylic, cotton, PE 52/31/17	0.52	26.3	2240	41	51	2005	19	84	2	4	0			
PVC[8]	0.40	10.7	667	177	70	815	32	163				447		
Fuel rich (under-ventilated) flaming phi 1.5-2.0														
LDPE	1.71	29.4	1696	196	334	2242	85	668						
Polystyrene	1.99	21.8	1662	86	299	1664	179	820						
Wood	1.71	9.8	967	134	80	752	19	155						
Plywood	1.54	9.4	986	96	55	714	14	120	0	1	0			
MDF	1.66	8.9	870	113	62	681	19	150	3	1	1			
PAN	1.69	19.1	1271	130	235	1460	60	489	72	2	3			
Polyamide 6	2.03	16.3	1135	130	248	1246	51	413	41	3	3			
PIR	2.08	14.0	937	333	136	1068	72	495	20	1	2	57		
PMMA	2.06	14.0	1108	239	260	1067	21	173	0					
CMHR PU	2.07	14.9	1041	246	197	1134	59	403	14	1	2	5		
Bouclé non-FR	2.12	14.2	1138	119	228	1080	104	594	35	1	2			4
Bouclé FR	2.03	13.3	920	146	184	1016	100	611	25	2	1	3	28	8
Velour	2.06	14.0	1211	126	239	1071	84	526	34	2	1			
PVC	1.82	7.5	389	137	98	573	70	473				585		

[1]LDPE low density polyethylene,[2]MDF medium density fibreboard,[3]PAN polyacrylonitrile,[4]PIR polyisocyanurate foam, [5] CMHR = combustion modified high resilience polyurethane foam FR (flame retarded),[6]Bouclé looped yarn mixed fabric (see Table 3),[7]Velour mixed fabric (see Table 3)[8]PVC polyvinylchloride (rigid 100% PVC)
[9]Oxygen consumed (mg/g)

4. Regulations

Incapacitating effects of smoke are considered quantitatively in the New Zealand Building Code, which stipulates a maximum fractional effective dose (FED) of CO that building occupants can be exposed to during fire evacuation. This is intended as a simplified but practical means of considering the risk of toxic injury when carrying out fire safety engineering calculations. This section will present how fire toxicity is considered in other jurisdictions.

A new Australian Fire Safety Verification Method (FSVM)[3] excludes an exposure criterion for CO except for in smouldering fire scenarios. The criterion was excluded from the FSVM because of the view that the ability to measure CO in a repeatable test varies by two orders of magnitude for common cellulosic fuel. It was decided that the use of FED for CO and CO_2 may be acceptable as part of a performance solution conducted outside the scope of this Verification Method (Brian Ashe, Australian Building Codes Board, personal communication, 2019).

In Europe, the European Commission funded BRE to investigate the feasibility of including smoke toxicity in the European Union (EU) Construction Products Regulations (CPR) (Yates, 2017). Information was collected from fire safety professionals, scientists and main CPR actors and stakeholders. The study's conclusions highlight issues around a lack of definition and regulation of toxicity and that relevant fire statistics are collected in different ways across EU Member States. Interviewees did not agree that construction product regulation of toxicity was required, but where this was agreed, it was felt that a harmonised approach should be taken. Another conclusion was that a thorough cost, benefit and impact analysis would be required before any new regulations were enacted. Some interviewees believed that flammability (and hence smoke toxicity) of furniture was a greater priority than construction materials.

An article by Babrauskas (2019) was written in response to recent discussions amongst the fire safety community about toxicity assessment methods and potential construction product regulation. Babrauskas refers to the body of fire toxicity research that has demonstrated that controlling HRR is the best way of managing the combustion toxicity hazards associated with construction products. Babrauskas cites shortcomings of bench-scale toxicity tests for construction products as being that:

- bench-scale LC_{50} values significantly exaggerate the differences between products compared to real-scale LC_{50} values
- HRR rather than LC_{50} is the main determinant of toxic gas production in fires
- life safety in fires can best be promoted by reducing HRR.

A current project at the University of Central Lancashire aims to improve the guidance provided in ISO/TS 19700 for the generation of fire effluent using the steady state tube furnace (SSTF) (Peck, 2020). This research will involve revising the testing methodology and a subsequent round robin to compare results from the SSTF with those from the ISO 9705 room corner test (which formed the basis of the EU CPR on fire performance). The improved guidance is intended to support a harmonised approach to testing of fire toxicity.

[3] https://www.abcb.gov.au/Resources/Publications/Education-Training/Fire-Safety-Verification-Method

5. Long-term toxic effects

The combustion products from building fires include species that have both acute and long-term toxic effects. The generation of lethal and irritant compounds during building fires has been the focus of many studies in the field of fire toxicity. More recently, interest has grown around understanding longer-term effects of toxic products on the environment and human health. Organic species, such as volatile organic compounds (VOCs), polycyclic aromatic hydrocarbons (PAHs) and dioxins, pose less immediate concerns for building occupant safety but are potential long-term, low-concentration threats (Public Health England, 2019).

5.1 Fire toxicity concerns in the media

Several major fire incidents over the last 2 years have raised questions about the impact of toxic combustion products on communities near to the fire site. Notable incidents include fires at Grenfell Tower (London, UK),[4] Notre Dame Cathedral (Paris, France)[5] and SkyCity convention centre (Auckland, New Zealand).[6]

The SkyCity convention centre fire occurred during construction, and much of the fuel materials were construction products rather than building contents. Media reports following the fire told of convention centre workers' experiencing dizziness, headaches, coughing and asthma flare-ups upon returning back to work in the building.[7]

Since the Grenfell Tower fire in 2017, Public Health England (2019) has assessed and monitored air quality in the area. Toxic products included in the monitoring programme are particulate matter, asbestos, dioxins and PAHs. After the tower was covered and work on site stopped, monitoring of PAHs and dioxins was stopped because they were not expected to be further released from the tower into the environment.

5.2 Firefighter exposure

Studies suggest that firefighters are at higher risk of cancer incidence than the non-firefighting population (Stec et al., 2018; LeMasters et al., 2006; Graveling & Crawford, 2010). A meta-analysis of 32 studies showed that firefighters have increasing summary risk estimates for multiple myeloma, non-Hodgkin's lymphoma, prostate cancer and testicular cancer (LeMasters et al., 2006). Many combustion byproducts produced in building fires are known or suspected human carcinogens (for example, benzene and formaldehyde) (Stec et al., 2018).

Firefighters' absorption of combustion byproducts was monitored by Fent et al. (2019) to understand how firefighting tactics effected absorption concentrations. Breath and urine samples were taken from firefighters responding to controlled residential fires using different fire attack tactics. Concentrations of PAHs increased from pre-firefighting to 3 hours post-firefighting for all assignments (Fent et al., 2019). The increase was greater for firefighters assigned to interior attack and lower for those

[4] https://www.bbc.com/news/uk-40301289
[5] https://www.bbc.com/news/world-europe-47941794
[6] https://www.newshub.co.nz/home/new-zealand/2019/10/skycity-fire-live-updates-burning-continues-as-third-day-dawns.html
[7] https://www.rnz.co.nz/news/national/401996/skycity-fire-workers-have-sore-throats-and-are-fainting-union-says

assigned to transitional attack (where the fire is first fought through an opening from the outside before the firefighters move inside the building).

Stec et al. (2018) conducted the first UK study on firefighter dermal exposures to PAHs and the impact of different practices on health outcomes. Samples were taken from skin, clothing and fire station locations (office and fire engines) and tested for the Environmental Protection Agency's 16 priority PAHs. Cancer slope factors (CSF) were used to estimate the risk of cancer from a lifetime exposure to an agent by ingestion or inhalation and showed that firefighters are at an elevated risk.

5.3 Post-fire building contamination

An early study on post-fire contamination measured concentrations of combustion products in an experimental box up to 30 days after the fire (Tsuchiya, 1992). Three experiments were conducted to investigate the effects of different types of fuel (timber only and synthetic polymers) and the relative humidity (RH) of the air supply (dry and 50% RH) on the concentrations of gases produced and their rate of decay. Exhaust air from the box was sampled using sorption tubes for a 30-day post-fire period. A flame ionisation detector (FID) was used to quantify the total volatile organic compounds (TVOC). The remaining gas sample was analysed using gas chromatography/mass spectrometry (GC/MS) to identify individual gas species. Field studies were conducted on five buildings that had been refurbished after a fire. Air samples from the buildings were taken using the same sorption tubes and analysed in the same way as the experimental samples. Some compounds (styrene and naphthalene) were found at elevated levels after the fire for several hundred and several thousand days respectively. For most compounds, a correlation was observed between the decay rate and boiling point of the compounds. As expected, compounds with lower boiling points decayed faster.

Recent research following the Grenfell Tower fire has highlighted the need to better understand post-fire environmental contamination levels and the associated long-term exposure risks (Stec et al., 2019). Samples of soil taken closest to Grenfell Tower showed increased cancer risk from dioxins, furans and PAHs through dermal exposure. Samples of debris and char were found to contain benzene, PAHs, dioxins and phosphorus flame retardants, and the fact that they are also present in soil indicates that these toxicants had leached from fire debris into the environment. In addition, soil samples taken 6 months after the fire within 150 m of the tower had PAH concentrations that exceeded guideline values. Findings also raised health concerns related to contamination in living spaces. For example, a volatile liquid that was a product of isocyanates was found on a window blind in a living space near the Grenfell site (Stec et al., 2019). Because of the complexity of soil systems, the researchers suggest that measuring indoor contamination levels from buildings exposed to fire deposits could provide a more controlled sampling environment than soil. Health monitoring of residents from the tower and surrounding area has been strongly recommended by the researchers involved in this work.

6. Summary

Fire toxicity contributes to the overall fire hazard and is one of the primary causes of death and injury in building fires. The hazards associated with smoke toxicity need to be considered alongside other fire safety factors. The toxic products produced by individual construction materials can give an indication of the likely types and concentrations of toxicants generated in a building fire. Accurately correlating bench-scale results to full-scale fires has been a challenge in the fire toxicity field. The steady state tube furnace has been shown to be able to replicate all fire stages, which other bench-scale methods cannot, and therefore offers a potential route to a harmonised approach to toxicant analysis.

In addition to acute toxicants, fire effluent can produce chronic toxicants that pose long-term risks to firefighters, residents and environments surrounding the fire site. Research into post-fire contamination is relatively new but indicates that levels of key chronic toxicants may not be adequately measured or managed in the post-fire period. Toxicant levels may therefore remain high in homes and nearby environments long term after a building fire.

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