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Review

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Fire performance of timber: review for use in wildland-urban interfaces

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Abstract: Wood is increasingly viewed as a more environmentally sustainable material owing to its low embodied energy, workability, and renewability, but its two major drawbacks are susceptibility to biological degradation and fire. Biodegradation is typically addressed through effective designs to exclude moisture or, where that is not possible, the use of either naturally durable or chemically protected timber. Naturally durable timbers are widely used globally while preservative treatments are increasingly used to protect less durable timbers. These practices have markedly extended the use and service life of timber in harsher environments. However, these treatments do not improve the fire performance of the timber and there is increasing interest in the use of fire resistive coatings or impregnation with fire retardants to allow use in bushfire prone areas. This review provides background on the problems associated with increased building and construction in the wildland-urban interface. It summarizes the codes, standards and state of the art practices needed for adequate fire safety in timber construction.

Keywords: bushfire; fire; fire-retardants; flammability; wildland-urban interface.

1 Introduction

One area where timber continues to be challenged is fire. The susceptibility of timber to fire is well known and was a major reason for the shift to less combustible materials in many urban settings (Frost and Jones 1989). However, timber can be safely employed using combinations of proper design, fire-resistant barriers and fire-retardant treatments (Sweet 1993). At the same time, climate change is leading to increasingly variable weather patterns including more extreme weather. Droughts over large areas of several continents, in combination with decades of wildland fire suppression policies that have allowed for the build-up of forest and wildland fuel, have led to historically large forest or bush fires not seen in North America since the early 20th century. Population growth has resulted in more structures being built within or on the edge of historically forested or natural bush areas (termed the wildland-urban interface or WUI). As risks of wildland fire increase, these structures are more prone to fire. In the last 25-years, massive fires have occurred in North America, Europe and Australia, highlighting the importance of building fire resilient or even fire-resistant structures.

Worldwide between 2012 and 2016, 17.5 million fires were reported that caused 220,000 fatalities and 350,000 injuries (Brushlinsky et al. 2018). Fires caused US$23 billion in property damage in 2017 (Lazar et al. 2020). The state-of-the-art in the field of fire-safety focusing specifically on wood construction was reviewed by White and Dietenberger (2010). An average of 900 homes were lost per year to wildfire in the 1990’s in the U.S.; that number grew to over 3000 homes/year between 2000 and 2010 (Bailey 2013). Over 38,000 homes in the U.S. were lost between 2000 and 2014 to fire in the WUI (Gollner et al. 2015). These increasing losses reflect more development in rural areas, poor fuel management policies and climate change and are likely to continue to increase (Krawchuk et al. 2009). Fires at the WUI occur from three possible mechanisms: flame contact, radiative heat exposure and ember exposure (Gollner et al. 2015). In recent years, the ignition of timber structures by radiated heat and flying embers has seen renewed research focus (Nazare et al. 2021).

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As carbon-neutral timber is used in ever-larger structures, understanding the nature of timber combustion and the methods for limiting it, will become increasingly important. The purpose of this review is to provide background on the problem and then summarize the state of the art with regard to fire-retardant protection of timber.

This review focuses on fire retardant systems that can be applied to solid timber either via impregnation or coatings; this excludes systems added to engineered wood products during their production (e.g. medium density fibreboard or particleboard).

2 Increasing risk of fire at the WUI

Understanding the growth of both fire hazard and the problematic effects of WUI fire requires recognizing the scope of the problem. Virtually all of the most significant fire events in the U.S. over the last 20 years have occurred at the WUI (Gollner et al. 2015; NIFC 2021). The National Interagency Fire Center tracks fire in state and local communities across the U.S (Figure 1).

There were 58,950 wildfires in the United States in 2020 that burned across almost 4.1 million hectares. While the number of fires were lower than the five and ten-year national averages (63,191 and 64,102, respectively), the hectares burned were well above both the five and ten-year national averages (3.16 mil. and 2.75 mil., respectively) (NIFC 2021).

Studies from Australia have shown that the probability of loss of a home to bushfires did not increase markedly between 1900 and 2003 and that the risk of bushfires to individual rural homes was relatively low (McAneney et al. 2009), however, this analysis did not include the particularly destructive Black Saturday bushfires from 2009 nor the 2019/2020 Black Summer bushfires. The effects of these megafires can be gauged from the proportion of insurance costs from bushfires in Australia more than doubling from 7 to 17% between 2001 and 2013 (Handmer et al. 2018). Annual forest area burned in Australia increased by 800% when comparing the period between 1988–2001 and 2002–2019 (Canadell et al. 2021).The increase in burned areas in the US and Australia, and accompanying insurance losses illustrate the increasingly challenging conditions for building in the WUI and the need to carefully consider design and treatment options for continued utilization of timber in these areas.

3 Effects of heat on timber

Understanding the effects of heating on timber properties in wood-based construction as well as the effects on each cell wall polymer can help in selecting the best methods for chemical protection.

Elevated temperatures have detrimental effects on timber relatively early in the exposure. Hemicelluloses tend to be most susceptible to degradation followed by lignin and finally, cellulose (Winandy and Rowell 2013; Winandy 2017). Hemicelluloses play important roles in integrating cellulose and lignin into a functional matrix and their loss can have profound effects on wood physical and mechanical properties (Green et al. 2003; Green and Evans 2008; Sweet and Winandy 1999; Winandy and

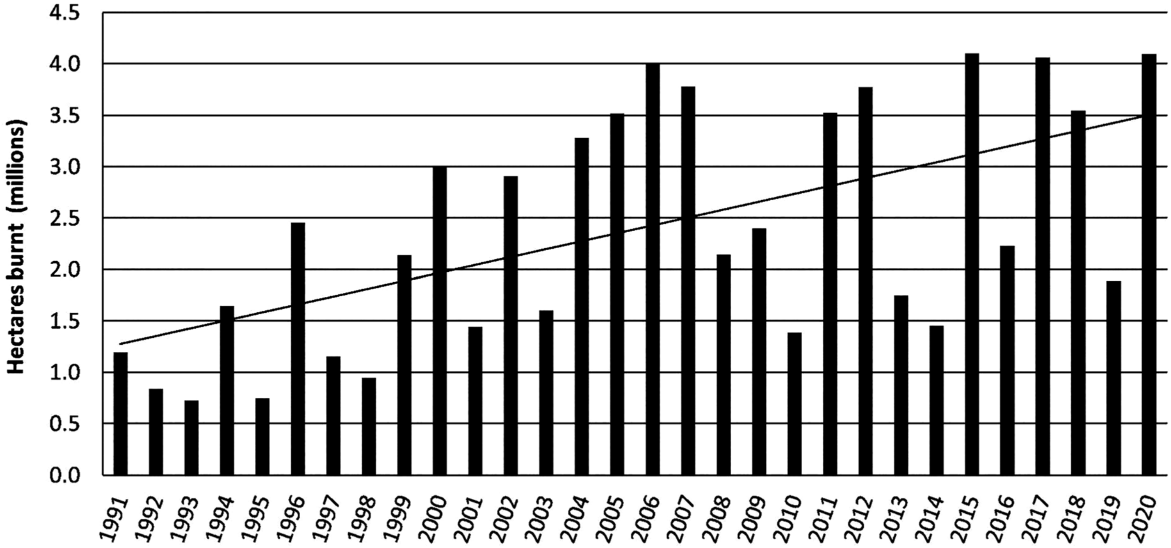

Figure 1: Area affected by wildfires in the US between 1991 and 2020 (NIFC 2021).

Lebow 2001; Winandy and Rowell 2013). Thermal degradation resulting from prolonged exposure to temperatures between 50 and 100 °C is of practical significance in engineered uses (LeVan et al. 1990). However, the thermal degradation rate is slow, and acid-mediated hydrolysis of wood carbohydrate components is often measured over months and years at ≤100 °C. The arabinose and galactose side-branch components of the hemicelluloses are especially sensitive to thermal degradation at temperatures between 50 and 100 °C (LeVan and Winandy 1990; Winandy 2001; 2013). Kinetic-based models predicting heating effects have been developed for both untreated and chemically-treated wood with and without natural defects (Green et al. 2003, Lebow and Winandy 1999).

A variety of thermochemical reactions progressively occur above 100 °C and each series of unique events can be categorized into multiple distinct processes and chemical reactions over various temperature ranges (Beall and Eickner 1970; Browne 1958; Dietenberger and Hasburgh 2016; Kollman 1960). Thermal degradation of wood material begins to accelerate exponentially as temperatures exceed 100 °C. Between 100 and 200 °C, wood becomes dehydrated as the bound water is released, generating water vapor and other noncombustible gases and liquids including CO_2, CO, formic acid, acetic acid, and glyoxal (Dietenberger and Hasburgh 2016). Each newly evolved acid then increases the rate of carbohydrate hydrolysis. The primary active in this type of thermal degradation is acetic acid produced by the rapid breakdown of acetyl groups associated with hemicelluloses (LeVan and Winandy 1990; Packman 1960). Hemicelluloses are the first polymers to degrade at 100 to 130 °C, lignin begins decomposition at 130 to 150 °C and then the cellulose begins to decompose at higher temperatures (Fengel and Wegener 1984; Stamm 1955, 1964). The process results in darkening and embrittlement of the wood.

Temperatures above 200 °C are associated with pyrolysis, combustion, glowing, and smoke production, depending on the conditions (Dietenberger et al. 2021). Pyrolysis or heating in the absence of oxygen releases water, carbon dioxide and carbon monoxide with the sensitivity of the polymers from most to least affect being hemicellulose, cellulose and lignin. Pyrolysis occurs between 225 and 470 °C and can be sub-categorized as the flame point (225–260 °C), the burning point (260–290 °C) and the flash point (330–470 °C) (Kollman 1960). Rapid pyrolysis induces formation of flammable gases including carbon monoxide, methane, formaldehyde, formic acid, acetic acid and methanol. Pyrolysis is complete at 400–500 °C, leaving a residual charcoal. Slow pyrolysis tends to produce fewer flammable gases and more charcoal while fast pyrolysis does the opposite. Oxidation of pyrolysis gases can only create flaming combustion when a minimum volatile air-fuel concentration is achieved (Babrauskas 2002; Hirata et al. 1991; McNaughton 1945).

Flaming combustion occurs in the presence of oxygen and consumes the flammable gases evolving from the wood. The process is exothermic and continues until heat produced in the flame is insufficient to support continued formation of pyrolysis gases within the flammability limit in the absence of an external ignition source. The process is more aggressive at higher oxygen levels. Initially, combustion creates a surface layer of char that insulates the unburned wood beneath and this helps explain why heavy timbers perform comparably well in fires, as indicated by a reduced burning rate correlated with char formation. Continued heating will eventually consume the char layer at the surface via oxidation of the solid phase, also referred to as smoldering, while new timber beneath pyrolyzes, thus creating a quasi-constant char thickness on a progressively smaller cross section.

The smoldering process is dependent on the oxygen concentration near the char surface (Richter et al. 2021). The onset temperature at the micro scale for wood char oxidation has been reported around 400 °C; however this onset temperature and the associated activation energy can be reduced to 350 °C or lower in the presence of chromated copper arsenate (CCA) (Wu et al. 2021). Continuous self-sustained smoldering poses a problem to timber structures as it can cause significant structural damage and collapse long after flaming combustion has stopped (Wiesner et al. 2021).

Lowden and Hull (2013) divided the temperature ranges into five distinct processes from 100 °C to 500 °C (Table 1). Stamm (1955) noted that these reactions could be modeled using a first-order Arrhenius equation between 93 °C and 250 °C and that the addition of moisture or steam

Table 1: Temperatures of wood pyrolysis and combustion (Lowden and Hull 2013).

Temperature range (°C)	Decomposition processes
>100	Evaporation of chemically unbound water
160 to 200	Cellulose, hemicellulose and lignin degrade, non-combustible gases form
200 to 225	Slow pyrolysis begins and most gases are non-combustible
225 to 275	Pyrolysis and flaming combustion with a pilot flame
280 to 500	Volatile gases produced (CO, methane, etc) and smoke particles; char forms as the wood structure breaks down.

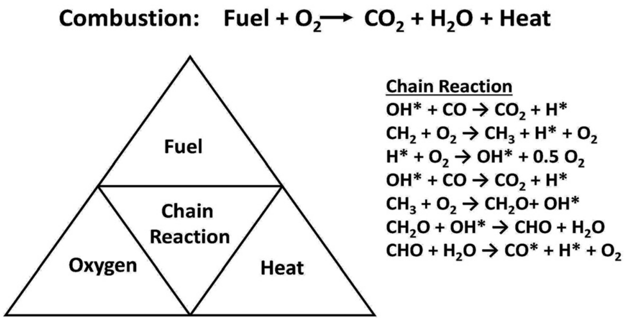

Figure 2: The four parts of combustion/fire tetrahedron and their chemical mechanisms. (Adapted from Lazar et al. 2020; Boryniec and Przygocki 2001).

appeared to accelerate reaction rates. Others have identified the four critical parts of combustion (i.e., the fire tetrahedron) and the resulting chemical mechanisms (Boryniec and Przygocki 2001; Lazar et al. 2020) (Figure 2).

4 Fire related building codes and standards

While the risks, hazards and effects of fire on commercial and residential timber construction are obvious, each region around the world describes risk in a slightly different fashion. Many issues related to fire effects are generally the same regardless of the intensity scale- or use. Thus, many preventative approaches can be broadly applied to each scenario with some modifications to fit the circumstances. However, some unique risk/hazard issues often require regional/national solutions (Table 2). For example, design, engineering and construction at or within the WUI is now becoming a global phenomenon, but with unique regional/national adaptations.

In North America the primary document(s) mandating building design, construction and materials are the model building codes written by the International Code Council (ICC) (ICC 2021a, b). These codes are then adopted by the states and local communities (with some minor exceptions due to state or local needs) as legal requirements for building construction and design. For most areas, these two International Building Codes detail structural design and engineering detailing for most situations across the U.S (Dietenberger et al. 2021). However, a specific complimentary ICC code was first developed in 2009 and is now mandated for structures in the WUI (ICC 2021c). The International WUI Code creates specific guidance on structural fire protection within the WUI related to building design, materials and site-specific elements. These special building and design requirements detail enhanced resistance to structural ignition issues, defensible space around the structure, fuel management within the "Ignition Zone" (usually detailed as a 360° zone of 30–70 m), and issues involving enhanced fire-resistant community planning

Table 2: Examples of construction standards to improve the fire- and durability-performance of wood materials in building construction in fire-prone exterior exposures.

Jurisdiction	Building elements	Test equipment	Exposure/heat output	Acceptance criteria	Relative standard
California	Exterior wall siding	Gas burner (100 × 1000 mm)	Direct flame contact from 150 kW for 10 min	No flame penetration, no glowing on unexposed face 70 min after test	SFM STANDARD 12-7A-1
	Windows (also for Canada)	Gas burner (100 × 1000 mm)	Direct flame contact from 150 kW until flame penetration	At least 8 min with no penetration	SFM STANDARD 12-7A-2
	Decking	Gas burner (300 × 300 mm)	80 kW burner 690 mm below deck for 3 min	Neat peak HRR of deck below 269 kW/m^2	SFM STANDARD 12-7A–4A
California, USA, Canada	Decking	Burning brands and wind tunnel	Class A brands and 5.4 m/s ventilation for 40 min	No falling particles that are still burning during test, absence of flaming after 40 min	SFM STANDARD 12-7A-4B ASTM E 108
Australia	Decking, windows, doors up to BAL-29	Cone calorimeter	25 kW/m^2 radiative heating	Peak HRR below 100 kW/m^2 and mean HRR below 60 kW/m^2 10 min after ignition	AS 3959
Australia	Exterior building systems up to BAL-40	3000 × 3000 mm radiant heating panel + wood crib	Heating curve for 10 min with peak exposure heat flux according to BAL zone	No formation of gaps, flaming on unexposed side; no flaming on exposed sides after 60 min	AS 1530.8.1
Australia	Exterior building systems in BAL-FZ	Furnace	Cellulosic standard temperature time curve for 30 min	No formation of gaps, flaming on unexposed side; no flaming on exposed sides after 60 min	AS 1530.8.2

(Bueche and Foley 2012; Gollner et al. 2015). These four factors are key components that dictate many of the WUI Code requirements.

Limiting the potential designs and materials that might lead to structural ignition is a key component of the WUI Code. Structural ignition is a significant, and often the primary, factor in wildfire spread within communities (Maranghides and Mell 2013). Conversely, preventing structural ignition or limiting fire size from individual homes (and thus reducing the risk of ignition of adjacent structures) would sharply reduce the threat of WUI fire to residents and communities (Cohen 2004). The WUI Code defines ignition-resistant building materials as capable of resisting ignition or sustained flaming combustion from wildfire exposure to burning embers and small flames (Bueche and Foley 2012).

Defensible space and fuel management are often confused. Bueche and Foley (2012) provide a splendid listing and clarifying graphical examples of how to create a three zone system of defensible space and fuel management. Their listing is far too extensive to fully review herein, but a few of their key ideas for each zone follow. Zone 1 is an area extending 5–10 m around a WUI structure and includes non-flammable cladding, roofing and ground cover, no trees or woody brush, no firewood, no open decks (not screened), and all debris removed around the structure and on roof and gutters. Zone 2 should extend 30–35 m away from structure. Storage structures or LP tanks should be located no closer than Zone 2. They also advocate periodically removing all woody or flammable debris, not using shrubs or flammable shelter to landscape around LP tanks, ensuring that shrubs should be more than 2.5 times further apart than their mature height, and spacing trees so there is at least 8–10 m between crowns and pruning lower branches to be no closer to one another than around 3 m from ground. Any firewood or brush should be located uphill or even with main structure (never downhill). The primary actions in Zone 3 are removal of any dead trees nearby and limiting highly flammable debris.

Enhanced fire-resistant community planning is critical to successfully avoiding or minimizing fire damage at the WUI. Local adoption and strict enforcement of the WUI code is critical to successfully weathering a WUI fire scenario. Local officials need to recognize these potential problems and prepare. Defensible space is critical to limiting damage at a structure or worse yet in a community. It often relates to the ability for individuals and/or fire fighters to arrive and then have access to tools or water so as to set-up and defend a structure. Too many structures were formerly, and probably still are, built that fail to plan for egress of residents and ingress of fire fighters and their equipment.

As mentioned earlier, two extremely critical ignition source issues in fire initiation at the WUI involve radiation and flying embers. Radiation breaks windows leading to interior or compartment fires. Shutters help, but creating a defensible space is often considered as the most cost-effective method of fire suppression in the WUI. This issue is critical because radiation is proportional to the 4th power of the temperature clearly showing why creating and maintaining defensible space is critical. Another critical ignition source is flying embers, especially relative to the choice of roofing materials. While fire-retardant treatments (FRT) can suppress ignition from flying embers, the most effective roofing choice at the WUI is often metal or other non-combustible materials. Reducing combustibility of wood with FRT's decreases flame spread and decreases the risk of ignition by flying embers. The biggest problem with FRT systems in this context is permanence in terms of resistance to leaching and ultraviolet light degradation which will be discussed more completely later in this paper.

Wood decks and other nearby combustibles present a unique problem related to structural ignition in WUI fires since they transition from a target fuel to an ignition source (Hasburgh et al. 2017). Two ASTM Standards have been developed to specifically address these two critical WUI fire ignition issues, ASTM E2632-20 Standard test method for evaluating the under-deck fire test response of deck materials and ASTM E2726-12a Standard test method for evaluating the fire-test-response of deck structures to burning brands (i.e., flying embers) (ASTM International 2020i; ASTM International 2020j).

Expected bush fire intensity levels in Australia are codified in AS 3959 (Standards Australia 2018c) which divides fire intensity into many different Bush Fire Attack Levels (BALs) corresponding to the expected maximum radiative heat flux that building elements in a BAL area may experience. Each BAL also denotes the potential risk from embers or flames (Table 3). For example, BAL-29 indicates a maximum transient heat flux of 29 kW/m^2 and elevated risk from windborne embers and burning debris near the structure. The appropriate BAL for each building site is calculated from the prevailing vegetation, its distance to the building envelope, the slope and the Fire Danger Index (FDI).

Europe has no unified standard defining fire intensity scales in the WUI (Intini et al. 2020); however, individual states (for example Italy and France) have criteria to define WUI fire risks and required mitigation measures. Other

Table 3: Bushfire attack levels specified in Australian Standard AS 3959.

Bush fire attack level (BAL)	Estimated heat flux exposure (kW/m^2)	Additional sources of heat
BAL-LOW	Excluded from assessment	No provisions
BAL-12.5	≤12.5	Ember attack
BAL-19	>12.5 ≤19	Increasing levels of ember attack plus burning debris
BAL-29	>19 ≤299	Increasing levels of ember attack plus burning debris
BAL-40	>29 ≤40	Increasing levels of ember attack plus burning debris, increased likelihood of contact with flames
BAL-FZ	<40	Direct exposure to flames and embers

jurisdictions, like Greece, have developed a country-specific fire index (Palaiologou et al. 2020) that quantifies and ranks the environmental and socioeconomic effects of bush fires; however, this index is defined *a posteriori*, giving an indication of damage but not a prediction of fire intensity scale that may be used to define construction requirements for timber.

5 Fire prevention approaches

While this review focusses on bushfire resisting timbers and fire retardants used in structures situated in the WUI, fire protection is an approach that involves site and vegetation management, proper site and building design, use of fire resistive materials and structural systems working collectively to ensure performance.

5.1 Site and vegetation management

The availability of combustible fuels represents a major consideration in any setting. In urban areas, fuels can be the timber itself, but more often, the cladding or the interior furnishings provide fuel. Fuel loads, including the interior furnishings can be estimated and incorporated into design factors but it would be unrealistic to attempt to control interior fuel loads because they are likely to change over time as a result of occupant use patterns.

Rural settings have the same concerns with regard to internal fuel loads, but provide an opportunity for creating greater separation between external fuel loads and the structure. Most pre-planning on building sites examines distance to forests/grassland, potential fuel load, slopes, and prevalent wind direction and then incorporates some level of vegetation management (Bueche and Foley 2012). These practices are relatively easy to address in the design and construction phase, but become more problematic once a structure is in use because they depend on regular vegetation management. Some communities mandate minimum separations between vegetation and structures, for example, mandating minimum distances between the ground and the lowest branch or removal of branches overhanging roofs. These practices create defensible space and are critical components of fire prevention efforts in parts of the Western U.S.

5.2 Planning/design

Recognition of the importance of establishing construction standards to improve the fire- and durability-performance of wood materials in building construction in fire-prone exterior exposures led to the development of Australian Standard AS 3959 (Marney and Russell 2008). This Standard provides construction details for structures built in bush fire prone areas and outlines methods for reducing bush fire danger with respect to building planning, design, siting and landscaping. It specifies that the FRT wood should not ignite when exposed to radiation of 10 kW/m^2 when tested using AS/NZS 3837 (Standards Australia 1998).

In addition to the definition of fire scale in the form of BALs, AS 3959 also specifies construction requirements for each BAL. Possible use of timber up to BAL 29 is specified in terms of material performance. This is defined by timber density, or for BAL 29, from a standardized cone calorimeter test according to AS/NZ 3837. This test method specifies that wood should not ignite when exposed to a radiation of 10 kW/m^2, that the maximum heat release rate when tests are performed at a radiation of level 25 kW/m^2 should be <100 kW/m^2 and that average heat release rate for 10 min should be <60 kW/m^2. Wood species that pass these requirements are labelled as Bushfire resistant timber (BRT). The original iteration of AS 3959 used the term fire-retardant-treated timber, based on performance concept of treated timber in the US (Chan and England 2001). This was later changed to allow the use of some dense and naturally durable Australian hardwood species. While some commercial FR chemical systems meet these test requirements, many are unable to do so after outdoor exposure (White 2009). AS 3959 specifies that FR treated timber for exterior exposure should be weathered according to ASTM D2898

Method B (ASTM International 2020a). Even fewer FR chemical systems are able to provide any significant level of enhanced biological durability in outdoor, above-ground use (commonly termed Use Category 3 (UC3) in North America or Hazard Class 3 (H3) in Australia).

A review by the Australian Commonwealth Scientific and Industrial Research Organization (CSIRO) of specific measures for enhancing fire-resistance of exterior-use products and maintaining resistance to fungal and termite attack recommended development of dual-preservative/fire retardant systems for exterior use in bushfire prone areas (Marney et al. 2004; Russell et al. 2007). At present, there are no nationally standardized commercially available exterior systems in Australia that provide both fire and biological protection, although several promising systems are in test and will be discussed later.

Besides the afore-mentioned tests at the material scale, technical advice in Australia allows the use of timber in all BAL zones dependent on successful testing at the system scale. This requires fulfilment of performance criteria according to AS 1530.8.1 (Standards Australia 2018a) up to BAL-40 and AS 1530.8.2 (Standards Australia 2018b) or BAL-FZ. The former imposes a 10 min transient heat flux profile in accordance with expected exposure heat flux in a bushfire, in addition to inclusion of a small wood crib to simulate embers and burning debris. BAL-FZ testing must be in a furnace to a standardized cellulosic time-temperature curve for 30 min. Other than tests at the material scale, performance requirements at system scales are mainly targeted towards the ability of the timber to play a separating function, meaning timber elements that fail the material test may still be used in a system, but the testing is more expensive and design-specific.

The lack of defined bush fire hazard categories in Europe means that there are also no unified performance requirements for fire resistant or fire-retardant treated timber for exterior use. However, fire retardancy for comparative purposes may be assessed within the European reaction for fire framework, which results in a Euroclass rating after completing a suite of different test standards structured around EN 13501-1:2018 (CEN 2018), assessing smoke production, heat release rate and production of flaming droplets.

5.3 Naturally fire-resistant timber

Some timbers have a naturally enhanced fire performance. Due to a combination of specific extractives present in the heartwood as well as the density of the timber. Density has long been known to be a good predictor of fire performance under a given fuel load since density controls the time to ignition and is also negatively correlated with the charring rate (Bartlett et al. 2016). Australia has a number of exceptionally dense species that are listed as bushfire resistant and can be used up to a BAL 29 level (Table 4). There is also the potential to use other species of similar densities following the line that density is the primary predictor of bushfire resistance, but these assertions must be supported by testing data.

Table 4: Bush fire resistant timbers as classified by AS 3959 (based on testing by Chan and England 2001).

Common name	Latin name(s)	Oven-dry density (kg/m^3)[a]
Blackbutt	*Eucalyptus pillularis*	710
Merbau (Kwila)	*Intsia bijga, E. palembanica*	650
Red ironbark	*Eucalyptus sideroxylon*	1130
Red rivergum	*Eucalyptus camaldulensis*	710
Silvertop ash	*Eucalyptus sieberi*	670
Spotted gum	*Corymbia maculata, C. henryi, C. citriodora*	740
Turpentine	*Syncarpia glomulifera*	680

[a] After Bootle (2005).

Interestingly, fire performance is not always related to density as evidenced by Coastal redwood (*Sequioa sempervirens*) from the US west coast, which has performed well in fire tests and is allowed for use as exterior cladding and decking in the Western U.S. This species has high loadings of heartwood extractives that, in addition to providing resistance to biodegradation, also impart fire retardant properties. Limited testing of selected timbers from Far North Queensland suggested a relationship between total extractives content and performance in cone calorimeter tests (F.Wiesner, In-press). These results as well as wider screening of timbers for their fire behavior merits further attention.

5.4 Fire-retardant treated timber

A fire-retardant treatment is defined as a chemical/physical method used to stop or slow the spread of fire, either through physically stopping the fire from igniting the wood with subsequent spreading of the flame front or by altering the chemical reactions of combustion. Flame spread is defined as the progressive movement of the flaming ignition zone across the surface of a combustible material. Most fire retardants are not designed to completely prevent ignition, but rather they accelerate the creation of a char

Table 5: Comparisons of various FRT chemicals.

FR chemical	Mode of action	References
Aluminum hydroxyls	Cools fuel source and dilutes gases	Popescu and Pfriem (2020)
Boric acid/borax	Form glassy film, limit flame spread but can promote smoldering	Wang et al. (2005)
Halogens	Free radical capture reducing heat	Sauerbier et al. (2020)
Magnesium hydroxyls	Cool fuel source and dilute gases	Popescu and Pfriem (2020)
Magnesium sulfate	Cool fuel source via endothermic dehydration	Elvira-León et al. (2016)
Nitrogen	Dilutes gases, reduces temperature	Horacek and Grabner (1996)
Nitrogen/phosphorous	Higher char yield	Lowden and Hull (2013)
Phosphorous	Accelerates char, reduces temperature	Stevens et al. (2006)
Potassium carbonate	Catalyzes wood degradation at lower temperature	He et al. (2017)
Silica dioxide	Forms barrier on char residue	He et al. (2017)
Titanium dioxide	Reduce heat release/delay ignition	Kumar et al. (2015)
Zinc dioxide	Reduce heat release/delay ignition	Kumar et al. (2015)

layer that limits further oxygen access and slows fire spread. The primary objectives of fire-retardant (FR) treatments of wood products are to impede pyrolysis and time to ignition (TTI), prevent flame spread and suppress production of toxic smoke (Green 1996). Together, or sometimes individually, these goals provide sufficient time for people to safely evacuate the structure or to prevent ignition during the transient passing of the fire front in a wildfire.

The different mechanisms of fire retardants can potentially be exploited to target their exterior use, based on the anticipated mode of attack from bushfires (i.e. radiation or embers, or both) and its intensity. For example, an increased critical heat flux for ignition or ignition time could reduce the probability of wood igniting under lower intensity fires. Alternatively, reducing the heat release rate (HRR) from wood once ignited, decreases the risk of flame spread along the burning front to other wooden elements. This in the intention of the 100 kW/m^2 HHR limit in AS 3959 (Standards Australia 2018c) and the 269 kW/m^2 limit in SFM 12-7A-4 (California State Fire Marshall 2016).

Many FR chemical systems have been used in a multitude of wood products. Fire retardants function via a number of mechanisms as they react to heat (Popescu and Pfriem, 2020) (Table 5). Some treatments cause greater char formation and/or react at lower temperatures, which insulates the wood below the char layer. Some systems cause ceramification, and some systems dilute the gas reactions in the combustion phase. An example of these five mechanisms of fire retardancy for 24 common FR chemical systems was compiled by Lowden and Hull (2013) (Figure 3).

In North America, FRT wood is specifically defined in the building codes as any wood product that, when impregnated with chemicals by a pressure process or other means during manufacture, shall have a listed flame spread index of 25 or less when tested for 10 min in accordance with ASTM Standard E84 (ANSI/UL 723) and show no evidence of significant progressive combustion when the test is continued for an addition 20-min. Additionally, the flame front shall not progress more than 3200 mm from the burner at any time (International Code Council 2021a). FRT wood products can be accredited in North America by submitting test data from standard test methods conducted by Code-accredited test/evaluation organizations (more detailed information on this will be discussed later). This certification method is mostly used by FR formulators who do not wish to publicly disclose their chemical composition. Formerly, many FR systems in North America were accredited by the American Wood Protection Association. A full listing is available of all the testing and data requirements for fire, strength, corrosion, hygroscopicity, and potential bioefficacy testing required for an AWPA accreditation (AWPA 2020a, b). Outside of North America, for many the required performance criteria are defined in ISO (ISO 2019), while others sometimes use a derivation of ASTM E108 (ASTM International 2020h).

Most jurisdictions in Australia allow the use of FR impregnation to improve fire performance of timber, thereby reducing its contribution to a fire and therefore limiting flame spread and fire growth. However, fire retardants are not explicitly accepted nor is guidance given for their potential roles in terms of structural capacity of fire-resistant building products as done in AS 1720.4:2006 (Standards Australia 2006). This approach is taken because FR treated timber can delay ignition, but often has little or no role once a fire is fully developed (Metz 1938). In fact, some formulations that reduce timber flammability can have a simultaneous detrimental effect on mechanical properties (LeVan and Winandy 1990), thus reducing the fire resistance of the structure.

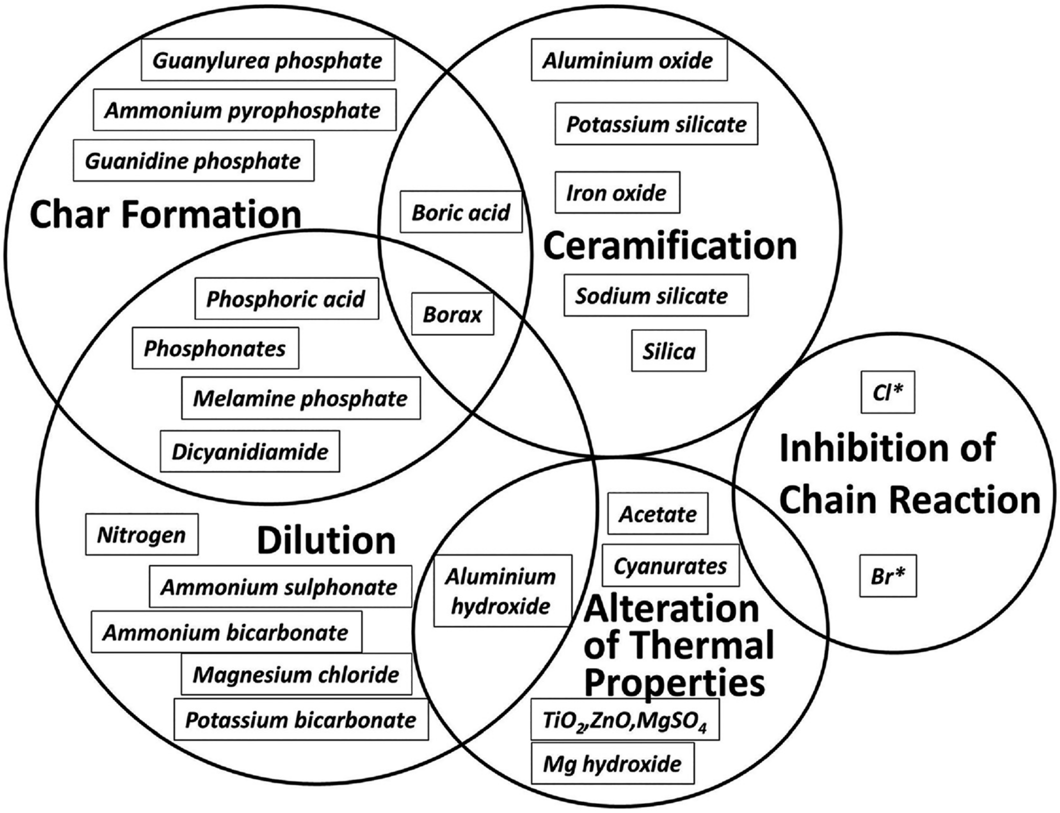

Figure 3: Examples of the five mechanism of fire retardancy. (Modified from Lowden and Hull 2013).

The ideal fire-retardant system would be soluble in water, have minimal effects on flexural properties of the wood, be non-corrosive to fasteners, be resistant to leaching, and be relatively inexpensive. A variety of compounds have been shown to improve fire performance of timber, but all some shortcomings.

Gases released as wood thermally degrades can be combustible. Char and tars are also produced, mainly from the lignin (Lowden and Hull 2013). Accordingly, most FR chemical systems significantly reduce the generation of flammable volatiles generated from the thermal breakdown of cellulose and hemicellulose (Dietenberger and Hasburgh 2016). FR treatments tend to delay ignition, reduce heat release and reduce flame spread (Rowell and Dietenberger 2013). A widely accepted theory for how many inorganic FR systems work is the “chemical theory” where FR chemicals lower pyrolytic temperature, which in turn, promotes char and less flaming volatiles (Holmes 1977; LeVan 1984; LeVan and Winandy 1990). While many FR chemical systems use phosphate or nitrogen sources to reduce heat release and the effective heat of combustion, those components tend to increase smoke generation. Thus, many FR systems also use a borate to counteract and minimize smoke generation (Dietenberger and Hasburgh 2016).

While most FR chemical systems modify some aspects of the thermochemical mechanism(s) of untreated wood pyrolysis, these thermochemical mechanism(s) still must follow basic thermo-kinetic principles. Thus, pyrolytic reaction rates for wood treated with various inorganic salt-based FR chemical systems can be effectively modeled using a simple dual-reaction model that distinguishes between the differential reaction mechanisms of the systems at low- and high-temperature pathways as well as for the differential reaction rates for each pathway (Tang 1967).

Most FR chemical systems negatively affect either or both the initial and long-term strength of FR-treated wood. These effects result from acid hydrolysis of carbohydrate, especially hemicelluloses, due to the generally acidic nature of most FR chemical systems (Gerhards 1970; LeVan and Winandy 1990; Sweet and Winandy 1999; Winandy 2013). In-service strength loss when FRT wood products are regularly exposed to in-service temperatures >50–60 C can be especially problematic and pre-qualification testing is critical (Lebow and Winandy 1999; Winandy 2001, 2013).

5.5 Overview of evaluation criteria for FRT systems

FR-treated wood is used in a range of temperature and moisture conditions. Recognizing this, both the European and North American engineering communities have developed Standards that separate commercial FRT wood products into three or four general service-use categories.

North American building codes may vary between States/Province and local municipalities, but they most all refer to the U.S. Codes (International Code Council 2021a; International Code Council 2021b) or the Canadian Code (NRCC 2015). These codes specify what products can be used in various uses and exposures. Issues related to use of FRT wood products in the United States are dealt with in ICC Section 2302 of the IBC (International Code Council 2021a) or Section R802 (International Code Council 2021b). In Canada, the National Building Code of Canada (NRCC 2015) contains requirements regarding the use of treated wood in buildings and the CSA O80 (2015) specifies treatments. These Codes or Standards specify requirements for the use or properties of FRT wood products. The requirements include evaluation methods and classification for various limits for: (1) fire retardancy, smoke generation and flame spread, (2) changes in engineering properties, and (3) hygroscopic and weathering issues.

North American performance requirements for fire retardancy and flame spread are defined in ASTM Standard E84 (ASTM International 2020g), which is not specific to potential bushfire exposure but provides performance ranking of exposed wood-based materials based on comparative surface burning measurements. In the E84 evaluations, a Class A FRT wood product must achieve a flame spread rating of <25 after 10 min. The FRT wood product must also show no evidence of further progressive combustion when the test is extended for an additional 20 min and the flame-front must not progress more than 3.2 m at any time during the test.

Engineering performance issues are evaluated in ASTM Standards D5516, D5664, D6305 and D6841 (ASTM International 2020c; ASTM International 2020d; ASTM International 2020e; ASTM International 2020f) and for hygroscopic and weathering issues in D3201 and D2898 (ASTM International 2020a; ASTM International 2020b), respectively. There are no specific limits on the effects of FRT on engineering properties of lumber and plywood, but specific test/evaluations and their requirements are listed in ASTM Standards D5516, D5664, D6305 and D6841. The moisture content of an FRT wood product cannot exceed 28% when conditioned at 92% relative humidity in accordance with ASTM D3201.

When directly exposed to extreme weather, many FR chemical systems lose efficacy due to leaching (White 2009). Thus, any FRT wood product intended for exterior use (i.e., directly exposed to weather) must first be subjected to one of four weathering methods described in ASTM Standard D2898 and then meet the requirements described in ASTM Standard E84 (Table 6).

In the United States, commercial building code-accepted fire-retardant systems are evaluated using the defined required performance criteria set forth in the IBC Section 2303.2 or relevant National Fire Protection

Table 6: Comparisons of the various wet-dry cycles used for each of the four weathering methods defined in ASTM D2898.

Property	Factors	Method A	Method B	Method C	Method D
Cycle	Number	12	42	252	7
	Cycle time (h)	168	24	8	336
	Total time (h)	2,016	1,000	2,016	2,328
Water exposure	Cycle time (h)	96	4+4	4	168
	Flow rate (L/min/m^2)	0.30	12.2	12.2	0.30
	Recirculation	No	Yes	yes	No
	Temperature (°C)	2–16	<32	2–32	2–16
	Total time (h)	1,152	336	1,008	1,152
	Flow rate (L/m^3)	20,700	246,000	738,000	20,700
Drying	Time (h)	72	4+4	4	120
	Temperature (°C)	57–60	60–66	63–68	57–60
	UV exposure	No	Yes	yes	No
	Air flow (m/s)	>0.127	>0.127	>0.127	>0.127
	Total time (h)	864	336	1,008	840
Rest	Time (h/cycle)	None	8	None	48
	Total time (h)	–	328	–	336

Association (NFPA) codes. Potential FR-systems can be evaluated and then listed by independent third-party testing, accreditation and inspection agencies using requirements set forth in:

(1) International Building Code, Section 2303.2 Fire-Retardant-Treated Wood
(2) National Fire Protection Association. NFPA 703, Standard for fire-retardant-treated wood and fire-retardant coatings for building materials (2021).
(3) ICC-ES Acceptance Criteria for Fire-Retardant-Treated Wood (AC66) (ICC Evaluation Service 2015).
(4) ICC-ES Acceptance Criteria for Surface-Applied Fire-Retardant Coatings (AC363) (ICC Evaluation Service 2016).

An ICC-ES Evaluation Service Report (ESR) or an Underwriter's Laboratory (UL) Evaluation Report (ER) recognizes product compliance to the building code and its multiple standards and code provisions, whereas an ICC-ES Evaluation Service Listing (ESL) recognizes product compliance to a single standard. Together, these reports recognize a product's compliance to multiple standards and building code provisions. They also identify various conditions and limitations for the use of that FRTW product. Thus, an ESR or an ER are typically accepted by most code authorities. A brief list of ES-ICC or UL issued reports evaluated under AC66 and AC363 and other similar FRTW evaluation protocols is shown in Table 7. Also listed is whether a system has been approved for interior or exterior uses. All listed FRTW systems are pressure treated except for one. ESR-4156 has been issued for an immersive dip-treatment per IBC Section 203.2. impregnation with chemicals by other treatment means (i.e. non-pressure process).

In Canada, the *National Building Code of Canada* (NRCC 2015) requires that any FRTW be pressure treated by a licensed treater per CSA Standard O80 (CSA 2015). FRTW must also be tested and certified for flamespread and smoke generation under Standard CAN4-S102 (SCC 2010) by an independent third-party testing and inspection agency. In general, listed FRTW in Canada meet virtually all the same performance requirements as set forth in the AC66 and AC363 Acceptance Criteria (ICC Evaluation Service 2015; ICC Evaluation Service 2016).

The effectiveness and performance conditions of FR treated timber in Europe and the UK are assessed within the same reaction to fire standard as any other building

Table 7: Code accredited fire-retardant-treated wood for either FRT systems under ICC-ES acceptance criteria AC66 or FR coatings and barrier technologies under ICC-ES acceptance criteria AC363 or Underwriters Laboratory (UL) evaluation.[a]

Third-party report#	Relevant evaluation criteria	FR tradename	Manufacturer	Treatment type	Interior/exterior use
ESR-2666	AC66	FirePro®	Koppers Performance Chemicals Inc.	Pressure treated	Interior
ESR-4373	AC66	ProWood®	UFP Industries, Inc.	Pressure treated	Interior
ESR-4156	AC66	Boraflame	Technologies Boralife Inc.	Immersive-dip treated	Interior
ESR-1159	AC66	FRX or Saferwood-FX or Teremex-FR	Chemco, Inc.	Pressure treated	Interior/exterior
ESR-2645	AC66	D-Blaze®	Viance, LLC	Pressure treated	Interior
ESR-1626	AC66	Dricon	Arxada Treatment Technologies, Inc.	Pressure treated	Interior
ESR-4584	AC66	Dricon-FS	Arxada Wood Protection, Inc.	Pressure treated	Interior
ESR-4056	AC66	FlameTech^{tm}	Fire Retardant Chemicals Technologies, LLC	Pressure treated	Interior
ESR-4244	AC66	FlamePro®	Koppers Performance Chemicals Inc.	Pressure treated	Interior
UL7002-01	IBC 2303.2	Pyro-Guard®	Hoover Treated Wood Products, Inc.	Pressure treated	Interior
–[b]	IBC 2303.2	Exterior Fire-X®	Hoover Treated Wood Products, Inc.	Pressure treated	Exterior
ESR-1365	AC363	LP® Flameblock® or LP® Blazeguard®	Louisiana-Pacific Corporation	Barrier	Interior (1-ply) or exterior (2-ply)
ESR-3872	AC363	FX Lumber Guard or FX Lumber Guard XT	Fire Retardant Coatings of Texas, LLC.	Coating	Interior

[a] A listing of FRT systems and their issued reports can be found at: https://icc-es.org/evaluation-report-program/reports-directory/ or at https://database.ul.com/certs/ER7002-01.pdf; [b] No UL evaluation report was published.

products, which occurs within the Euroclass system specified in EN 13501 (CEN 2018). In addition, FR treated timber products in Europe or the UK are certified for three different use categories, which are intended to ensure that FR treatments maintain their efficiency throughout the anticipated service life.

In the European system, the EN-16755 Standard (CEN 2017) defines service-use categories for various types of FRT wood including two categories of interior FRT products and one exterior category. The INT1 level is for service-use at humidity levels generally ≤65% and INT2 is specific for humidity levels ≤85%. These categories recognize that many interior-use FR systems are hygroscopic and high humidity conditions can cause the water-soluble chemicals in the FRT system to migrate toward the surface, which can often be accelerated by exposure to cycling relative humidity. These chemicals can crystallize on the wood surface in a process known as blooming. The third category is for exterior service-use conditions and mandates passing specific testing requirements for both blooming and exterior weathering. Östman and Tsantaridis (2016a) have reviewed and discussed the scope, objectives and methods employed for this European approach for FRT wood products standardization.

In the United Kingdom, FRT wood products are used and specified in the Flame Retardant Specification Manual (WPA 2018). This Wood Protection Association (WPA) Specification defines three use-categories of INT1, INT2 and EXT. The uses of each are generally similar to the European system, with only slight differences in the test methods used to classify each product. Similarly to Europe, FR treated timber in Australia must pass the same procedures as other materials in addition to ensuring continued performance for exterior timber which must be weathered before testing, to exclude performance loss from leaching. This weathering is specified as the procedures in ASTM D2898.

From the above it may concluded that the use and certification of FR treated timber is more extensively developed in North America, where certified systems are listed as ES-ICC approved, while European or Australian procedures do not maintain listings of officially certified products.

5.6 FR chemicals

Water-soluble inorganic salts are most often used as FR chemical systems for interior applications, since there is no direct wetting, UV weathering and/or exposure to elevated relative humidity. These would include monoammonium and diammonium phosphate, polyphosphates, various sulfates, various nitrogen compounds, zinc chloride, sodium tetraborate, and boric acid. Most of these inorganic salts are prone to leaching, either from direct exposure to water or exposure to high humidity that leads to surface migration and crystallization (i.e., blooming) (Gardner 1965; Holmes and Knispel 1981; Kawarasaki et al. 2018; LeVan and Holmes 1986; Marney et al. 2004; Sweet et al. 1996; Östman et al. 2001; Östman and Tsantaridis 2016b). Juneja (1972a) patented a leach resistant FR system and then reported its effectiveness (Juneja 1972b; Juneja and Calve 1977; Juneja and Shields 1973). Lopez (1995) patented an FR system comprised of diammonium phosphate, dicyandiamide, an undisclosed urea-nitrogen complex and titanium dioxide as a cosolvent to prevent component separation.

The most commonly used FR chemical systems globally have been based on phosphorous, and its various inorganic and organic salts. Most FR systems are supplemented with borax or borates to neutralize the pH and decrease the risk of strength loss from acid hydrolysis of the wood. Phosphates and nitrogen compounds tend to inhibit release of flaming volatiles and promote char formation, while borates offer limited biological resistance and serve as flame and smoke inhibitors (Marney et al. 2004). It is also thought that some level of synergy in flame retardancy results from various combinations of phosphates and borates (Mantanis et al. 2019).

Many water-soluble inorganic salts have also been evaluated and used in combination with nitrogen-based systems. While the nitrogen-based systems individually provide a significant level of fire retardancy, nitrogen also liberates nitrogen gases that dilute combustion volatiles promoting a certain level of synergy when combined with several of the water-soluble inorganic salts listed above (Lazar et al. 2020; Lewin et al. 1975; Lewin 1997). Guanylurea phosphate (GUP) when synthesized from dicyandiamide and phosphoric acid, is a recognized effective interior fire-retardant chemical system (Oberley 1983). GUP is commonly used in combination with boric acid as an FR treatment in North America and China (Wang et al. 2005). The system alters thermal decomposition and its sub-processes and decreases production of volatile pyrolytic products (Wang et al. 2006). A number of phosphate-free, nitrogen-based FR systems have also been developed but precise formulations are often proprietary. One proprietary phosphate-free FR chemical system based on a nitrogen-borate combination has been successfully used in North America for close to 20 years (Winandy and Herdman 2003; Winandy and McNamara 2003; Winandy and Richards 2003).

Many FR chemical systems function by either dilution or quenching of the combustible gases; while others involve endothermic degradation of the FR that then lowers the temperature of combustion (Sauerbier et al. 2020). Phosphate-based FR systems tend to both accelerate charring and dampen reaction temperatures as these decomposition reactions are endothermic (Sauerbier et al. 2020). The efficacy of phosphate-based FR systems is usually considered to be proportional to their acidity (Stevens et al. 2006). Conversely, by-products of decomposition of nitrogen-based FR systems dilute flammable gases and also reduce combustion temperatures as these reactions are endothermic (Horacek and Grabner 1996). Phosphorous and nitrogen are often recognized as behaving synergistically by directing pyrolysis toward char formation, water vapor release and production of fewer flaming volatiles (Lowden and Hull 2013).

Boric acid and borax mixtures have some efficacy in retarding flame spread via char formation and have a rather low melting point (Uner et al. 2016). Borates also tend to form glassy films when exposed to high temperatures (Wang et al. 2004). Borax and boric acid mixtures are normally used together because borax alone tends to reduce flame spread but can promote smoldering or glowing whereas boric acid tends to inhibit smoldering but has little effect on flame spread (LeVan and Tran 1990).

Silicates can provide measurable fire retardancy by filling the wood cell lumens with incombustible material and may also possess intumescence that forms a heat-resistant protective surface (Bulewicz et al. 1985; Mai and Militz 2004). Nano-alkaline silicates have also been shown to provide significant fire retardancy (Giudice and Pereyra 2009). However, it can be difficult to achieve adequate silica penetration into wood and the deposited material remains susceptible to leaching in wet environments (Lowden and Hull 2013). Silicates have also been evaluated for their potential against fungal and insect attack, but the results have been mixed (Sauerbier et al. 2020). Several other FRT systems are described in Table 5.

Combinations of silicon and phosphorous have promise as FR systems (Kandola et al. 1996), as do silicon, phosphorous and nitrogen systems (Li et al. 2006). These studies suggest that phosphorous provides char formation, nitrogen promotes dilution of volatiles and silicon offers thermal stability by forming an additional layer of protection over the char.

One critical issue associated with the higher loadings needed to achieve flame spread and smoke generation requirements is the associated potential for these loadings to affect other timber properties. Most currently used inorganic- and some organic-salt fire retardant FR systems require chemical retentions of at least 40–80 kg/m^3 to achieve acceptable Fire Retardancy under the ASTM E-84 test method. By comparison, typical copper based preservative retentions vary from 1.6–9.6 kg/m^3 depending on the decay hazard. These higher loadings enhance the potential for acid hydrolysis of the wood but many of these systems are also hygroscopic and can result in elevated moisture levels that increase the risk of acid hydrolysis as well as fastener corrosion. While not directly proven, there is likely some amount of synergy relative to strength loss as a result of these higher FR-salt retentions and their resulting higher wood moisture contents.

Another critically important consideration in any fire testing is wood moisture content at the time of ignition. Hasburgh et al. (2018) found that test results from ASTM E84 (ANSI/UL 723) varied based on the type of pre-test wood conditioning and wood moisture content at time of test. They found that the current E84 method of constant mass was insufficient because sorption isotherms revealed that the pre-test wood sample condition could influence tested wood moisture content by up to 48%, depending on whether the samples equilibrated under absorbing or desorbing conditions.

5.7 Potential of dual FR- and preservative-(FR&P)-treatment systems

There long been a desire for a dual FR and preservative treatment (FR&P) system. The technical literature on dual FR&P systems and their chemical compositions and performance was collated from 1956 to 1992 by White and Sweet (1992). The more recent work on development of FR&P system was reviewed by Russell et al. (2007) and by Marney and Russell (2008). They noted four potential avenues to achieving a reliable FR&P: (1) combine an existing preservative with known FR chemicals, (2) chemical modification of an existing FR chemical with known preservative chemicals, (3) fixing a known preservative that also has FR qualities, or (4) inorganic modification (i.e. ceramification) to form wood-inorganic composites.

One attempt combining the first two approaches combined mixtures of known exterior FR systems such as dicyandiamide-phosphoric acid, DPF, MDPF, and UDPF with known preservative systems such as IPBC (3-iodo-2-propynyl-butyl carbamate) or DDAC (dodecyl-dimethyl-ammonium chloride) (Sweet et al. 1996). Systems comprised of combinations of DDAC-UDPF or DDAC-IPBC-MDPF were found to be effective as dual FR&P systems. Dual FR&P system had been earlier patented by LeVan and DeGroot (1993). Still another patented exterior FR&P system combines borax, boric acid, boric oxide, urea, magnesium chloride, ammonium polyphosphate, ammonium thiosulphate and trimethylamine (Thompson 1992). It is important to note that, while promising and patented, none of these systems appears to be commercially used.

A method for the chemical modification of wood was developed that compared phosphoramidates with phosphortriamidates cured at 115 °C (Chen 2008; Lee et al. 2004a, b). While the phosphoramidate system provided improved fire and fungal resistance, the phosphortriamidates method failed to provide adequate fungal resistance. The use of melamine urea formaldehyde (MF) and phenol formaldehyde (PF) resins to modify wood for enhanced dimensional stability, strength, durability and fire resistance has also been successfully accomplished (Xie et al. 2016). Systems combining the use of traditional interior FR, such as GUP/Boric acid modified with polymerized MF resins, were found to be a reliable method for inducing fire retardancy for exterior uses (Lin et al. 2020).

More traditional, dual-treatment systems have also been studied. While dual-treatment processes are more expensive than single-treatment systems, a barium chloride/boric acid treatment followed by a secondary diammonium phosphate/boric acid treatment, and application of a water-resistant adhesive coating provided fire and termite resistance (Ishikawa and Adachi 1991).

Schubert and Manning (1997) patented a zirconium-borate system that could be either applied a single-stage treatment or a dual-treatment. The zirconium greatly inhibited boron leaching but fire, fungal and termite resistance were not evaluated.

5.8 Proprietary fire retardants

As noted earlier, many fire retardants are not publicly disclosed because the suppliers want to protect their art without the cost of patenting. It is important to note that few of these patents have ever been successfully commercialized. This illustrates the difficulty of developing a fire-resistive physical or chemical system that enhances fire performance, can be successfully impregnated into timber without inducing negative effects on the wood or accelerating corrosion and finally can withstand direct or intermittent exposure to natural weathering.

6 Coating systems

Generally, flame retardant surface (FRST) coatings are designed to delay ignition and impede the rate of burn rather than provide a fire-resistive barrier. Surface applied coatings, which intumesce, are typically used on steel construction to protect the steel from heat (Weil 2011). However, FRST or FR coatings are not accepted in North America as a substitute for FRT wood. Studies have indicated that the long-term performance of fire-resistive coatings for wood exposed to outdoor weathering have shown limited durability and require periodic reapplication (White and Dietenberger 2010). Two basic categories of FRST exist. Fire retardant coatings generally reduce flammability initiation point so as to build char and reduce flame spread, whereas fire resistive coatings add flame resistance to the substrate (White 1984, 1986).

6.1 Traditional surface-coating systems

FRST systems have promise for effective structural fire/flame protection because they place the active components directly at the primary point of ignition. However, the long-term efficacy of FRST systems and coatings is often questioned relative to their durability and ability to retain the desired functionality under in-service conditions (Lazar et al. 2020). While many FRST systems have shown promise using small-scale benchtop tests like ASTM E84, they tend to perform poorly in large-scale methods more commonly accepted in wood construction such as ASTM E119 (ANSI/UL 723) (White 1986, 1997).

Fourteen alkyd- and latex-paints, varnish, stains, or penetrating oil systems, some modified with phosphate- or resin-modified systems were evaluated for smoke development (measured as “specific optical density”) from A-C grade Douglas-fir plywood (Brenden 1973). Several alkyl-resin paint systems were superior to an FRST containing proprietary FR chemicals; whereas under non-flaming test conditions none of the 14 systems reduced smoke development compared to untreated Douglas-fir plywood. An FRST containing GUP, penterythritol, phosphoric acid and an MF resin applied as an aqueous, intumescent and translucent wood varnish has only been evaluated under laboratory conditions by Xiao and coworkers (Xiao et al. 2018). These combinations suggest that there is considerable potential for combining materials to produce effective FR coatings; however, cost and long-term performance are likely to be limiting factors.

6.2 Intumescent-coating systems

Intumescent coatings have long been used for steel structures. They expand when heated, forming an insulation layer and slowing heating to the substrate. Some testing on timber for interior fire exposure has been undertaken for intumescent paint (Lucherini et al. 2019). Charring of the timber was delayed but not entirely prevented. A potential barrier for implementation of intumescent paints on timber is uncertainty about their comparative effectiveness compared to established gypsum board systems.

Intumescent coatings can efficiently impart flame resistance to flammable materials including wood. These coatings swell to many times their original thickness when exposed to heat forming a thick, porous layer of char that insulates the combustible material from the heat source (LeVan 1984; Wladyka-Przybylak and Kozlowski 1999). The early research and development and conceptual chemistry of the intumescent coating concept was reviewed (Vandersall 1971). However, while interest in the use of intumescent coatings for flame- and fire-protection on wood is increasing, especially in mass timber structures, several obstacles remain. The weathering of intumescent coated wood in exterior applications exposed to rain and sunlight remains especially problematic and must be addressed before these systems are used in applications where exposure to regular wetting and/or UV exposure are possible (Weil 2011).

Intumescent flame retardants usually incorporate multiple components including a base carbonizing compound, an inorganic acid source that activates the primary carbon source at ≤250 °C, a blowing or foaming agent and a secondary carbon source that serves as the feedstock for a char layer (Lazar et al. 2020). The acid source reacts with the secondary carbon source to form a carbonaceous layer, which in turn is expanded by the actions of the blowing agent and then further reinforced by cross-linking and condensation reactions within the char layer. Ammonium polyphosphate is one common component because it serves as both an acid source (phosphate) and a blowing agent (ammonia) (Camino et al. 1985).

Guanylurea phosphate and melamine-urea-formaldehyde resin have also been combined in a surface-applied varnish mixture and shown to have superior intumescent FR performance (Xiao et al. 2018). A 12% GUP concentration provided both translucency and fire suppression via intumescence. Another successful system incorporating urea, dicyandiamide, monoammonium phosphate and dextrin inhibited ignition, heat release and mass loss at up to 35 kW/m^2 for 30 min (Wladyka-Przybylak and Kozlowski 1999).

The addition of nano-particles based on silica technology effectively enhanced and fortified char formation of an intumescent coating in a fire scenario (Kozlowski et al. 2015). Their approach involved combining nano-silica with amine-formaldehyde and various phosphorus compounds, such as UDPF, MDPF, or ammonium sulphate, and boric acid. They also reviewed many other patents based on other nano-particle systems.

7 Summary

Increased building and construction in the wildland urban interface coupled with changing climates and forest management issues will be associated with an every-increasing risk of fire. In response, many entities have promulgated modified building codes, standards and state of the art practices for achieving fire-resistant timber construction in Australia, Europe and North America. While the fire issues are common to all three continents, this review highlights regional differences in how fire safety requirements for the WUI are specified and assessed and in the allowed application of FRT for the WUI. FRT use remains inconsistent globally, with extensive use in North America and much less in either Europe or Australia. The development of easily applied, long lasting exterior fire retardants remains challenging, but will become increasingly important as bushfire risk increases. There are also a number of research and code needs and a need to adopt new or revised regulations, standards and/or practices to better manage fire risk. Timber remains an attractive option for house construction, but continued use will depend on improved fire performance through treatments or design practices.

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