WHAKARATONGA IWI

FIRE EMERGENCY NEW ZEALAND

TOXICITY OF BUILDING CONTENTS IN BUILDING FIRES

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Inhalation of toxic smoke is the primary cause of death and injury in building fires. The issue is exacerbated by the increasing use of synthetic materials and chemical additives in building materials, contents and furnishings, such as polyurethane foam for furniture products.

This evidence review explores the contribution of common furnishing materials to fire death or injury as a result of toxic smoke inhalation in New Zealand.

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Toxicity of building contents in building fires

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Preface

The overall aim of the work is to better understand the issues relating to fire toxicity of materials commonly found in New Zealand buildings. The study will identify any gaps where further research may be needed to reflect the New Zealand built environment.

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Contents

1. Introduction

Inhalation of toxic smoke is one of the primary causes of death and injury in building fires [1][2][3]. Fire smoke contains a hazardous mixture of toxic products which are generated by building materials and contents as they burn. The type and concentration of toxic products in smoke varies depending on the materials present and the fire conditions. The heat release rate (HRR) of burning materials is known to be the best predictor of the fire hazard [4] and will determine the rate at which smoke and toxic products are generated and transported through the building [5].

The increased use of synthetic materials in modern furniture and building materials worldwide has contributed to an increased fire threat. One example is the rise in UK fire fatalities between 1950-80, which has been attributed to an increased use of synthetic polymers and chemical additives in building materials and furniture [6]. The presence of these materials in building fires has resulted in different types and yields of toxic species in fire effluent, as well as faster rates of fire development and smoke spread. Flame-retardants are used in many cases to reduce the flammability of common materials. Potential effects associated with flame-retardants are discussed in this report, as well as suggestions for alternative methods for achieving reduced flammability.

The aim of this scoping study is to review available literature on the hazards posed by common furnishings in New Zealand building fires. A new Product Safety Policy Statement for foam-filled furniture has recently been introduced in New Zealand [7] that aims to reduce the fire-related risk of foam-filled furniture. This study reviews international research in the area of foam-filled furniture and highlights risk mitigation initiatives. This report is intended to inform the direction of future research by identifying areas where further work may be needed to address specific concerns relevant to the New Zealand built environment.

2. Fire behaviour of building contents

Building contents in modern buildings are typically made from a range of synthetic polymers. Examples include polyethylene (PE) in television and computer parts, polystyrene (PS) in appliance housings, polyvinylchloride (PVC) in vinyl flooring, nylon carpets and polyurethane foam (PUF) in upholstered furniture. A study into the influence of building contents on residential fires compared the peak HRR for a modern chair, a modern sofa and a modern table [8]. Room calorimeter tests showed that the sofa had the highest peak HRR and the table had the lowest. The time taken to reach peak HRR was similar for the chair and sofa and much longer for the table [8]. Upholstered sofas can have a HRR greater than 3000kW [9]. In furniture calorimeter tests, televisions and laptops exhibited far lower peak HRR (range 1 – 10kW) than upholstered chairs with and without flame-retardants (range 17 – 1379 kW) and took much longer to reach peak HRR [10].

Carbon monoxide (CO) and hydrogen cyanide (HCN) are two major asphyxiant gases present in fires that can lead to incapacitation. Whilst CO is present in all fires, HCN is only generated when there are nitrogen-containing fuels present, such as in nylons and PUF. HCN is more potent than CO and short exposure can rapidly lead to incapacitation. Therefore, HCN exposure is a key component in upholstered furniture fires. The yield of HCN generated during combustion has been found to be directly related to the nitrogen content in the PUF [11]. PUF with more nitrogen has the potential to generate greater yields of HCN during combustion.

The contribution of common polymers to fire toxicity under different ventilation conditions was compared [12]. Most of the polymers exhibited low toxic species yield in well-ventilated conditions which increased in under-ventilated conditions. Yields of HCN from a range of nitrogen-containing materials including PUF was found to increase by 1-2 orders of magnitude between well-ventilated to ventilation-controlled conditions [13]. The formulation of PUF can be adjusted to produce either a more flexible foam (such as that used in furniture padding) or a more rigid foam (typically used as insulation) [14]. The toxicity of rigid polyurethane insulation was compared with glass wool, stone wool, phenolic foam, expanded polystyrene and polyisocyanurate insulation products in a range of fire scenarios [15]. For a given room size and ventilation condition, HCN was the major toxicant generated by polyurethane and the fractional effective dose (FED) of HCN, a measure of toxic potency, produced by polyurethane was greater than all other materials tested, except for polyisocyanurate [15]. Under well-ventilated conditions, the contribution of HCN and CO to the FED of polyurethane was approximately 60% and 40% respectively [15]. Glass wool and stone wool products displayed a low fire toxicity. The generation of dense smoke in upholstered furniture fires means that oxygen levels and visibility are quickly reduced. In these under-ventilated conditions, high concentrations of CO and HCN, as well as irritant gases and low visibility, are major contributors to the fire hazard.

The main cause of fatal residential fires in New Zealand has been found to be cigarettes igniting fabrics in the living room or bedroom [16]. Upholstered furniture was involved in over a third (35.4%) of fatal fires in NZ between 1996 – 2000 [17].

2.1 Upholstered furniture

Modern upholstered furniture typically contains a PUF padding. PUF is a cheap, lightweight and durable alternative to traditional padding materials such as horsehair and cotton. The fire hazards associated with PUF in upholstered furniture have been studied internationally [18][19] and in New Zealand [20][21][22][23] in response to the major role furniture plays in residential fires. A key European project was Combustion Behaviour of Upholstered Furniture (CBUF) [18] which was set up to develop methods to measure the burning behaviour of upholstered furniture. Results from full-scale furniture tests and computer modelling showed that upholstered furniture dominates fire development in the early stages of a fire. Major risks associated with the combustion of PUF are that the material can be easily ignited by cigarettes and small flames [17], generate major toxicants [15][24][25] and enable rapid fire growth and flame spread [26] [27]. Anecdotally, FENZ have attended several fatal fires recently that were caused by radiant heat from heaters igniting furniture.

The combustion properties of PUF in furniture are partly dependent on its chemical composition. Polyurethanes are made by the polymerisation of polyols (typically polyester or polyether) with a blowing agent isocyanate. The type and amount of each component and other additives (such as reaction catalysts, surfactants and flame-retardants) will influence time to ignition and HRR [19]. The density of the foam, which depends on the amount of blowing agent used, was found to be the major determinant of its combustion properties. Lower-density foams, which contained a greater proportion of isocyanate blowing agent, produced more smoke and had higher HRR than higher density foams [27]. A study of upholstered furniture in New Zealand found that there were no obvious differences between the combustion properties of 10 different PUF (with the exception of one foam that was fire-retarded) based on both cone- and furniture-calorimeter experiments [20]. The exception mentioned above was a fire-retarded PUF which took longer to ignite but then had a higher HRR than the non-fire-retarded foams after ignition. The PUF with the highest density, in combination with a polypropylene fabric cover, had the highest total and peak HRR in the second shortest time. In the same study, fabric materials were found to have a greater influence on combustion properties of the furniture than the PUF [20]. Using a woollen fabric cover resulted in a lower peak HRR and the time taken to reach the peak HRR was longer than when a polypropylene cover was used. A different New Zealand study investigated the fire properties of six chairs with the same style, fabric and size, but a different foam type [22]. The results showed that different foams showed different degrees of fire hazard, but that all had rapid-fire growth. The range of peak HRR of the different foams was between 1.34 MW and 1.82 MW and the time to reach peak HRR was between 138.1 and 210.4 seconds. Detail on the chemical compositions of the foams was not included in the study.

3. Reducing the flammability of polyurethane foams

3.1 Furniture flammability regulations

The UK Furniture and Furnishings (Fire) (Safety) Regulations 1988 (FFR) [28] and California's Technical Bulletin 117 (TB117:2013) [29] are two notable flammability regulations for domestic upholstered furniture. The FFR are seen as the strictest regulations for domestic furniture, because of the inclusion of the Crib 5 test which requires adequate resistance to a small wooden crib flaming ignition source, as well as cigarette and match tests. In Europe, furniture flammability is regulated by the General Product Safety Directive, with individual Member States deciding the level of requirements to set within their own jurisdiction. Some countries have adopted the cigarette and match tests for domestic furniture, whereas others, and also New Zealand, only have flammability regulations for furniture used in public spaces, such as health-care institutions and prisons [30] [31].

The FFR were implemented to reduce the number of fire deaths and injuries attributed to foam-filled furniture. Prior to the FFR, the UK experienced a rise in fire deaths and injuries from smoke inhalation which has been directly attributed to an increased use of PUF in upholstered furniture. A statistical review of the FFRs in 2009 found that the number of lethal fires related to furniture and furnishings was lower in the review period (2002 – 2007), than in the years before the FFRs were introduced (1981 – 1985) [32]. One conclusion of the report is that the reduction in fatal fires was likely due to the effectiveness of the Crib 5 test in improving the resistance of foams to a wooden-crib ignition source [32]. Since the FFRs were introduced, changes in smoking habits, increased use of domestic smoke alarms and safer heating devices are other factors that could have contributed to the overall downward trend in fatal fires. The 2009 review concluded that an increase in smoke alarms was likely to have contributed in part to the reduction in fatal fires from furniture and furnishings, but more so to fires started by other means and that smoking behaviour did not have an effect. Overall, the review estimated that the FFRs had accounted for 54 fewer deaths, 780 fewer non-casualties and 1065 fewer fires each year in the UK for the review period 2002-07 [32].

3.2 Use of flame-retardants

3.2.1 Background

Furniture flammability requirements are typically achieved through the use of additive flame-retardants. When furniture flammability requirements were first introduced, halogenated flame-retardants (usually brominated or chlorinated) were most widely used due to their cost and availability. Growing evidence of their adverse health and environmental effects has resulted in some halogenated systems now being recognised as global contaminants [33] and no longer used. Developments in flame-retardant chemistry has resulted in over 100 different types of flame-retardants being available for use in a range of products and materials [34]. Alternatives to banned systems include phosphorous-containing, nitrogen-containing, inorganic and novel brominated flame-retardants. Phosphorous flame-retardants have been found to be the main replacement for halogenated flame-retardants in studies of PUF furniture [35][36], but there has also been debate about their toxicity, particularly when they contain halogens [37].

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 [33][38]. Concerns about the use of flame-retardants are related to human and environmental exposure [39] [40] [34] [41] and smoke toxicity during a fire [42]. Whilst many studies have investigated these issues, a full review is outside of the scope of this work.

In relation to toxicity, the use of gas-phase flame-retardants, which inhibit complete combustion, have been shown to increase CO and HCN yields in fire effluent [43]. A recent UK study that compared sofas made with non-fire retarded PUF and one with natural materials, showed that a flame-retarded sofa bed (meeting UK FFR criteria) burnt more slowly but produced greater quantities of CO and HCN in the process [42]. By contrast, a review of the risks of flame-retardants in European furniture [44] 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 [45] and cigarette & match ignition requirements. If these requirements were met, then 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 [44]. A study that was part-funded by the North American Fire Retardant Association found that flame-retarded PUF, in combination with a flame-retardant cotton barrier material, resulted in lower yields of CO and HCN, than when a non-flame-retardant PUF was used [25].

3.2.2 Revision to furniture flammability regulations

There appears to be a trend towards finding alternatives that produce the desired flammability reduction without increasing toxic species production. Studies into the fire safety benefits vs risks associated with the use of traditional flame-retardants [33][46] concluded that flammability regulations can cause greater adverse environmental health impacts than fire safety benefits. Recommendations included that the health and environmental impacts of any flame-retardants, or alternative means for achieving non-flammability, should be evaluated before the implementation of such standards. Similarly, a 2006 Norwegian report assessed key considerations of increasing flammability requirements for mattresses and upholstered furniture in Norway, including potential environmental impacts of flame-retardants. The report cites concerns connected to the potential release of flame-retardants at different stages of the furniture's lifecycle but also that there would be a large benefit in terms of the potential reduction in fatalities and injuries. Overall the study recommended that fire safety requirements for mattresses and upholstered furniture be increased in high fire risk buildings [31].

The effectiveness of using flame-retardants to meet California TB117 has been studied [46]. The study evaluated the risks and benefits associated with the flame-retardants typically used to meet the state regulations. The study concluded that a fire safety benefit as a result of the TB117 had not been established and the use of traditional flame-retardants, which are no longer in use, have been associated with adverse health impacts. Changes to California TB117, made in 2013, reflect efforts of environmental groups and others to encourage the uptake of alternative technologies to meet flammability requirements. The revised TB117:2013 does not include the open flame test requirement, instead only including smoulder tests for fabric, filling, decking and barrier materials. TB117:2013 can be met without the use of flame-retardants, but the regulation does not prescribe how the standards must be met [47]. Anecdotally, the use of barrier fabrics to meet the flammability requirements have increased.

Recent activity related to the UK FFRs reflects concerns that the regulations do not reflect modern-furniture design and construction [42] and pressures to reduce the use of flame-retardants to achieve fire safety in upholstered furniture. The July 2019 report titled 'Toxic Chemicals in Everyday Life' from the UK Environmental Audit Committee (EAC) identified that flame-retardants in furniture were partly responsible for the growing chemical contamination in the UK [48]. The EAC recommends that chemical flame-retardants in domestic furniture should be reduced and that the FFR be revised in line with California TB117:2013.

3.2.3 Alternatives for achieving reduced flammability

In response to the known concerns around some flame-retardants used in PUF, alternative systems have been developed. Flame-retardants used in a range of consumer products include mineral- , phosphorous-, nitrogen-, silicon-based and nanocomposite systems [49]. A range of flame-retardants that are alternatives to traditional halogenated flame-retardants have been reviewed by the US Environmental Protection Agency (EPA) for the risk they pose to environmental and public health [50]. The EPA review focuses on flame-retardants most commonly used in PUF and can be used to understand and compare the hazards associated with different options.

Two detailed studies have assessed the risks associated with a range of flame-retardant chemicals used in PUF and other consumer products and identify possible safer alternatives [30] [51]. Of these, one study also attempted to investigate the effect of flammability requirements on the number of fire fatalities across the EU. An accurate correlation was not possible due to lack of available and consistent data across EU Member States. It was reported that decreases in fatal fires were observed in countries with and without consumer product flammability requirements [51]. The UK Department for Environment, Food & Rural Affairs (DEFRA) has recommended the investigation of graphite impregnated foam and the continued development and use of nanocomposite foam as alternatives to conventional PUF for furniture [30]. DEFRA has also recommended better design and use of inherent flame-retardant materials to reduce the need for flame-retardants [30].

A proprietary reactive flame-retardant system, which was chemically integrated into PUF, showed no indication of migration into the environment following accelerated ageing [10]. In addition, there was no indication of the flame-retardant in post-fire residue. Reactive flame-retardants can enhance flame-retardancy in small amounts or low concentrations and without degrading mechanical properties of the polymer [14].

A novel polyester polyol was synthesised using dimethyl methylphosphonate (DMMP) to be used as a flame-retardant in PUF. The study showed that PUF incorporating the novel system had greater tensile strength and improved fire resistance. In addition, results of accelerated ageing tests indicate that the flame-retardant properties are likely to be maintained as the PUF ages [52].

The fire properties of rigid PUFs containing different combinations of nanostructured additives and traditional phosphorus flame retardants were studied. The rigid PUFs containing nanostructures had a heat release rate that was 56% lower than the non-flame-retarded foam, and 26% lower than when only the traditional phosphorous flame-retardant system was used [53]. A rapid growing clay coating for PUF was shown to reduce peak heat release rates in cone calorimeter and real scale furniture tests by 42% and 53% respectively [54]. The incorporation of carbon-based composites has been shown to improve fire retardancy of polymers as well as improving other material properties [55].

A 2010 study into wool-based inter-liners noted that there was little available data and research on inter-liner development. Lack of support for their development and a focus on improving PUF were cited as two possible reasons for the lack of available studies [56]. A recent study assessed the effectiveness of barrier fabrics on PUF samples using the cone calorimeter [57]. The results showed that the use of flame-retardant chemicals in the barrier fabric helped to extinguish the flame and that the barrier fabric itself was important in reducing the HRR of the burning foam. In a separate study, large-scale testing (Furniture Heat Release Calorimeter and ISO 9705 Test Room) showed that chairs with barrier fabrics had lower peak HRR (average 31kW) than chairs without a barrier (average 1400kW) and also resulted in lower production of CO, HCN, temperature and smoke optical density [10].

4. Post-fire contamination

Combustion products produced in building fires include those that cause immediate survival threats (CO, HCN, irritant gases, particulates) and long-term contamination (polycyclic aromatic hydrocarbons (PAHs), benzene, isocyanates, dioxins and furans, aldehydes, inhalable fibres, particulates) [58]. During and after a fire, human exposure to these toxicants can be via inhalation, dermal absorption or oral ingestion. Some products can also cause corrosion to building materials and environmental contamination.

Health effects of long-term exposure to fire contaminants has been studied in the context of firefighters and their elevated cancer incidence [59]. Exposure to PAH carcinogens is thought to be a major contributor. A study, which was the first in the UK, looked at firefighter exposure to PAH carcinogens. The results of analysis of wipe samples from skin, personal protective equipment and firefighters' work environment, showed an elevated risk of cancer due to dermal exposure [60].

The effect of fire effluent exposure of occupants and buildings surrounding a fire has been less well studied. Volatile and semi-volatile compounds (VOCs/SVOCs) produced in fires were analysed during a series of experimental house fires [61]. The carcinogenic PAH benzo(a)pyrene was found in at least one sampling interval in most of the experimental fires. In addition, in experiments where the initial fuel source was upholstered furniture, flame-retardants were detected in both gas and soot particulate samples. The study reports that the release of flame-retardants 'is significant as they pose toxicological concerns separate from those presented by the PAHs' [61].

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 [62]. Samples of soil taken closest to Grenfell Tower showed increased cancer risk from dioxins and 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 150m 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, which was a product of isocyanates, was found on a window blind in a living space. 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 [62].

5. Summary & future work

This work reviewed literature relating to the hazard posed by building contents in building fires. Of these, polyurethane foam is known to be a major hazard. The fire performance of polyurethane foams has been well studied and their use in upholstered furniture is a known risk in domestic building fires that result in deaths and injuries. To reduce the risk of flammability, there is a trend towards flame-retardant systems that do not contribute to adverse health effects and environmental contamination. Flame-retardants with novel formulations may be being used before their longer-term effects are fully understood or assessed. Alternatives to flame-retardants have been the focus of several reviews, including non-chemical alternatives such as barrier fabrics. To better understand the issues relating to flame-retardants in foam furnishings and to ensure these are adequately managed in New Zealand, future work is recommended that:

- Reviews the known risks related to flame-retardants that would likely be used to meet furniture flammability guidelines in New Zealand. This should include the risks associated with the flame-retardants throughout the furniture product's lifecycle and could establish whether any restrictions or guidelines would be of benefit.

- Investigates typical polyurethane foam and furnishings used in New Zealand, with and without flame-retardants, in terms of their toxicity and rate of spread of toxic species.

- Investigates the feasibility of novel chemical and non-chemical options to achieve reduced flammability and any potential impacts of the use of flame-retardants.

- Supports innovative research into the development of novel innovations for achieving reduced flammability in upholstered furniture.

Recent findings of environmental contamination after the Grenfell Tower fire highlight issues of longer-term fire toxicity that currently may not be adequately managed overseas and in New Zealand. Occupants returning to buildings that have been contaminated by fire effluent, and those living in the surrounding area, may be exposed to harmful levels of toxicants in the form of volatile or semi-volatile gases or deposits in household dust. The existence of these species may not be visibly obvious, and it is unknown whether remedial activities decrease exposure levels sufficiently. In this area, future work is recommended to:

- Measure the level of pollutants after fire that returning occupants may be exposed to, to better understand the potential toxicity risks. This information could be used to provide guidance to occupants on how post-fire contamination can be managed / mitigated.

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