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Inventory of major materials present in and around houses and their combustion emission products

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Report to Bushfire CRC

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bushfire CRC

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Abbreviations

ABS	Acrylonitrile butadiene styrene
CNS	Central nervous system
CO	Carbon monoxide
CO_2	Carbon dioxide
FP	Fluoropolymer
FR	Fire retardant
HBr	Hydrogen bromide
HCl	Hydrogen chloride
HC	Hydrocarbons
HCN	Hydrogen cyanide
HF	Hydrogen fluoride
H_2S	Hydrogen sulphide
ICA	Isocyanic acid
MDF	Medium-density fibreboard
NH_3	Ammonia
NO	Nitric oxide or nitrogen monoxide
NO_2	Nitrogen dioxide
NOx	Nitrogen oxides
PAHs	Polycyclic aromatic hydrocarbons
PC	Polycarbonate
PE	Polyethylene
PIR	Polyisocyanurate
PP	Polypropylene
PUR	Polyurethane
PS	Polystyrene
PVC	Polyvinylchloride
RUI	Rural Urban Interface
SO_2	Sulphur dioxide
STEL	Short-term exposure limit
SVOCs	Semi-volatile organic compounds
TDI	Toluene diisocyanate
THC	Total hydrocarbons
TWA	Time-weighted average
VOCs	Volatile organic compounds

1. INTRODUCTION

Population shifts towards city centres and the expanding rural-urban fringe are likely to increase firefighting in urban and rural-urban settings. At present, extensive research on occupational exposures has been conducted at bushfires within Australia [1]; however the complexity and heterogeneous setting of the rural-urban interface (RUI) makes it difficult to extrapolate existing research findings to the urban and rural-urban context. There are many unknowns including exposures to additional air toxics emitted from burning materials in structures and contents, different firefighting tactics to ensure protection of people and property and more complex fire behaviour and smoke plume dispersion in urban and rural-urban settings. The combustion products are likely to be strong irritants, asphyxiants and potential carcinogens. For example, burning plastics are known to generate toxic fumes such as hydrogen cyanide and inorganic acids as well as particulates containing carcinogenic substances. Furthermore residues in ash and dust are also likely to contain harmful chemicals causing potential health hazard for people involved in clean-up after fires. Although research has been conducted on emission products from a range of materials, focus was primarily on toxicity of fire effluents in the context of structural fires. These studies do not take into account that at bushfires in the RUI, exposures will not be to individual structures but to a combination of several houses burning as well as their surroundings. Currently little is known about air toxics species emitted and exposure concentrations inhaled by fire and emergency workers during firefighting at bushfires that extend into the RUI. While at structural fires, firefighters in general wear breathing apparatus protecting them against harmful chemicals in the air, fire fighting at the RUI is often done without or with minimal respiratory protection. However, the likelihood for exposure to toxic fumes and particles, both during and after fires is high. Quantification of exposure concentrations for fire fighting in urbanised areas is required to assess exposure risks to firefighters and emergency service workers and to identify and, where possible, mitigate risks to the short- and long-term health.

2. OBJECTIVES

The objectives of the research project are (1) to identify and characterise potential hazards due to exposure to air toxics while fighting bushfires that extend into the RUI and (2) to assess exposure risks. In order to assess firefighter's exposures to air toxics, we need to gather information on the types and amount of materials in the structure and contents of homes and other objects commonly found around a house (e.g. car) that are typically available for burning. The research plan is displayed in Figure 1.

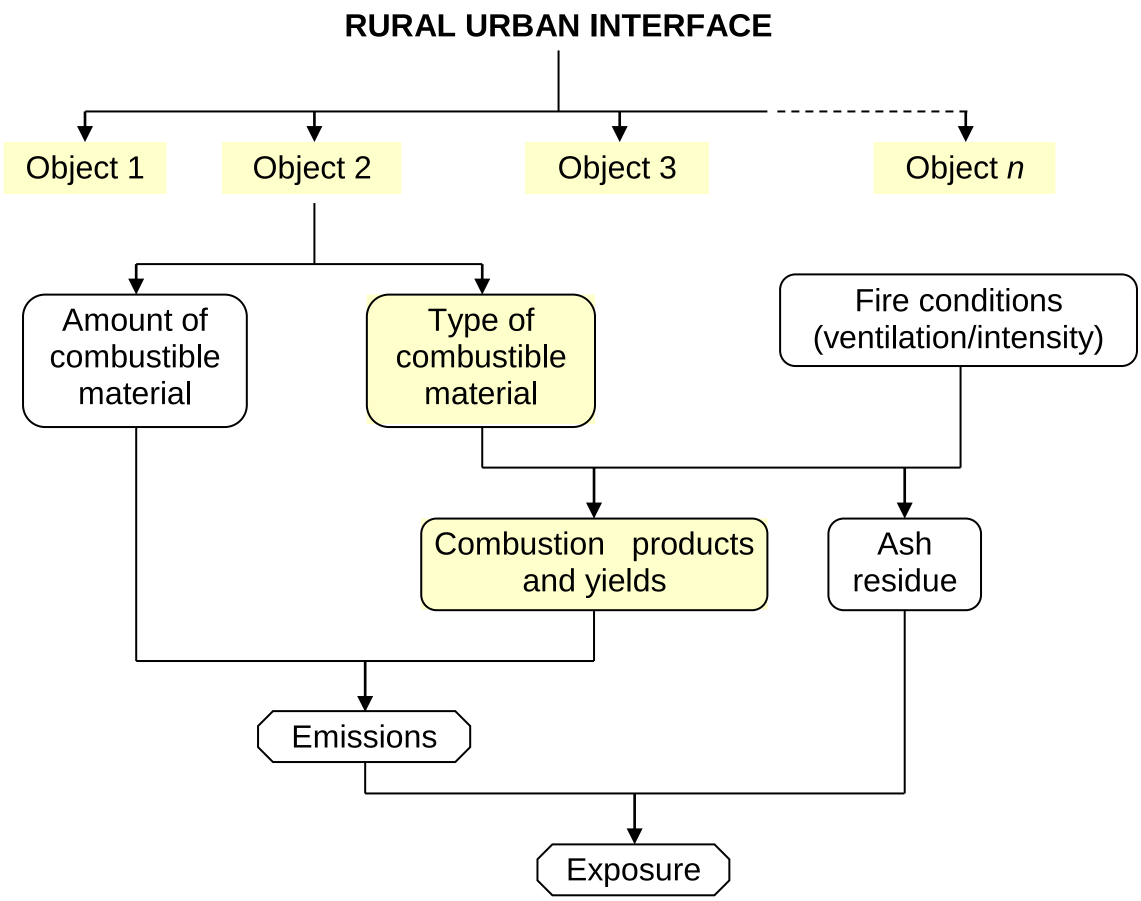


Figure 1 Schematic of the research plan

This report focuses on the highlighted parts displayed in Figure 1.

The first step is to identify major objects or items that are typically found in and around a house and identify the major materials that these objects are made of. The focus is on house structure, house contents and house surroundings. This step will enable us to highlight the major classes of combustible materials typically found at the RUI.

The second step is to determine the emission products released while materials identified in the first part are burning. At a first instance, this will be based on available literature data. Review of the current state of knowledge on the types and yields of combustion products will enable us to identify gaps and produce the design of experimental burns that will significantly add to the existing body of information.

The inventory for this report was based on reviews of existing Australian and international literature data which includes peer-reviewed journal papers, publicly available reports, statistical data from the Australian Bureau of Statistics, and data from Australian building and furnishing websites.

3. OBJECTS PRESENT AT THE RURAL URBAN INTERFACE

Sources of combustible materials at the RUI are varied and are divided into five main categories as follows:

- House structure or building materials including frame, walls/cladding, roofing, flooring and insulation
- House contents including furniture, appliances, personal items
- House surroundings including fencing, decking, outdoor furniture, water tanks, garbage bins
- Cars, caravans, boats
- Other (for example chemicals in sheds)

The assessment of materials for each of these categories is described in the following sections.

3.1 House structure

According to the Australian Bureau of Statistics, in 1999, the most common material for outside walls of Australian houses was brick (71%), followed by timber. The majority of homes featured timber frames (64%) and had roofing of either tiles (63%) or metal sheeting (33%). Fibro/asbestos cement was used as a material for outside walls and roofing in 9% and 2% of homes respectively.

Table 1 lists common materials used for frame of house structure, outside walls, roofing, flooring and thermal insulation and whether the material is combustible or not.

Table 1 Common materials found in house structure

Item	Material	Combustible?
Wall/Cladding	Double brick, brick veneer	No
	Timber	Yes
	Fibre/asbestos cement sheets	No
	Weatherboard	Yes
	Plywood sheets	Yes
	Steel/Aluminium	No
	Concrete	No
	Polystyrene (PS), Polyvinyl chloride (PVC)	Yes
	Paint	Yes
Frame	Timber/wood	Yes
	Steel	No
Roofing	Tiles, slate	No
	Metal sheeting	No
	Fibro/asbestos cement	No
	Bitumen	Yes
	PVC or polypropylene (PP) roofing membrane	Yes
Insulation	Glass wool, Rock wool, mineral wool (incl. phenolic binders)	No
	Polyester, PS	Yes
	Polyurethane (PUR), Polyisocyanurate (PIR)	Yes
Flooring	Hardwood floor	Yes
	Carpet (wool, synthetic)	Yes
	Vinyl, linoleum, PVC	Yes
	Ceramic tiles	No
	Plywood, Particle board, medium-density fibreboard (MDF)	Yes
Window frame	Rigid PVC	Yes

3.2 House contents

Information on items and amounts of materials in a typical Australian home is scarce. A survey of the amount of furniture (characterised as either hard or soft) was conducted for 40 homes in Melbourne as part of an indoor air study conducted by CSIRO Marine & Atmospheric Research for DEWHA [2]. Although the survey did not identify individual furniture items, it provides an estimate of furniture loading in typical Australian dwellings.

An extensive survey of combustible contents in residential living rooms was conducted in Canada [3]. The results were based on 598 surveys aiming at identifying the main types of combustible furniture. The major aim was to gather more complete information about the combustible contents and configuration of residential living room areas, which will aid in the evaluation of fire safety in residential buildings. Another survey was conducted on combustible contents in multi-family dwellings [4]. In this particular study the inventory of contents was based on real-estate website listings of homes for sale, in particular photographs showing the furnishings of various rooms.

To assess the typical content of Australian homes at the RUI, we rely on information either available from other studies conducted in Australia or overseas. As a result, these represent average estimates, but provide an adequate indication of combustible materials present in a house. It is not feasible to precisely determine the type and amount of items in each house as these can vary substantially depending on occupants.

Table 2 lists the typical contents found in homes and the major composition materials.

Table 2 Common items found in homes and their composition materials

Room	Item	Material	Combustible?
All	Cables	Fluoropolymer (FP), PVC, polyethylene (PE)	Yes
		Nitrile rubber	Yes
Living room/ Dining room	Coffee table/ side table	Wood, MDF	Yes
	Bookcase/ entertainment unit	MDF, Particleboard	Yes
	Table and chairs	Timber	Yes
		Metal	No
		PUR	Yes
		Fabric, leather	Yes
	Sofa (or any other upholstered furniture)	PUR (upholstery)	Yes
		Wood (frame)	Yes
		Steel (frame)	No
		Cotton, polyester	Yes
		Leather	Yes
	TV	PS	Yes (20%)
	CD/DVDs	PS, polycarbonate (PC)	Yes
	Curtains/blinds	Cotton	Yes
		Textile (vinyl, polyester)	Yes
		Timber	Yes
		Aluminium	No
		PVC foam	Yes
	Books	Paper	Yes

Table 2, ctd

Room	**Item**	**Material**	**Combustible?**
Bedroom	Bed	Timber	Yes
		Metal	No
		PUR	Yes
	Mattress	PUR	Yes
		Latex	Yes
	Bedside/ drawer chest	Timber, MDF	Yes
		PUR	Yes
		Metal	No
	Pillows	Polyester, PUR, latex	Yes
		Wool, down, feathers	Yes
	Wardrobe	Melamine particleboard, MDF	Yes
		Timber	Yes
	Clothes	Wool, Cotton	Yes
		Nylon (Polyamide), Polyester	Yes
Kitchen	Cabinets	MDF, Particleboard	Yes
		Melamine MDF	Yes
		PVC	Yes
	Chairs	PVC, PP	Yes
	Appliances	Acrylonitrile Butadiene Styrene (ABS), PP, PC	Yes
Bathroom	Vanity cupboard	MDF, particleboard	Yes
		Melamine MDF, particleboard	Yes
Office	Desk	Timber	Yes
		MDF	Yes
	Chair	PVC, PP, fabric, leather	Yes
	Computer		
	Books	Paper	Yes

3.3 House surroundings

Major items found around a home (excluding vegetation) are listed in Table 3.

Table 3 Common items found around a house

Item	Material	Combustible?
Fence	Timber (treated)	Yes
	PVC	Yes
	Aluminium	No
	Steel	No
Decking	Timber (treated)	Yes
Outdoor furniture	PVC	Yes
	Wood	Yes
	Teak	Yes
	Wicker (synthetic resin)	No
	Aluminium	No
	Wrought iron	No
Water tanks	Steel	No
	PE	Yes
Garbage bins	PE	Yes

3.4 Cars and/or other transport

Previous studies have shown that cars can contain between 150-200 kg of combustible materials, with polymers contributing a significant fraction to the amount of total combustibles [5, 6]. Major materials from cars are listed in Table 4.

Table 4 Car components and material composition

Car component	Material	Combustible
Door panel	ABS	Yes
Lining	PP	Yes
Floor material	PVC	Yes
Dashboard	PVC, ABS	Yes
Seats	PUR, polyester	Yes
Car body	Fibreglass, PC	Yes
Car paint	PUR	Yes
Car bumper	PUR, PP, ABS	Yes
Tyres	Rubber	Yes
Fluids	Petrol, oil	Yes

Source: [5]

3.5 Other

Other items likely to be present in sheds or garages include chemicals, pesticides, insecticides, petrol, oil, paints.

Among these, paint is likely to contribute the most to toxic emissions during house fires, as it is commonly used in and around the house. Paints are a combination of many chemicals, and contain pigments, binding elements, solvents and additives. Titanium dioxide is a common pigment used in commercial paints. Binders include synthetic or natural resins such as acrylics, PUR, polyesters, melamine resins, epoxy or oils. Common solvents used in paints include water, alcohols, ketones, aliphatics and aromatics. Additives are also a key feature of paints and can vary considerably depending on what other elements are used in the paints.

4. COMBUSTIBLE MATERIAL DATA

Major combustible materials in house structure, house contents and any other objects found around the home can be classified as follows

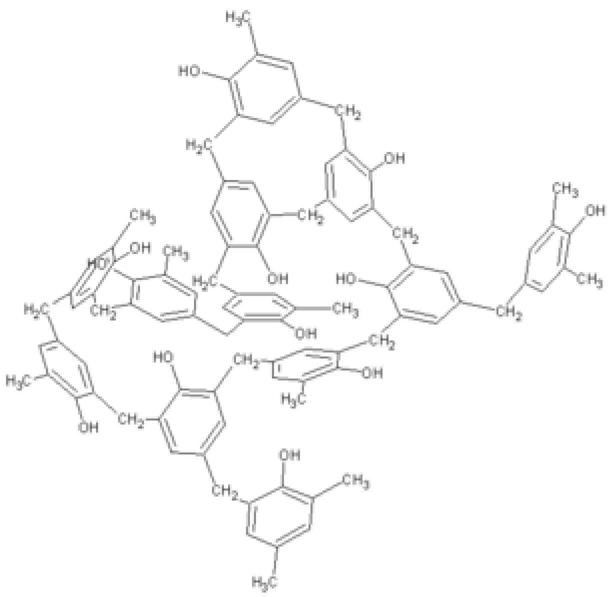
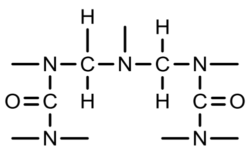
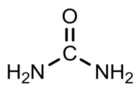
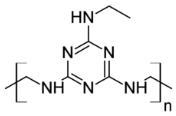
- Wood and wood-based products
- Synthetic polymeric materials
- Textile
- Other

4.1 Wood and wood-based products

Wood and wood-based products are common materials used in various applications including building structure, flooring, roofing membranes and furniture.

Engineered or manufactured wood products most commonly found in homes include particleboard, medium-density fibreboards (MDF) and plywood. These are widely used in flooring, shelving and cabinetry. Particleboard is a composite material made from wood particle and a synthetic resin. MDF is also a composite material made from wood fibres, wax and resin binder. Plywood is made from thin layers of wood glued together. The most commonly resins used in the manufacturing of these wood-products are formaldehyde-based resin, either urea- or phenol-formaldehyde. MDF and particleboard are also frequently used with melamine in the design of kitchen and bathroom cabinets. The chemical structures of the various resins are shown in Table 5. Both urea formaldehyde and melamine contain nitrogen.

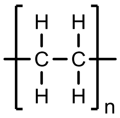
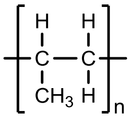
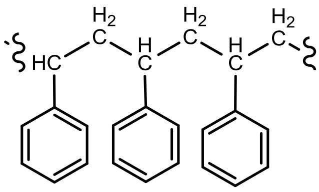
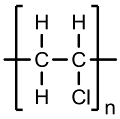
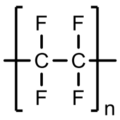
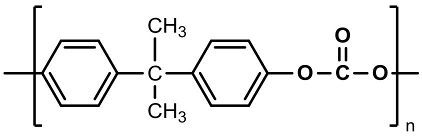
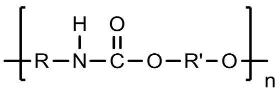
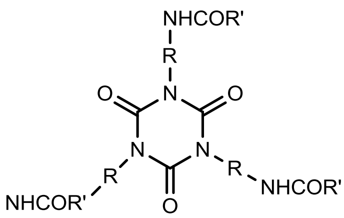
Table 5 Molecular structures of common resins

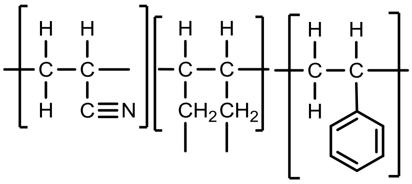
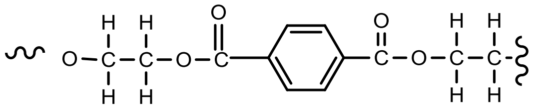
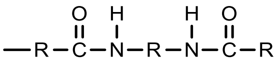
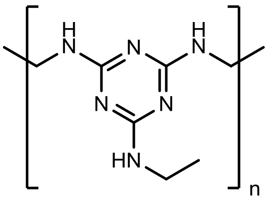
Resin	Structure
Phenol formaldehyde resin	
Urea-formaldehyde	
Urea	
Melamine - main constituent of high-pressure laminates	

4.2 Synthetic polymeric materials

Polymeric materials or often referred to as plastics have a wide range of properties and therefore play a significant and ubiquitous role in everyday life. They are commonly used as furnishings, construction materials, textiles and in vehicle applications. The most common plastics, their chemical structures and most common applications/uses are shown in Table 6. While some polymers are solely composed of carbon, hydrogen and oxygen, others contain halogens, nitrogen and sulphur.

Table 6 Major polymers used as materials in house structure and house contents

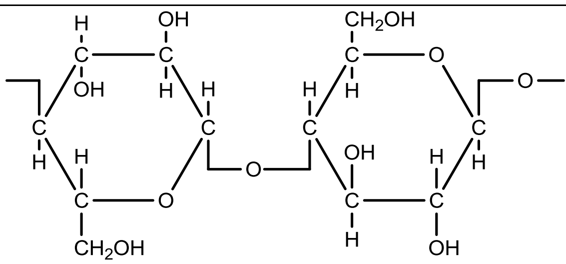
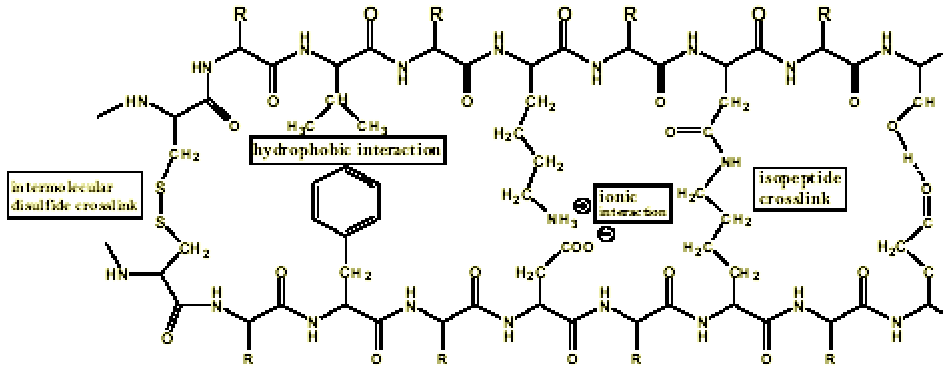
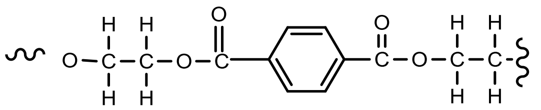
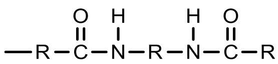
Polymer	Chemical structure	Application/Use
Polyethylene (PE)		- Plastic bags - Cable insulation
Polypropylene (PP)		- Food containers - Appliances - Roofing membranes - Carpets, rugs, mats - Cars – bumpers
Polystyrene (PS)		- Packaging foam - Food containers - CD/cassette boxes - TV - Fridge liners - Insulation
Polyvinyl chloride (PVC)		- Pipes and guttering - Cable insulation - Window frames - Flooring - Upholstery - Curtains/blinds - Roofing membranes - Cabinets - Outdoor furniture
Fluoropolymer (FP)		- Cable-base material
Polycarbonate (PC) (made from Bisphenol A,		- Electronic components - Compact discs, DVDs - Automotive components
Polyurethane (PUR)		- Foams (sofa, mattress) - Thermal insulation - Surface coatings
Polyisocyanurate (PIR)		- Thermal insulation
Polymer	**Chemical structure**	**Application/Use**

Acrylonitrile butadiene styrene (ABS)		- Electronic equipment cases - Appliances - Car components
Polyester		- Fibres/textiles - Insulation
Polyamide (Nylon)		- Fibres - Car (brushes)
Melamine resin		- main constituent of high-pressure laminates - laminate on particle board and MDF - cabinets (kitchen) - kitchen utensils and plates

4.3 Textiles

Textiles can be either natural or synthetic and molecular structures of major textile fabrics are listed in Table 7.

Table 7 Molecular structures of major textile fabrics

Textile	**Structure**
Cotton (>90% cellulose)	 Cellulose
Wool	
Polyester	
Polyamide (Nylon)	

5. COMBUSTION PRODUCTS AND YIELDS

Burning materials, either natural or man-made, release a complex mixture of combustion products into the air, many of which are linked to adverse health effects including increased risk of cardiovascular or respiratory disease and cancer. The composition and yields of combustion products that are generated in the fire vary with the nature of burning material, the physical conditions of the fire (e.g. fire ventilation and fire intensity) and distance from the fire. In order to investigate and understand the emissions of toxic pollutants from burning materials, it is important to understand the role that each of these factors may play.

5.1 Factors affecting combustion products and yields

5.1.1 Type of material

The type of material is an important factor driving the composition of combustion products.

- The combustion of polymers that are based on **carbon, hydrogen and oxygen** (e.g. PE, PP, PS) are likely to emit similar products to those emitted during combustion of cellulosic material such as wood (e.g. carbon monoxide (CO), carbon dioxide (CO_2), hydrocarbons, polycyclic aromatic hydrocarbons (PAHs)). Benzene is one of the principal components of combustion products and generally produced at the highest yield [7]. The presence of an aromatic ring in the structure as for PS results in increased yields of PAHs and other aromatic compounds, such as phenyl-substituted PAHs ([8, 9]and references therein).

- Incomplete combustion of **nitrogen-containing polymers** such as wool, silk, PUR, nylon, and ABS produces hydrogen cyanide (HCN), nitriles and ammonia (NH_3) in addition to hydrocarbons, whereas ventilated conditions produce nitric oxide (NO) and nitrogen dioxide (NO_2). Binders used in the production of particleboards, plywood, glass wool and mineral wool are often urea-based resins that produce HCN and NH_3 during combustion as well as isocyanates. Tests conduced by [10] have shown highest levels of isocyanates emitted from glass wool, closely followed by PUR foams. This is not unexpected as PUR is produced by reacting isocyanates with a polyol, such as polyether or polyester. Different types of isocyanates are used during the production of flexible or rigid PUR foams and therefore combustion of PUR foams can produce different types of isocyanates. Additionally the formulations of certain synthetic polymers (such as rigid and flexible PUR foams) are variable and therefore combustion products can vary as well. Some PUR formulations may contain aromatic structures which would result in increased yields of PAHs and aromatic compounds. PUR and PIR have a high fire toxicity due to the formation of HCN [11].

- Combustion of materials containing **chloride, fluorine or bromine** results in the release of hydrogen halides (hydrogen chloride (HCl), hydrogen fluoride (HF), hydrogen bromide (HBr)) and halogenated organics.

- Burning materials containing **sulphur** (e.g. rubber, wool) results in additional gases such as sulphur dioxide (SO_2), hydrogen sulphide (H_2S) and other organic sulphur compounds.

- A range of polymeric materials also contain fire-retardant agents which may change the composition of emission products. As an example, fire-retardant PUR is more toxic because of the formation of bicyclic phosphate ester in the smoke. Stec and Hull [11] have shown that the presence of halogens (presumably from flame retardants) increase CO production under well-ventilated conditions.

Table 8 Major classes of materials and their combustion products

Material	**Combustion product**
Organic material, e.g. wood, PE, PP, PS, PVC, PUR	CO, CO_2, aliphatic, aromatic and oxygenated hyrdrocarbons (HC), PAHs
Nitrogen-containing material e.g., wool, nylon, PUR, ABS, melamine, urea-formaldehyde	HCN, NOx (NO, NO_2), NH_3, nitriles, amines, isocyanates, organic nitro-compounds
Halogen-containing material, e.g. PVC, FP	Halides (HCl, HF), Dioxins, chlorinated PAHs or hydrocarbons
Sulphur-containing material, e.g. rubber, wool	SO_2, H_2S, organic sulphur compounds

5.1.2 Fire ventilation

Well ventilated or flaming fires (i.e. ample oxygen available) result in a more complete combustion releasing primarily water, CO_2 and in the case of nitrogen- or sulphur-containing material nitrogen oxides (NOx) and SO_2. On the other hand oxygen-deficient fires (i.e. vitiated or smouldering fires) result in the release of incomplete combustion products including CO, aliphatic, aromatic and oxygenated HC and particulates, and in the case of nitrogen-containing material HCN, NH_3 and nitrogenated HC. As a result non-flaming and smouldering combustion releases more toxic products than flaming combustion.

Several studies have shown that yields of CO, total hydrocarbons, volatile organic compounds (VOCs) and PAHs increased with decreasing oxygen availability [7, 12-14]. At well-ventilated conditions low molecular weight PAHs such as naphthalene dominate whereas at vitiated conditions higher molecular weight PAHs (e.g. benzo(a)pyrene (B(a)P)) are primarily produced.

PVC combustion has a different behaviour due to the flaming quenching properties of HCl, which inhibits conversion of CO to CO_2, resulting in high CO levels under well-ventilated conditions [13].

Nitrogenous species were also strongly influenced by the degree of ventilation. HCN was measured during both well-ventilated and vitiated conditions, but generally the yields of HCN produced during vitiated conditions were much higher than those measured during well-ventilated tests [11, 13, 14]. NO was the major component measured during well ventilated conditions, with small amounts of NO_2, while NH_3 dominated at vitiated conditions [7, 14].

Yields of hydrogen halides are generally independent of fire ventilation [12, 13]. Slightly higher production of HCl during combustion of PVC pellets in a tube furnace was measured during well ventilated conditions [14].

The presence of fire retardants in certain materials can also have a significant impact on the burning properties often leading to unsteady burning behaviour [14].

In summary,

- Yield increases with ventilation for CO_2, NO, NO_2 and SO_2
- Yield decreases with ventilation for CO, HCN, NH_3, H_2S, aliphatic and aromatic hydrocarbons, aldehydes and PAHs
- Yield is independent of ventilation for halides (HCl, HF and HBr)

5.1.3 Fire temperature

Fire temperature may affect the composition and yields of combustion products and several studies have investigated the influence of temperature on the type and amount of combustion products.

Stec et al [13] have shown that a temperature increase from 650 to 850°C did not affect yields of CO, total hydrocarbons, HCl or HCN for most of the polymers studied (PE, PS, PVC, nylon). The combustion of PS however showed a noticeable increase at 650°C under well-ventilated conditions. This increase is attributed to the enhanced stability of the aromatic molecules of the polymer, which are more completely oxidised at higher temperatures.

Wang et al [9, 15] and Font et al [16] observed increasing PAH levels with increasing temperatures during combustion of PS and PE, while Durlak et al [17] showed that with increasing temperatures from 600 to 1200°C an exponential decrease in total mass yields of PAHs was observed during combustion of PS, which they relate to a more complete combustion at higher temperatures. The study also showed that while at lower temperatures gaseous PAHs dominated, particle-phase PAHs dominated at higher temperatures. Emission factors for alkanes and olefins during combustion of PE decreased with increasing temperatures [16]. For PVC, behaviour of PAH emissions was more unstable, with a slight decrease in PAHs with increasing temperature [15].

In the case of polyurethane (PUR) foam, a fire burning at different temperatures is likely to generate different emission products. While at lower temperatures, emission products may comprise isocyanates, organo-nitriles and other nitrogen-containing organic compounds, increasing temperatures to 700-1000°C will result in the predominant release of hydrogen cyanide [12, 18].

5.2 Combustion products

A number of studies have been carried out to assess emissions from materials commonly found at structural fires and are summarised in Table 9. The experimental tests included both bench-scale and large-scale experiments and were either conducted on individual (or pure) materials or on a mixture of materials (e.g. room fire). Experimental burns under controlled simulated conditions in the laboratory provide essential information on combustion products and their variability according to fuel type and combustion conditions.

The combustion products can be categorised into 5 major classes:

1. Inorganic gases
    a. Carbonaceous species: CO, CO_2
    b. Nitrogenous species: NO, NO_2, NH_3, HCN
    c. Sulphurous species: SO_2, H_2S
    d. Halides: HCl, HBr, HF
2. VOCs and SVCOs
    a. Aliphatic hydrocarbons (alkanes, alkenes)
    b. Aromatic hydrocarbons (benzene, toluene, styrene, indene)
    c. Oxygenated VOCs (aldehydes, ketones, alcohols, acids)
    d. Nitrogenated VOCs (isocyanates, amines, nitriles)
    e. Chlorinated VOCs
3. PAHs
4. Dioxins and other Persistent Organic Pollutants (POPs)
5. Particulate matter

As can be seen in Table 9, the most extensively studied class of combustion products is inorganic gases. A small number of studies also investigated other pollutants including VOCs, PAHs, dioxins and particle characterisation.

Table 9 Summary of studies looking at emissions from a variety of combustible materials

	Material	Test method	Analysis	Comment	Reference
Wood	Millet straws	Tubular reactor	Inorganic and organic gases (nitrogenous and carbonaceous species)	Temp (800-1000°C)	[19]
	Pellet	fluidised sand bed reactor	CO, CO_2, total HC (THC), formaldehyde, HCN, acids, isocyanates, VOCs	Temp range (500-100°C)	[20]
	Birch	Tubular oven	PAHs	700°C	[8]
	Pine	Combustor	CO, CO_2, VOCs, formaldehyde, PAHs	Temp range (300-950°C)	[21]
	Pine	Cone calorimeter	Isocyanates, amines, aminoisocyanates	Well-ventilated combustion	[10]
	Pine	Tube furnace	CO, CO_2, HCl, HF, HCN, NO, NH_3, isocyanates	Well-ventilated and vitiated conditions	[14]
	Spruce	Grab samples canisters	VOCs		[22]
	Wood & treated wood			Review	[23]
Plywood	Pine (Urea-formaldehyde resin)	Combustor	CO, CO_2, VOCs, formaldehyde, PAHs	Temp range (300-950°C)	[21]
		Cone calorimeter	Isocyanates, amines, aminoisocyanates	Well-ventilated combustion	[10]
		Grab samples canisters	VOCs		[22]

Table 9, ctd

	Material	Test method	Analysis	Comment	Reference
Particleboard	Urea-formaldehyde resin	fluidised sand bed reactor	CO, CO_2, THC, formaldehyde, HCN, acids, isocyanates, VOCs	Temp range (500-1000°C)	[20]
	Pine (phenol-formaldehyde resin)	Combustor	CO, CO_2, VOCs, formaldehyde, PAHs	Temp range (300-950°C)	[21]
	Binder ?	Cone calorimeter	Isocyanates, amines, aminoisocyanates	Well-ventilated combustion	[10]
	Glued veneer	fluidised sand bed reactor	CO, CO_2, THC, formaldehyde, HCN, acids, isocyanates, VOCs	Temp range (750-850°C) different types of adhesives, UF, polyvinyl acetate, emulsion polymer isocyanate (EPI), melamine urea formaldehyde (MUF) and phenol resorcinol formaldehyde	[20]
	Pine veneer	Cone calorimeter	CO, CO_2, NOx	600°C	[24]
	Urea-melamine resin	Cone calorimeter	CO, CO_2, NOx	600°C	[24]
	Urea-melamine-formaldehyde resin	Cone calorimeter	CO, CO_2, NOx	600°C	[24]
	Nitrocellulose varnish	Cone calorimeter	CO, CO_2, NOx	600°C	[24]
	phthalic and carbamide resins and nitrocellulose	Cone calorimeter	CO, CO_2, NOx	600°C	[24]
	MDF	Tube furnace, ISO room	CO, CO_2, HCN, HC, soot	Different ventilation conditions; bench-scale to large scale fire test	[25]
	MDF-FR (fire retardant) (containing nitrogen, bromine, phosphorus)	Tube furnace, ISO room	CO, CO_2, smoke yield	Different ventilation conditions; bench-scale to large scale fire test	[25]

Table 9, ctd

	Material	Test method	Analysis	Comment	Reference
Polyethylene (PE)	Pellet	2-stage muffle furnace	CO, CO_2, light HC, PAHs, particulates	Temp range (500-1000°C) Brief review	[15]
	Pellet	Cone calorimeter	Isocyanates, amines, aminoisocyanates	Well-ventilated combustion	[10]
	Pellet	Tube furnace, ISO room	CO, CO_2, HC, soot	Different ventilation conditions; bench-scale to large scale fire test	[25]
	Pellet (FR)	Tube furnace	CO, CO_2, HCl, HF, HCN, NO, NH_3, isocyanates, VOCs, aldehydes, PAHs	Well-ventilated and vitiated conditions	[14]
	High density PE	Tube furnace	VOCs, SVOCs, PAHs	Temp range (600-900°C)	[16]
	Low density PE	Tube furnace	CO, CO_2, HCN, HCl, HC	Temp (650°C, 850°C) Different air flows (change ventilation conditions)	[13]
	Low density PE	Tube furnace (static and steady-state)	CO, CO_2, HCl, HCN, Organics	Different ventilation conditions and apparatus	[12]
	LDPE (shopping bag)	Tube furnace	Free radicals, heavy metals, PAHs	Soot and ash residue; temp (600-750°C)	[26]
	HDPE (trash bag)	Tube furnace	Free radicals, heavy metals, PAHs	Soot and ash residue; temp (600-750°C)	[26]
	PE plastic bags (contains N and Cl)	Tubular reactor	Inorganic and organic gases (nitrogenous and carbonaceous species)	Temp (800-1000°C)	[19]
	Cable	Cone calorimeter	Isocyanates, amines, aminoisocyanates	Well-ventilated combustion	[10]
	PET (beverage bottle)	Tube furnace	Free radicals, heavy metals, PAHs	Soot and ash residue; temp (600-750°C)	[26]

Table 9, ctd

	Material	Test method	Analysis	Comment	Reference
Polypropylene (PP)	Pellet	Tubular oven	PAHs	700°C	[8]
	Pellet	Cone calorimeter	CO, CO_2, NO, NO_2, N_2O, HCN, HCl, SO_2	Irradiation (25&50kW/m2)	[27]
	Pellet	Large-scale experiment	CO, CO_2, NO, NO_2, HC, HCl, SO_2, HCN, NH_3, organic species	60 kg burned	[7]
	Pellet	Tube furnace	CO, CO_2, HCN, NOx, smoke, HC	Well ventilated 650°C Small under-ventilated 650°C Large under-ventilated 825°C	[28]
	Pellet with FR (ammonium phosphate)	Tube furnace	CO, CO_2, HCN, NOx, smoke, HC	Well ventilated 650°C Small under-ventilated 650°C Large under-ventilated 825°C	[28]
	Pellet	Cone calorimeter; ISO room	CO, CO_2, HCN, NOx, HCl, SO_2, HC	Different ventilation conditions and temperatures	[29]
	Pellet	Tube furnace, ISO room	CO, CO_2, HC, soot	Different ventilation conditions; bench-scale to large scale fire test	[25]
	Food container	Tube furnace	Free radicals, heavy metals, PAHs	Soot and ash residue; temp (600-750°C)	[26]

Table 9, ctd

	Material	Test method	Analysis	Comment	Reference
Polystyrene (PS)	Granulated	2-stage muffle furnace	CO, CO_2, light HC, PAHs, particulates	Temp range (500-1000°C) Brief review	[15]
	Pellet	Tubular oven	PAHs	700°C	[8]
	Pellet (∅ 100-300um)	Tube furnace	PAHS (gas and particle phase)	Temp range (800-1200°C)	[17]
	Pellet	Tube furnace	CO, CO_2, HCN, HCl, HC	Temp (650, 750, 850°C) Different air flows (change ventilation conditions)	[13]
	Pellet	Tube furnace (static and steady-state)	CO, CO_2, HCl, HCN, Organics	Different ventilation conditions and apparatus	[12]
	Pellet	Tube furnace, ISO room	CO, CO_2, smoke	Different ventilation conditions; bench-scale to large scale fire test	[25]
	Styrofoam cups	2-stage muffle furnace	CO, CO_2, NOx, PAHs, particulates	Temp range (500-1000°C) Brief review	[9]
	Insulation material	Tube furnace	Free radicals, heavy metals, PAHs	Soot and ash residue; temp (600-750°C)	[26]
	Extruded PS (insulation)	Tube furnace	CO, CO_2, HCN, NOx, HCl, HBr	Well-ventilated to under-ventilated	[11]
	Expanded PS (insulation)	Tube furnace	CO, CO_2, HCN, NOx, HCl, HBr	Well-ventilated to under-ventilated	[11]
	Expanded PS	Cone calorimeter	Isocyanates, amines, aminoisocyanates	Well-ventilated combustion	[10]

Table 9, ctd

	Material	**Test method**	**Analysis**	**Comment**	**Reference**
Polyvinyl chloride (PVC)	Powder form	Tube furnace	Chlorinated PAHs	Temp range (600-900°C)	[30]
	Granulated	2-stage muffle furnace	CO, CO_2, light HC, PAHs, particulates	Temp range (500-1000°C)	[15]
				Brief review	
	Pellet	Tube furnace	CO, CO_2, HCl, HF, HCN, NO, NH_3, isocyanates, VOCs, aldehydes, PAHs	Well-ventilated and vitiated conditions	[14]
	Pellet	Tube furnace	CO, CO_2, HCN, HCl, HC	Temp (650, 750, 850°C)	[13]
				Different air flows (change ventilation conditions)	
	Pellet	Tube furnace (static and steady-state)	CO, CO_2, HCl, HCN, Organics	Different ventilation conditions and apparatus	[12]
	Plastic bottle	Tube furnace	Free radicals, heavy metals, PAHs	Soot and ash residue; temp (600-750°C)	[26]
	Unplasticized PVC bldg product	Sealed test room	HCl		[31]
	Carpet	Cone calorimeter	Isocyanates, amines, aminoisocyanates	Well-ventilated combustion	[10]
	Carpet	Tube furnace	CO, CO_2, HCl, HF, HCN, NO, NH_3, isocyanates	Well-ventilated and vitiated conditions	[14]
	Cable	Cone calorimeter	Isocyanates, amines, aminoisocyanates	Well-ventilated combustion	[10]

Table 9, ctd

	Material	Test method	Analysis	Comment	Reference
Fluoropolymer (FP)	Fluoropolymer	Cone calorimeter	Isocyanates, amines, aminoisocyanates	Well-ventilated combustion	[10]
	FP cable	Cone calorimeter	Isocyanates, amines, aminoisocyanates	Well-ventilated combustion	[10]
	FP cable	Tube furnace	CO, CO_2, HCl, HF, HCN, NO, NH_3, isocyanates, particles	Well-ventilated and vitiated conditions	[14]
Polyurethane (PUR) and Polyisocyanurate (PIR)	Flexible foam	Cone calorimeter	Isocyanates, amines, aminoisocyanates	Well-ventilated combustion	[10]
	Mattress	Tube furnace	CO, CO_2, HCl, HF, HCN, NO, NH_3, isocyanates, particles	Well-ventilated and vitiated conditions	[14]
	Rigid foam	Cone calorimeter	Isocyanates, amines, aminoisocyanates	Well-ventilated combustion	[10]
	Rigid foam (FR)	Tube furnace	CO, CO_2, HCl, HF, HCN, NO, NH_3, isocyanates	Well-ventilated and vitiated conditions	[14]
	Insulation	Tube furnace	CO, CO_2, HCN, NOx, HCl, HBr	Well-ventilated to under-ventilated	[11]
	PUR car paint	DIN 53436 furnace	Isocyanates	under N2 and O2 at 600°C	[32]
	Rigid PUR foam			Review	[33]
	Flexible and rigid foam			Review	[18]
	PIR rigid foam	Cone calorimeter	Isocyanates, amines, aminoisocyanates	Well-ventilated combustion	[10]
	PIR insulation	Tube furnace	CO, CO_2, HCN, NOx, HCl, HBr	Well-ventilated to under-ventilated	[11]
	Melamine	Cone calorimeter	Isocyanates, amines, aminoisocyanates	Well-ventilated combustion	[10]

Table 9, ctd

	Material	**Test method**	**Analysis**	**Comment**	**Reference**
Poly-ester	Used polyester fabric	Lab-scale reactor	CO, CO_2, light HC, PAHs, PCDD/Fs, PCBs	Temp range (650-1050°C) Pyrolysis and combustion	[34]
	Polyester (w/out & w/ FR)	Tube furnace	CO, CO_2, HCN, NOx, SO_2, H_2S	Temp (450, 550, 750°C)	[35]
Nylon (Polyamide)	Polyamide 6	Tube furnace	CO, CO_2, HCN, NOx, smoke, HC	Well ventilated 650°C Small under-ventilated 650°C Large under-ventilated 825°C	[28]
	Polyamide 6 with FR	Tube furnace	CO, CO_2, HCN, NOx, smoke, HC	Well ventilated 650°C Small under-ventilated 650°C Large under-ventilated 825°C	[28]
	Nylon 66 (solid pellet)	Cone calorimeter	CO, CO_2, NO, NO_2, N_2O, HCN, HCl, SO_2	Irradiation (25&50kW/m2)	[27]
	Nylon 6.6 (pellet)	Tube furnace	CO, CO_2, HCN, HCl, HC	Temp (650, 750, 850°C) Different air flows (change ventilation conditions)	[13]
	Nylon 6.6 (pellet)	Tube furnace (static and steady-state)	CO, CO_2, HCl, HCN, Organics	Different ventilation conditions and apparatus	[12]
	Nylon 66	Large-scale experiment	CO, CO_2, NO, CO_2, HC, HCl, SO_2, HCN, NH_3, organic species	55kg or 75 kg burned	[7]
	Polyamide	Tube furnace	CO, CO_2, HCN, NOx, SO_2, H_2S	Temp (450, 550, 750°C)	[35]
	Nylon 6.6 (pellet)	Tube furnace, cone calorimeter, ISO room	CO, CO_2, HCN, NOx, SO_2, HCl, HC	Different ventilation conditions and temperature	[29]
	Nylon 6.6 (pellet)	Tube furnace, ISO room	CO, CO_2, HCN, NOx, HC, soot	Different ventilation conditions; bench-scale to large scale fire test	[25]

Table 9, ctd

	Material	**Test method**	**Analysis**	**Comment**	**Reference**
Textile	Linen (w/out & w/ FR)	Tube furnace	CO, CO_2, HCN, NOx, SO_2, H_2S	Temp (450, 550, 750°C)	[35]
	Cotton (w/out & w/ FR)	Tube furnace	CO, CO_2, HCN, NOx, SO_2, H_2S	Temp (450, 550, 750°C)	[35]
	Hemp (w/out & w/ FR)	Tube furnace	CO, CO_2, HCN, NOx, SO_2, H_2S	Temp (450, 550, 750°C)	[35]
	Wool (w/out & w/ FR)	Tube furnace	CO, CO_2, HCN, NOx, SO_2, H_2S	Temp (450, 550, 750°C)	[35]
	Wool	Cone calorimeter	Isocyanates, amines, aminoisocyanates	Well-ventilated combustion	[10]
	Polyacrylic (w/out & w/ FR)	Tube furnace	CO, CO_2, HCN, NOx, SO_2, H_2S	Temp (450, 550, 750°C)	[35]
Insulation materials	Glass wool	Tube furnace	CO, CO_2, HCN, NOx, HCl, HBr	Well-ventilated to under-ventilated	[11]
		Cone calorimeter	Isocyanates, amines, aminoisocyanates	Well-ventilated combustion	[10]
	Mineral wool	Cone calorimeter	Isocyanates, amines, aminoisocyanates	Well-ventilated combustion	[10]
	Stone wool	Tube furnace	CO, CO_2, HCN, NOx, HCl, HBr	Well-ventilated to under-ventilated	[11]
	Phenolic	Tube furnace	CO, CO_2, HCN, NOx, HCl, HBr	Well-ventilated to under-ventilated	[11]
	Bitumen	Cone calorimeter	Isocyanates, amines, aminoisocyanates	Well-ventilated combustion	[10]
	Nitrile rubber	Cone calorimeter	Isocyanates, amines, aminoisocyanates	Well-ventilated combustion	[10]

Table 9, ctd

	Material	Test method	Analysis	Comment	Reference
Furniture items	Sofa (steel frame; 14 cushions – cotton-polyester fabric)	Room-scale fire test	CO, CO_2, HCN, HCl, HF, HBr, NO, NO_2, formaldehyde, acrolein		[36]
	Sofa with PUR upholstering	Full-scale experiment	Isocyanates, amines, aminoisocyanates	Well-ventilated combustion	[10]
	Foam sofa	Grab samples canisters in room fire	VOCs		[22]
	Sofa (PUR foam)	Room-scale & full-scale exp	CO, CO_2, HCN, NH_3, SO_2, VOCs, aldehydes, isocyanates	Smouldering foam	[37]
	Bookcase (particleboard with UF resin & laminated vinyl finish)	Room-scale fire test	CO, CO_2, HCN, HCl, HF, HBr, NO, NO_2, formaldehyde, acrolein		[36]
	Rigid PVC product sheet	Room-scale fire test	CO, CO_2, HCN, HCl, HF, HBr, NO, NO_2, formaldehyde, acrolein		[36]
	Household wiring cable (nylon and PVC insulation)	Room-scale fire test	CO, CO_2, HCN, HCl, HF, HBr, NO, NO_2, formaldehyde, acrolein		[36]
	Mattress (PUR)	Large-scale experiment	Isocyanates, amines, aminoisocyanates	Well-ventilated combustion	[10]
	Mattress (PUR)	Grab samples canisters in room fire	VOCs		[22]

Table 9, ctd

	Material	Test method	Analysis	Comment	Reference
Large-scale fires	Simulated house fire		Chlorinated HC, PAHs		[38]
	Simulated room fire		CO, CO_2, HCN, HCl, HBr, NOx, VOCs, PAHs, dioxins	Sofa, armchair, bookshelf, coffee table, carpet, curtains, books, TV	[39]
	Range of natural polymers	Room fire	CO, CO_2, HCN, NOx, SOx, Acrolein	Various openings of the room wool, leather, rayon, cotton, plywood, paper	[40]
	Range of natural & synthetic polymers	Room fire	CO, CO_2, HCN, NOx, SOx, Acrolein	Various openings of the room polyacrylonitrile, rigid & flexible PUR foam, nylon 6, polyester, PE, PP, wood, plywood, paper	[40]
	Automobile fire	Small-scale fire test with components	CO, CO_2, HCN, NO, NO_2, NH_3, HCl, HBr, HF, SO_2		[5]

5.3 Combustion yields

Considering the various factors that influence the composition and yields of emission products, it is not feasible to determine one single emission factor for a specific combustion product, but rather a range of values specific to each fire condition. Literature data has provided quantitative analysis of combustion product yields from a range of materials. As highlighted in Table 9, several studies looked at the effect of either temperature or ventilation conditions on the yields of major combustion products. Table 10 provides a summary of combustion product yields derived from literature data. The combustion products presented include inorganic gases (CO, CO_2, NOx, HCN, NH_3 and HCl), total hydrocarbons (THC), total VOCs, PAHs, isocyanates and particle mass (PM).

Table 10 Combustion product yields based on literature data

Material	Combustion condition	Yield [mg/g material] CO_2	CO	NOx	HCN	THC	VOC	PAH	Isocyanate	PM	Reference
Wood		1630	58	1.4	0.01		1-20	0.01-1.0[a]			[6, 8, 41]
	Ventilated	~1750	7-9						0.0035-0.025	2.4	[10, 14]
	Vitiated	~750	140						0.005		[14]
Plywood									0.018		[10]
MDF							1-20	0.1-1.0			[41]
	Ventilated	~1100-1500	~10-48	0.33-0.41	<1	~10			0.75	3.9	[10, 24, 25]
	Vitiated	~800	~160		~4	~100					[25]
w/ veneer		860-2250	14-70	0.33-1.45							[24]
PE		2820	60	1.7	0.017	15-175[b]	5-30	1, 0-30[c], 0.75[d]			[6, 41], [16], [26]
	Ventilated	~1500-3000	~10			~1-25		10	0.003	20-35.2	[10, 13, 15, 25, 41]
	Vitiated	~400-1000	~150			~300-600		25		30	[13, 15, 25]
PE (FR)	Ventilated	~1500-1700	~10-50				~2	~1			[14]
	Vitiated	~300-700	~50-100				~60-90	~8-12.5			[14]
PE cable									0.013	50.6	[10]
PP						7-43		~0.005-0.35[e], 0.63[f]			[6, 8], [26]
	Ventilated	~2500-3140	~10-30			~10					[7, 25, 27, 29]
	Vitiated	~1500	~100-150			~30-75					[7, 25, 27, 29]

[a] Yields of individual PAHs range from ~0.015-0.18 mg/g. Major PAHs include phenanthrene, fluoranthene, pyrene and acenaphthylene
[b] Highest yield observed at 600°C, lowest yield observed at 900°C
[c] Highest yield observed at 900°C, lowest yield observed at 600°C
[d] PAH yield in soot emissions (major PAH was naph); PAH yield in ash residue (0.40 mg/g) – major PAH was B(a)P
[e] Range of yields for individual PAHs; major PAHs include phenanthrene, fluoranthene and pyrene
[f] PAH yield in soot emissions (major PAH was naph); PAH yield in ash residue (0.27 mg/g) – major PAH was B(a)P

Table 10, ctd

Material	Combustion condition	Yield [mg/g]										Reference
		CO_2	CO	NOx	HCN	HCl	THC	VOC	PAH	Isocyanate	PM	
PS		2200	220	0.8	0.014		13-16	5-30	10[g], 12.5-23.2[h], 1.07[i]			[6, 8, 41], [9, 17], [26]
	Ventilated	~1700-3000	~10-50				0		~4-12	0	40-125.8	[9, 10, 13, 15, 25]
	vitiated	~750-2000	~100-300				~90		~18-40		~160	[9, 13, 15, 25]
EPS						HBr						
	Ventilated	~3000	~125			~3						[11]
	vitiated	~1350	~200			~0.5						[11]
PVC		1460	116	0.6	0.009	320	23	10-50	1-5, 1.41[j]			[6, 41], [26]
	Ventilated	~1000-1400	~20-200			~130-500	~5-10	~1	~0.5-8		1	[13-15]
	Vitiated	~500-750	~20-200			~150-500	~10-45	~25	~3-12		30	[13-15]
PVC carpet	Ventilated	~500	~50			240				0.077	57.4	[10, 14]
	vitiated	~500	~50			180						
PVC cable										0.006	38.6	[10]
FP										0	25.4	[10]
FP cable[k]		390	170			130, 20[k]				0.062	101.7	[10, 14]
ABS								5-30	10			[41]

[g] Yields of individual PAHs range from ~0.2-4.1 mg/g. Major PAHs include phenanthrene, 2-phenylnaphthalene, fluoranthene and benzo(b)fluoranthene
[h] Yield of PAHs in particle phase:12.5 mg/g and in gaseous phase: 23.18 mg/g
[i] PAH yield in soot emissions (major PAH was naph); PAH yield in ash residue (0.51 mg/g) – major PAH was B(a)P
[j] PAH yield in soot emissions (major PAH was naph); PAH yield in ash residue (1.09 mg/g) – major PAH was B(a)P
[k] No difference in yields for CO_2, CO, HCl, HF between well ventilated and vitiated conditions

Table 10, ctd

Material	Combustion condition	Yield [mg/g]											Reference
		CO_2	CO	NOx	HCN	NH_3	HCl	THC	VOC	PAH	Isocyanate	PM	
PUR		1990	160	90	1.8				1-50	1-10			[6, 41]
PUR rigid	Ventilated	1700-2250	~60-75	~8-21	~6-8	~1	~10-13	1-4			1.3-3.4		[10, 11, 14, 41]
	vitiated	~600-800	~75-250	~15	~12-17	~1	~2-5						[14, 28]
PUR flexible	Ventilated	~1800	~40	~2-5	1.5-4			2-5			0.87-1.6	26.1	[10, 14, 41]
	vitiated	~1000	~150		9	1-2							[14]
PIR	Ventilated	~2250	~75	~16	~6		~6				7.0		[10, 11]
	vitiated	~600	~250	~14	~17		~2						[11]
Melamine											1.98	18	[10]
Polyester		~100-1750[l]	~35-115[l]	~0.01-0.10[l]	~1								[35]
	Pyrolysis	150-280	87-165					85-410[l]	13-40[m]				[34]
	Combustion	1300-1640	170-260					65-150	13-40				[34]
Nylon		2500	20	8	1.5								[6]
	Ventilated	~2000-2400	~7-22	~1-40	~1	~1		~1-15					[7, 13, 25, 27, 29]
	Vitiated	~1000	~60-350	~0.5-2.5	~4-70	4-10		~18-300					[7, 13, 25, 27, 29]
		~150-1700[n]	~5-140[l]	~0.01-0.25[l]	~2-5[l]								[35]
Textile		1430	51	1.2	0.009				1	0.1			[6, 41]
Cotton		~350-1350[l]	~100-210[l]	~0.02-0.15[l]									[35]
Wool		~100-1300[l]	~25-60[l]	~0.01-0.18[l]	~1.5-12[l]						1.3	21.9	[10, 35]

[l] Total light hydrocarbons
[m] Total SVOCs
[n] Yields are temperature dependent

Table 10, ctd

Material	**Combustion condition**	**Yield [mg/g]**												**Reference**
		CO_2	**CO**	**NOx**	**HCN**	**NH_3**	**HCl**	**SO_2**	**THC**	**VOC**	**PAH**	**Isocyanate**	**PM**	
Glass wool	ventilated											82.1	28.1	[10]
Mineral wool	ventilated											68.9	54.2	[10]
Bitumen	ventilated											0.093	38.1	[10]
Rubber		2530	200	4.7	0.016			60		50	10	3.68	24.6	[6, 10, 41]
Simulated room fire[o]		620-680	23-35		0.6-1.6	0.6-1.0	0.14-0.9	4.0-4.6		0.6-2.2	0.5-1.3			[39]
Car components[p]	Pyrolytic	240-410	21-360		ND-4.9		ND-340	21[q]						[5]
	Flaming	610-2400	23-96	ND-9.5	ND-5.3	ND-2.3	ND-390	ND-11						[5]
Automobile fire		2400	63	< D.L.	1.6	< D.L.	13	5.0	37[r]	8.5[s]	1.1[t]	0.24[u]	64	[5]

[o] Includes sofa, armchairs, bookshelves, coffee table, carpet, curtains, books and TV units
[p] Includes door panel, ventilation system, floor material, dashboard, upholster material from seats, lacquered plate from car body, electrical wirings, tyre
[q] Tyre emission
[r] Measured with a THC analyser which includes both lighter and heavier hydrocarbons
[s] Measured on Tenax tubes which is a more selective method; Major VOC emitted was benzene with a yield of 3 mg/g, followed by toluene and styrene (0.5-0.7 mg/g); formaldehyde yield of 1.1 mg/g
[t] This yield includes both gas- and particle phase PAHs; Yield for particle-phase PAHs was 0.09 mg/g.
[u] ICA was the major isocyanate identified with a yield of 0.21 mg/g

5.4 Fire stages

A fire generally undergoes various fire stages ranging from pyrolysis to well-ventilated and under-ventilated flaming combustion, and type and amount of gases produced in those different stages will vary significantly. The under-ventilated or smouldering combustion is generally considered to be the most hazardous fire scenario due to the high release of emission products such as CO, HCN, particulates and other organic irritants [12].

In the event of a fire a mixture of materials is burned which may change the fire conditions and emission rates or composition. The majority of experimental burns were conducted on a pure or single material.

6. HEALTH EFFECTS AND EXPOSURE STANDARDS

Smoke generated during combustion of various objects present in and around homes contains a wide range of airborne contaminants that have the potential to impact health and/or impair people's mental and physical ability to perform tasks, if exposures are sufficiently high. Previously we have identified key air toxics in bushfire smoke that have the potential to cause health problems [1]. Additional air toxics are released during combustion of materials other than cellulose and are likely to cause additive health effects. In the following section we discuss major gases present in smoke and their potential health effects.

6.1 Smoke components

6.1.1 Inorganic gases

Carbon monoxide and carbon dioxide

Combustion of any carbonaceous material will result in the production of CO and CO_2. Both gases are the most common and universal combustion products. The ratios of CO_2 to CO will define the combustion efficiency as CO_2 is primarily emitted during flaming combustion, while CO concentrations increase with decreasing oxygen availability.

CO is a colourless and odourless gas that inhibits the oxygen carrying capacity of the blood, hence resulting in asphyxia. An additional effect is that CO can increase the respiratory intake of other gases present in the smoke by stimulating the respiratory centre in the brain. Elevated CO levels in smoke can hence result in increased inhalation of other toxic gases which may not have been inhaled at lower CO levels. CO_2 is in itself not a toxic gas. However, similar to CO, exposure to elevated levels of CO_2 (> 20,000 ppm) can lead to increased breathing resulting in increased inhalation of other toxic gases.

Nitrogenous species

Nitrogen oxides are toxic gases that can cause lung damage. NO_2 is more toxic than NO. At low concentrations, NO aids breathing by widening the blood vessels in the lung area and facilitating passage of oxygen into the bloodstream, whereas at high concentrations, NO can be lethal. NO can combine with oxyhemoglobin to form methemoglobin, which will reduce the oxygen carrying capacity in the blood and result in hypoxia. NO_2 is a highly acid irritant than can cause pulmonary oedema.

NH_3 is a colourless gas with a pungent odour and very irritating to the eyes, nose and throat. It is produced during combustion of nitrogen-containing materials such as nylon, melamine and PUR.

HCN is a colourless gas with a slight odour of bitter almonds and is highly toxic. This is due to the cyanide ion, which inhibits cytochrome c oxidase, thus inhibiting the protein from functioning and resulting in chemical asphyxiation of cells. HCN is lighter than air and can therefore be swept up and be carried away from the fire area. Nitrogen-containing materials are known to emit HCN generally at low concentrations and therefore HCN presents less of a health hazard than CO. However, in combination with other toxic gases, it may produce synergistic effects or symptoms.

Sulphurous species

H_2S is a colourless gas with a strong odour of rotten egg detectable at 1ppm. H_2S is an eye irritant at concentrations ranging from 20-150 ppm. SO_2 is a pungent (detectable at 3-5ppm) gas and highly irritating to the eyes and respiratory tract.

Halides

Halides are pulmonary irritants which generally give off a strong odour. Higher HCl concentrations are produced during flaming of PVC material as a result of the high temperatures. HCl can combine with water forming a dense white smoke which can considerably reduce visibility.

6.1.2 Volatile and semi-volatile organic compounds

VOCs and SVOCs are emitted during combustion of any organic or synthetic polymer. Unsatured hydrocarbons have generally a higher toxic effect than saturated hydrocarbons. Aliphatic hydrocarbons are irritating to the eyes and the respiratory tract and may cause headaches and dizziness.

Benzene, toluene and styrene are the most common combustion products from plastics. Benzene is a human carcinogen and long-term exposure to excessive levels of benzene causes leukemia. Exposures to low levels of benzene can cause headaches, dizziness, rapid heart rate and confusion. Toluene is less toxic than benzene, but exposures to low to moderate levels can cause headaches, confusion and nausea, symptoms which usually disappear once exposure is stopped.

Oxygenated VOCs such as aldehydes, ketones and acids are often strong respiratory irritants that reduce cilia activity. In lungs this reduces the efficient removal of particles and microorganisms from the respiratory tract. Some of the oxygenated are also carcinogens. Formaldehyde most certainly causes upper respiratory irritation at levels exceeding 1.2 mg/m^3 [42]. Formaldehyde has also recently been classified by the International Agency for Research on Cancer (IARC) as a human nasal carcinogen [43]. Acrolein causes irritation at levels as low as 0.23 mg/m^3 and is a more potent irritant than formaldehyde [44].

Isocyanates are powerful irritants to the mucous membranes of the eyes and gastrointestinal and respiratory tracts. They are also sensitisers and exposure to isocyanates can lead to severe asthma attacks in susceptible people.

6.1.3 Polycyclic aromatic hydrocarbons (PAHs)

PAHs are not directly associated with acute effects; however long-term exposure to PAHs can cause cancer, kidney and liver damage. The most common carcinogenic PAH is B(a)P. Some PAHs, such as naphthalene, anthracene and B(a)P can also cause skin irritation.

6.2 Health effects

The various air toxics present in smoke can cause a variety of acute and/or chronic health effects, including

- Asphyxia (CO, HCN)

- Eye, nose, throat, lung and/or skin irritation. The most common irritants encountered in smoke are acetic acid, acrolein, formic acid, NH_3, formaldehyde, furaldehyde, H_2S, SO_2, hydrocarbons and particulate matter.
- Shortness of breath, coughing, wheezing, exacerbation of pre-existing respiratory conditions
- Exacerbation of cardiac conditions
- Effects on the central nervous system (e.g. headaches, dizziness, drowsiness, nausea, confusion, loss of coordination or judgement, fatigue, irritability)
- Change in breathing rate, which results in increased intake of pollutants
- Carcinogens

6.3 Occupational exposure standards

In order to assess risks associated with firefighting at the RUI, we refer to occupational exposure standards (OES). These provide important tools to determine whether exposure is likely to be a risk to health and whether controls need to be implemented. In Australia OES are provided by the Australian Safety and Compensation Council (ASCC) (http://hsis.ascc.gov.au/SearchES.aspx) and those relevant to this study are listed in Table 11. The OES are represented as 8-hour time-weighted average (TWA) concentration and 15-minute short-term exposure limit (STEL).

Table 11 Occupational exposure standards of a range of air toxics present in smoke

		TWA [mg/m^3]	STEL [mg/m^3]	Carcinogen category	Health effects / Symptoms
Inorganic gases	CO	34			Asphyxiant
	CO_2	9000	54000		Headaches; changes to respiratory patterns
	NO	31			Hypoxia at high concentrations
	NO_2	5.6	9.4		Increase in the severity of respiratory symptoms, decreased lung function and increased susceptibility to infectious respiratory diseases.
	NH_3	17	24		Respiratory irritant; headaches and nausea at high concentrations
	HCN	11 (peak)			Chemical asphyxiant (headache, fatigue, confusion, anxiety)
	HCl	7.5 (peak)			Severe irritant to eyes, skin and respiratory system
	HBr	9.9 (peak)			Strong irritant of eyes, nose and throat
	HF	2.6 (peak)			Severe pulmonary irritant
	H_2S	14	21		Effect on the CNS; eye, nose and throat irritation, shortness of breath
	SO_2	5.2	13		Irritation to eyes and respiratory tract; breathing difficulty

Table 11, ctd

		TWA [mg/m^3]	STEL [mg/m^3]	Carcinogen category	Health effects / Symptoms
Aliphatic HC	Alkanes (C12-C26) (branched & linear)			2	
	Butane	1900			Asphyxiant
	Heptane	1640	2050		Skin and respiratory irritant, CNS effect (headache, nausea, dizziness), may cause cardiac effects
	Hexane	72			Irritant gas; can effect the nervous system
	Methane				Asphyxiant
	Pentane	1770	2210		Skin and strong eye irritant, coughing, wheezing, shortness of breath; nausea, headaches, weakness, dizziness, inability to concentrate, loss of coordination and judgment (90,000-120,000ppm)
	Propane				Asphyxiant
	1,3-butadiene	22		1	Eye, nose, throat and skin irritation
	Cyclopentadiene	203			Skin, eye and respiratory tract irritation; headache, dizziness (high conc.)
	Acetylene				Asphyxiant
	Ethylene, Propylene				Asphyxiant
Aromatic HC	Benzene	3.2		1	Nerve inflammation; skin and respiratory irritant; effect on the CNS; leukemia
	Ethyl benzene	434	543	2b	Eye, nose throat and skin irritation; headache, nausea, dizziness, fatigue
	Indene	48			Eye, nose, throat and skin irritation; Cumulative liver and kidney damage
	Styrene	213	426		Irritation of eyes, nose, throat and skin
	Toluene	191	574		Irritation of eyes, skin and respiratory tract; fatigue, confusion, headache, dizziness
	Xylenes	350	655		Eye, nose and throat irritation; headache, fatigue, nausea, motor incoordination

Table 11, ctd

		TWA [mg/m^3]	STEL [mg/m^3]	Carcinogen category	Health effects / Symptoms
Oxygenated and nitrogenated VOCs	Acetaldehyde	36	91	3	Eye, nose and throat irritation; headache,
	Acetic acid	25	37		Eye and respiratory irritant
	Acetone	1185	2375		Dizziness, nausea, drowsiness, headache; eye and throat irritation
	Acrolein	0.23	0.69		Severe eye and pulmonary irritant; difficulty breathing, chest congestion; nausea; may increase blood pressure and heart rate
	Acrylic acid	5.9			Severe eye, nose and respiratory irritant
	Butanol	303			Headache; eye, nose and throat irritation
	Butanone	445	890		Irritation, headache, nausea
	Crotonaldehyde	5.7			Eye, nose, throat and lung irritant; coughing, shortness of breath
	Formaldehyde	1.2	2.5	2	Irritation of eyes and respiratory tract; coughing, headache
	Formic acid	9.4	19		Severe irritant to eye, nose and respiratory tract
	Furfuraldehyde	7.9		3	irritant of the skin, eyes, mucous membranes, and respiratory tract; headache
	Methanol	262	328		Headache, nausea, dizziness; eye, nose and throat irritation
	Phenol	4		3 (Mutagen)	Eye, nose and throat irritation; neurosis, CNS effects; liver & kidney damage
	Valeraldehyde	176			Skin, eye and respiratory tract irritation; dizziness;
	Isocyanates	0.02	0.07	3	Respiratory effects; sensitisation
	Acetonitrile	67	101		Eye, nose and throat irritation; nausea, headache
	Acrylonitrile	4.3		2	Effects on the nervous system; headache, nausea
	Acrylamide	0.03		2	Skin, eye and respiratory tract irritation

Table 11, ctd

		TWA [mg/m^3]	STEL [mg/m^3]	Carcinogen category	Health effects / Symptoms
Nitrogenated and chlorniated VOCs	Methylamine	13			Breathing difficulty, sore throat, headache
	Ethylamine	3.8	11		Severe eye and skin, nose, throat and lung irritant
	Isopropylamine	12	24		Eye, nose, throat and lung irritation, coughing,
	Trimethylamine	24	36		Eye and skin irritation
	Nitrobenzene	5			Skin and eye irritation; headache, dizziness
	Nitrotoluene	11			Nausea, headache, drowsiness, shortness of breath
	Chloro alkanes (C_{10}-C_{13})			3	
	Chlorobenzene	46			Eye and nose irritation; effect on CNS
	1,4 dichlorobenzene	150	300	3	Irritation to eyes, skin and throat; effects on skin, liver and CNS
	Chlorotoluene	259			Dizziness, difficulty breathing
	Vinyl chloride	13		1	Dizziness, drowsiness, headache
PAHs	Naphthalene	52	79	3	Eye, nose, throat and skin irritation
	Biphenyl	1.3			Eye and skin irritation; headache, nausea
	Chrysene			3	
	Benzo(a)pyrene			2	
	Other PAHs			2	
	Dioxins				
	Asbestos	0.1f/ml		1	
	Mineral wool	0.5f/ml		3	

7. SUMMARY

The set of literature data reviewed in this report provides essential information on production yields of important combustion products. The majority of data was collected under controlled and well-defined combustion conditions. These well-controlled bench-scale fire tests allow for quantitative analysis of combustion products generated at specific combustion conditions or fire stages. Stec et al [25] have shown a good relationship between bench-scale and large scale fire tests, suggesting that bench-scale tests are a reliable method to characterise combustion product yields of various materials.

Major materials found in house structure and house contents have been the focus of various studies with the most common combustion products investigated being CO, CO_2, hydrocarbons, PAHs and smoke as well as HCN and NOx for nitrogen-containing materials and HCl or HF for PVC and FP. Acute fire hazard has been linked primarily to CO, as well as HCN (for N-containing materials) and HCl (for PVC). Organic compounds were also considered to be a potential hazard but in most studies individual compounds have either not been identified or quantified.

As highlighted in Table 10, several combustion products present a large range of values for their emission factors, which may be linked to fuel layout, composition of material and/or test method.

As the vitiated conditions represent the most hazardous scenario, experimental burns will focus on that particular scenario to better assess the yields of inorganic gases, VOCs and SVOCs.

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