Toxicity of gases released by construction materials during building fires

Smoke and toxic gases are one of the main causes of death and injury during building fires. This hazard is made worse by the increasing use of synthetic materials and chemical additives in modern construction materials. Although furniture and fittings are usually the first items to catch fire, sometimes the building itself ignites early on, adding to the mix of toxic gases produced. A literature review by BRANZ investigated combustion products released by modern building materials during fires and examined the effectiveness of bench-scale approaches for assessing their toxicity.

In a burning building, the gases within smoke may choke or cause irritation to the occupants, resulting in disorientation or obscured visibility. This may hinder escape, as the occupants may move more slowly or become trapped. They may become completely incapacitated if they collapse or are unable to breathe. Even though the number of fatal fires has decreased in New Zealand and elsewhere, the number of deaths caused by smoke inhalation has remained about the same. Smoke inhalation remains the main cause of death and injury during building fires.

Toxic chemicals in smoke may also have longer-term effects on health. Several international studies showed an increased risk of cancer in firefighters due to their exposure to a range of carcinogenic chemicals produced by fires (Table 1). Levels of toxic chemicals in fire sites may pose a risk not only to firefighters but also to people at the site after the fire - including fire investigators, insurance company personnel and returning building occupants. The toxins in smoke could also contaminate the local environment, including inside nearby buildings, meaning nearby residents could be at risk from long-term exposure to toxins if they are not managed adequately. Unwanted fires also release particles into the atmosphere, contributing to air pollution.

A more widespread use of synthetic materials in homes and other buildings to replace traditional materials has been driven by energy-efficiency targets and the need for affordable buildings. This means an increase in lightweight polymer-based materials being used in place of stone, brick and other natural materials.

BRANZ undertook an international literature review to collate the research relevant to the toxic gases produced by New Zealand building materials in fires and found that research into smoke toxicity has increased recently. International work in this area is helping to inform:

- updating or replacement of prescriptive building codes with performance-based criteria for fire safety
- development of tools to assess fire toxicity more accurately
- understanding of smoke toxicity in general, as previous research in fire safety engineering tended to focus on heat release.

Fire-released toxins in commonly used building materials

Combustible materials commonly used in New Zealand for low-rise residential buildings include timber and uPVC weatherboards, timber framing, particleboard and strand board flooring, polyurethane wall insulation, polystyrene, fibreglass and polyester timber floor insulation. Current BRANZ research also shows that the use of engineered laminated wood products is growing in New Zealand buildings.

BRANZ reviewed the chemicals contained in these products and the implication for their release as toxic compounds during fires.

Chemical preservatives in timber

The issue of burning treated timber and its general effect on air quality is already known. Although councils across New Zealand advise against or prohibit burning treated timber (due to arsenic contamination of the air), some households do use it as firewood in winter.

Treated timber contains preservatives to prevent it from rotting or being eaten by burrowing insects. The chemicals used are set out in NZS 3640:2003 *Chemical preservation of round and sawn timber* under different degrees of environmental exposure to the timber (the hazard class). The chemicals used in treated timber may have implications during building fires (Table 2).

Engineered wood products

Engineered wood products are made of laminated timber stuck together with structural adhesives. These adhesives can contain resorcinol, phenolic or polyurethane or mixtures of these. In particular, recent research found that phenol-resorcinol-formaldehyde adhesives not only have the potential to release harmful gases but can also produce other types of toxic gas during combustion when the timber and adhesive react together. Polyurethane products contain nitrogen and can produce hydrogen cyanide during burning, which is a major asphyxiant.

Flame retardants in materials

Flame retardants are used in some construction materials in New Zealand, including cladding materials. There is ongoing debate about whether their benefit to fire safety is outweighed by their overall toxicity in smoke and their associated health risks, and the results of different studies are not conclusive.

Published investigations of flame retardants are related to furniture rather than construction materials. Research in the United Kingdom showed that gas-phase retardants in burning furniture materials can increase carbon monoxide and hydrogen cyanide asphyxiants in smoke. A European review concluded that flame retardants posed no additional toxic risk as long as certain requirements were met. Conversely, research in North America showed lower emissions of carbon monoxide and hydrogen cyanide in a flame-retarded cotton material. An expert report following the Grenfell Tower fire in London showed that ventilation conditions

Table 1. Toxic gases and particles typically released during building fires, where they come from and the risk to human health.

TOXIC GASES AND PARTICLES		TYPICAL SOURCE	MAIN RISK
Inorganic gases	CO (carbon monoxide)	All fires	Asphyxiation
	CO_2 (carbon dioxide)		
	HCN (hydrogen cyanide)	Nitrogen-containing fuels (e.g. nylon, polyurethane)	
	NO_2 (nitrogen dioxide)	Nitrogen-containing fuels (e.g. nylon, polyurethane)	Chemical irritation Lung damage
	NH_3 (ammonia)		
	HCl (hydrogen chloride)	Chlorine-containing fuels (e.g. PVC)	Chemical irritation Lung damage More CO and HCN produced
	HBr (hydrogen bromide)	Bromine-containing fuels (e.g. brominated flame-retardant materials)	
	HF (hydrogen fluoride)	Fluorine-containing fuels (e.g. non-stick coating, PTFE, flammability-lowering coating polyvinyl fluoride (PVDF)	Chemical irritation Lung damage
	SO_2 (sulphur dioxide)	Sulphur-containing materials (e.g. wool)	
Volatile organic compounds (VOCs)	Organic irritants (e.g. acrolein, formaldehyde)	Cellulosic materials under non-flaming combustion	Chemical irritation
	Isocyanates	Nitrogen-containing fuels (e.g. polyurethane)	Chemical irritation Asthma, cancer
	Phenol	General for many fires	Chemical irritation
	Styrene	Polystyrene fires	Chemical irritation
	Benzene	General for all fires	Cancer
Semi-volatile organic compounds (SVOCs)	Polycyclic aromatic hydrocarbons (PAHS) (e.g. benzo(a)pyrene)	General for all fires, particularly aromatic fuels	Cancer
	Dioxins/furans	Fires with fuels containing chlorine or bromine	Cancer, impacts immune system etc
Particles	Soot particles of various sizes	All fires	Obscures vision Soot deposits in the lungs

Table 2. Preservatives in timber and where they are found in buildings.

PRESERVATIVE	HAZARD CLASS	APPLICATIONS
Copper chrome arsenate (CCA)	Can be used in all hazard classes	Interior finishing timber, wall framing, cladding, fascias, joinery, structural and decking, house piles, poles
Copper quaternary	H3.1, H3.2, H4, H5	Cladding, fascias, joinery, fence posts, landscaping timbers), house piles and poles
Copper azole (CuAz)		
Propiconazole/tebuconazole/permethrin (PTP)	H1.2, H3.1	Wall framing, cladding, fascias, 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, fascias, joinery, structural and decking
Triadimefon and cyproconazole	H1.2	LVL glueline veneer treatment (when formulated as a suspension and added to phenol formaldehyde resin)

during the fire can change the rate of release and concentrations of gases in flame-retarded foam. In fuel-rich under-ventilated conditions, the rate of release of carbon monoxide and hydrogen cyanide was higher (Table 3).

Synthetic polymers in insulation

Synthetic polymers are used in many parts of a building as they are lightweight, affordable and durable. Insulation is particularly of interest for potential smoke toxicity and has been the focus of several international studies. Synthetic insulation is more flammable than traditional materials and likely to produce more toxic chemicals while on fire.

In one study, glass wool, stone wool, expanded polystyrene foam, phenolic foam, polyurethane foam and polyisocyanurate foam were investigated under a range of fire conditions. The polyurethane and polyisocyanurate foams were found to be the most toxic, both releasing significant quantities of hydrogen cyanide and lesser amounts of carbon monoxide (another asphyxiant), nitrogen dioxide and hydrogen chloride (lung-damaging irritants).

In the recent Grenfell Tower fire in London, the polyethylene insulation within the aluminium cladding contributed to rapid fire spread up and around the building, and the presence of polyisocyanurate and phenolic foam insulation boards behind these panels and elsewhere also contributed to the rate and extent of vertical fire spread. The main contributor of toxic smoke and gases was from the building materials in the initial stages of the fire, and smoke inhalation was found to be the main cause of death during this disaster.

Measuring toxicity in burning building materials

Measuring the hazard due to toxic gases from burning building materials is difficult, as replicating the scenario of a building (and its contents) on fire and at full scale is expensive. This means that fire-toxicity testing efforts are usually confined to bench-scale experiments that can replicate a range of conditions accurately.

Several bench-scale methods have been developed (Figure 1). Although assessment of the toxicity can be based on animal tests, these methods are not included here. In the experiments shown, the toxicity is based on chemical analyses. Of these bench-scale methods, the steady state tube furnace can successfully replicate all stages of a fire, whereas the other methods can recreate individual fire stages.

Full-scale experiments in real houses have been completed successfully in the USA and Australia. However, because it is expensive and hazardous to replicate real fires at full scale in a research setting, large-scale apparatus has instead been used to validate the bench-scale methods and to enable a greater insight into the toxicity of real fire scenarios. Research showed that the ISO 9705 room calorimeter can be used to attain under-ventilated conditions at room-scale and that combustion products of larger-scale fires (such as those in a storage-configuration facility) are not significantly different to those from relatively smaller-scale scenarios.

Table 3. Production of toxic gases from commonly used building materials on fire under well-ventilated and fuel-rich (under-ventilated) conditions (Purser, 2018).

WELL-VENTILATED CONDITIONS

MATERIAL	QUANTITY OF GAS PRODUCED (MG/G)					
	CO	CO_2	HCN	NO_2	HCL	NO
Wood	6	1,696				
Plywood	6	1,774	0	1		2
MDF	7	1,680	0	1		3
Polystyrene	61	2,644				
PIR[1]	48	2,340	3	1	69	2
CMHR PU[2]	41	2,156	4	1	9	3

FUEL-RICH (UNDER-VENTILATED) CONDITIONS

MATERIAL	QUANTITY OF GAS PRODUCED (MG/G)					
	CO	CO_2	HCN	NO_2	HCL	NO
Wood	134	967				
Plywood	96	986	0	0		1
MDF	113	870	3	1		1
Polystyrene	86	1,662				
PIR[1]	333	937	20	2	57	1
CMHR PU[2]	246	1,041	14	2	5	1

[1] Polyisocyanurate foam.

[2] Combustion-modified high-resilience polyurethane foam (fire retarded).

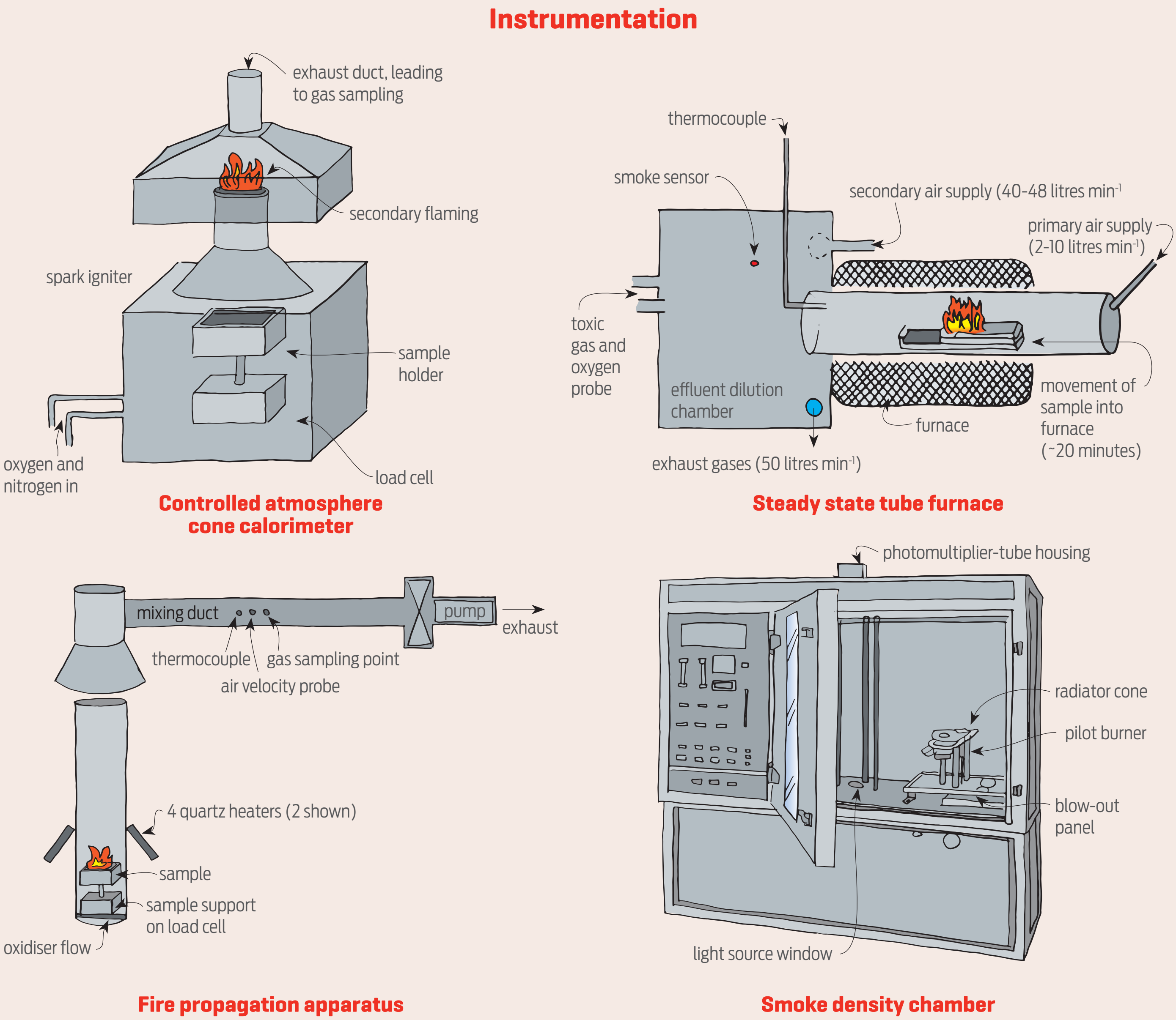

Figure 1. Bench-scale instruments for assessing the toxicity of smoke and gases from building materials.

Conclusions

- The increasing use of synthetic materials and chemical additives in building products has increased the hazard from smoke exposure during building fires. Exposure to toxic gases in smoke was already identified as the main cause of death and injury in building fires.
- The toxic gases produced by individual construction materials can give an indication of the likely types and concentrations generated in a building fire, but accurately correlating bench-scale results to full-scale fires has been a challenge in the fire toxicity field.
- The steady state tube furnace is able to replicate all fire stages, which other bench-scale methods cannot, and therefore offers a potential route to a harmonised approach to analysis of toxic emissions.
- As well as the toxic gases that are produced during a fire, toxic contaminants may remain on site or in the surrounding environment long afterwards.
- Research into post-fire contamination is relatively new. Levels of key chronic toxicants on site or in surrounding areas may not be adequately measured or managed after the fire.

More information

BRANZ Study Report SR454 *Toxicity of combustible building materials - scoping study*

Purser, D. (2018). *Effects of exposure of Grenfell occupants to toxic fire products - causes of incapacitation and death.* Retrieved from www.grenfelltowerinquiry.org.uk/evidence/professor-david-pursers-expert-report