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Combined Fire Retardant and Wood Preservative Treatments for Outdoor Wood Applications – A Review of the Literature

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Abstract. A collaborative Australian national project funded jointly by the Commonwealth Scientific and Industrial Research Organisation and the Forest & Wood Products Research and Development Corporation has been undertaken to develop a 'proof of concept' for a combined fire retardant/wood preservative treatment technology for *P. radiata* to satisfy the requirements of both the Australian Bushfire and Wood Preservation Standards. The focus of the work was on products that found use in exposed outdoor, above-ground applications. This paper reviews the literature currently available regarding the impregnation of wood with chemical systems that offer resistance to both fire and biodegradation and are also suitable for exterior applications. We have found that in general, researchers have chosen to utilise the dual functionality of boron compounds to achieve both fire retardancy and wood preservation. Often, such systems are applied in multi-step processes, which involve an impregnation step followed by a curing step. Because of the leaching problems associated with boron, a great deal of effort has gone into the development of systems which fix the boron into wood so that its preservation properties can be maintained throughout the useful life of the material.

Keywords: fire, retardant, wood, preservative, biodegradation, termites, fungi, outdoor, leaching, impregnation

1 Introduction

Australia is one of the most bushfire-prone countries in the world. Despite rigorous precautions and total fire ban days, widespread seasonal grass and bushfires regularly occur. During the Australian summer, bushfires are prevalent at the wildland–urban interface and impact greatly both in terms of property loss and loss of life; this problem is growing with the continued expansion of urbanisation as a result of lifestyle choices [1]. As such there is a need for construction materials, which will assist to minimise the impacts of bushfires at these high-risk urban interfaces.

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Lightweight timber construction has a long history in Australia where it is the most common house construction type. The lightweight timber house can be more cost effective and flexible in design than its masonry counterpart and there are many situations where a lightweight building may result in the lowest lifecycle energy use (e.g., hot and humid climates, sloping or shaded sites or sensitive landscapes).

Radiata Pine or *P. radiata* is the most commonly used timber for these constructions and is grown on plantations covering more than 750,000 ha throughout Australia. Compared to other species, including native eucalypts, Radiata Pine grows faster, produces larger yields of useable timber and is competitively priced. It is however, not naturally resistant to attack by decay fungi and other wood destroying organisms, and is prone to damage by insects. It also has no natural resistance to fire and is not recommended for use in bushfire prone areas. It has a Class 4 durability rating, which indicates that when untreated, it's in-ground and above-ground life expectancy is less than 7 years. This durability rating is in accordance with an Australian standard [2] that is a guide for producers and users of timber products as to the probable life expectancy of timbers when used in in-ground and above-ground applications. Any durability class can be achieved by Radiata Pine by treating with appropriate preservatives. These preservatives protect the wood against biodegradation but do not imbue the wood with any fire protection.

A collaborative Australian national project funded jointly by the Commonwealth Scientific and Industrial Research Organisation (CSIRO) and the Forest & Wood Products Research and Development Corporation (FWPRDC) was undertaken to address this problem. The project was concerned with the development of a 'proof of concept' for a single-step combined fire retardant/wood preservative treatment technology for *P. radiata* to satisfy both the Australian bushfire and wood preservation standards [3, 4]. The focus of this project was on combining an existing Australasian Wood Preservation Committee (AWPC) approved Hazard Class H3 preservative as specified in the standard, with a fire retardant to achieve a treatment suitable for use in exposed outdoor, above-ground applications.

The Australian bushfire standard (for which there are no direct equivalent American or European standards) aims to reduce the risk of property damage occurring in the event of a bushfire (or wildfire) attack. It specifies that the fire retardant treated timber should not ignite when exposed to a radiation of 10 kW m^{-2} in an oxygen consumption calorimeter [5] (equivalent standards are ISO 5660 [6] and ASTM E1354 [7]). In addition it specifies that when tested in the cone calorimeter at an irradiance level of 25 kW m^{-2}, the maximum heat release rate should be less than 100 kW m^{-2} and the average heat release rate for 10 min after ignition should not be greater than 60 kW m^{-2}. The Australian wood preservation standard aims to specify the requirements for preservative treated sawn and round timber for protection against decay, insect or marine borer attack. To meet the Hazard Class H3 specification, preservative treated wood needs to have a mass loss of less than 3% and 5% when exposed to fungi and termites, respectively. Although there are no equivalent International or American standards to the Australian wood preservation standard, ASTM D1413 [8] and CEN/TR 14839

[9] endeavour to assess the durability of wood with respect to decay by fungi and ASTM D3345 [10] and EN 118 [11] aim to evaluate the resistance of wood to termites.

The intended approach in the joint project was to first identify candidate fire retardants and preservatives and then ascertain if they were compatible with each other. The next step was to establish baseline fire and preservative performance data (for both preservative and fire retardant treated wood), followed by a preliminary screening exercise to eliminate any poorly performing additives. The final step was to evaluate the performance of the combined systems (derived from the screening step) using the Australian bushfire and wood preservation standards. The details of this project can be obtained by contacting the FWPRDC [12].

Prior to the commencement of the project, a review of the current available literature regarding the impregnation of wood using single-step fire retardant/wood preservative treatment systems was undertaken. This paper summarises the findings of that review.

2 Combined Fire Retardant/Wood Preservative Systems

There are several ways of producing a combined fire retardant/wood preservative treatment system.

- Modification of an existing preservative suitable for in-ground applications by the addition of a fire retardant chemical.
- Chemical modification of wood using conventional fire retardants that demonstrate good biocide resistance.
- The fixing into wood of conventional preservatives that demonstrate good fire retardance.
- Inorganic modification of wood to form wood-inorganic composites.

White and Sweet [13] produced an extensive literature review covering the period 1956–1992. This is a particularly valuable review paper because it covered approaches used to produce a combined fire retardant-preservative treatment for wood. They found that the most promising approaches were *in situ* deposition of insoluble inorganic compounds and organic polymers that included nitrogen and phosphorus in the polymer chain. Prior to 1956, Stamm and co-workers at the Forest Products Laboratory, Wisconsin, USA, published reviews on the treatment of wood by both preservatives and fire retardants, however these were considered separately and not as combined systems [14–16]. Since 1992, further studies have been carried out. A summary of these is presented in this paper.

2.1 Modification of an Existing Preservative with a Fire Retardant

Thompson [17] treated wood with a one step system using a combination of boron compounds, urea, magnesium chloride, ammonium polyphosphate, ammonium thiosulphate and triethylamine. The compositions were applied to wood by various methods. These methods included spraying, dipping, brushing, immersing and pressure impregnation, depending on the material being treated and its intended purpose. The inorganic salts were encapsulated by a water-based acrylic resin and carried into the wood during treatment. The compounds were mixed in specific sequences to avoid coagulation. Once the water had evaporated, the inorganic salts were retained in the treated wood. The compositions were resistant to weathering and leaching, and were considered suitable for exterior use. This patent, which expired in 2000, provided no examples demonstrating the fire retardant or preservative efficacy of the invented compounds; in addition, the resistance of the active components to leaching was not demonstrated. The philosophy underlying the idea is an eminently sensible one in that the fire retardant additive is encapsulated and does not become available until such time as the encapsulation is disrupted, which is likely to occur in the event of a fire. One would, however, hope that the preservative function of the formulation is not also encapsulated, otherwise the anti-fungal and anti-termite properties would be affected throughout the useful life of the timber.

Sweet et al. [18] investigated combining preservatives with leach resistant fire retardants to treat Southern Yellow Pine, Western Hemlock and Pacific Silver Fir in a single-step process. They looked at a number of systems and found that the most effective combinations consisted of fire retardants such as urea or melamine, dicyandiamide, phosphoric acid and formaldehyde (UDPF or MDPF) at concentrations of *ca.* 7.5–25% with preservatives such as didecyl-dimethyl-ammonium chloride (DDAC) at concentrations of *ca.* 0.19–7.5% or a combination of DDAC and 3-iodo-2-propynyl-butyl carbamate (IPBC). This work was also covered by a patent by Levan and DeGroot which expired in 2001 [19]. The fire performance before and after weathering, of the various treatment combinations was evaluated using a number of well established standard fire tests [20–22]. The decay resistance was determined using a 1978 version of the American soil block standard [8]. The two different weathering regimes used were: 1000 h of exposure according to method B of a 1981 version of the American accelerated weathering test [23], and a 13-day distilled water immersion treatment with regular replacement of the water. The authors found that these combinations yielded good decay resistance with a mass loss of $<2\%$ upon exposure to the prescribed fungi. It was also found that the UDPF/DDAC combination achieved good fire performance results with a weight loss improvement of *ca.* 80% over the control for the fire tube tests, while the MDPF/DDAC and UDPF/DDAC combinations achieved post leaching heat release rate improvements of *ca.* 70% and 80%, respectively, with respect to the control for the OSU calorimeter test. The results presented suggest that these combinations would be suitable for both interior and exterior applications.

Schubert and Manning [24] reported that aqueous compositions of a zirconium borate containing preservative were leach resistant and imparted fire, fungi and termite resistant properties to wood. The preservative was formed by combining a source of boron and a water-soluble zirconium salt. The wood was treated by impregnation in either a single-step with the combined boron and zirconium solution (ZrO_2–B_2O_3) or in two steps by treating with the zirconium salt solution followed by treatment with an aqueous solution of the boron compound, thus forming the preservative composition within the structure of the wood. These authors performed leaching studies on treated samples of Southern Yellow Pine using the AWPA leaching standard [25] and showed that *ca.* 30% of the ZrO_2–B_2O_3 was retained after 1000 h of leaching. However, their claim presented no evidence of anti-termite, or fire retardant property determinations, either before or post leaching.

Basson and Conradie impregnated wood with a combination of fire retardant and preservative [26]. The fire retardant was formulated as an aqueous solution containing urea, phosphoric acid and ethanol and the preservative was formulated as a dry salts mixture of boric acid and borax penta-hydrate. The borate salts were dissolved in water prior to combination with the fire retardant solution. Treatment was carried out via pressure impregnation. The treated wood was then close-stacked and completely covered to ensure that the required depth of penetration of the active ingredients into the wood could be achieved by diffusion. Leaching studies showed that their treatment not only reduced the leachability of borates by up to 32%, but also improved the uptake volume of the aqueous treatment composition by *ca.* 50% with respect to borates only. The authors claimed that their formulation imparted a high degree of fire retardation to the material as well as providing long term and wide spectrum protection against fungal decay and wood destroying insects. However, this patent presented no direct evidence of this activity except by inference to the amount of boron retained within the cellulosic.

Baysal [27] impregnated Scots Pine with combinations of melamine formaldehyde (MF), boric acid (BA) and borax (BX) and found that the fire resistant properties of the wood were improved. Oxygen index (OI) [28] and thermo-gravimetric – differential thermal analysis were used to assess the fire retardancy and thermal stability respectively of these combinations. The combination of MF with a mixture of BA and BX was found to enable a lower quantity of total additive to be used whilst achieving similar or better fire performance. At treatment levels of 10% and 2.35% (v/v) for MF and BA + BX respectively, an improvement in OI of *ca.* 45% was achieved when compared to the control. The results indicated that BA, BX and MF on their own, did not behave as well in terms of fire performance when combined with each other. This work did not include data for preservative efficacy and thus relied upon the recognised boric acid equivalents (BAE) performance.

Lopez [29] treated wood via pressure impregnation, with a stable aqueous preservative composition that comprised a boron compound, a melamine binder resin and a urea casein activator resin. After treatment, the wood was dried in ambient air until the moisture content was at or below 19%. The author found that the composition imparted fire, insect, fungal and moisture resistant properties to the wood and was leach resistant. It was also claimed that the structural strength of the wood was improved, and the treatment was non-corrosive to metals. The treated material – Douglas Fir Plywood, was subjected to a surface burning characterisation test [30]. The fire test results were expressed in terms of flame spread index (FSI), and the smoke developed index (SDI). A FSI of five and a SDI of 15 was achieved for the treated wood, i.e., a performance relatively similar to asbestos cement board. Although the author did not test a control or untreated specimen alongside the treated materials, the results obtained indicated a performance much better than the FSI literature value of 91 for untreated wood [31]. This result was consistent for smaller sized specimens. Similarly, the author treated particle board, and found that both the FSI and SDI increased to *ca*. 21 and 50, respectively. With MDF boards, the FSI and SDI were *ca*. 28 and 103, respectively. Although the plywood and particle board met the Class 1/Class A specification of 25 for flame spread, this was not the case for the MDF. It needs to be noted that in this patent, there were no examples showing the evidence of biocidal properties, although the fire properties, chemical retention structural strength and anti-corrosion were well demonstrated.

2.2 Chemical Modification of Wood using Conventional Fire Retardants

An effective means of fire retarding wood was via the use of halogen compounds, where the mechanism of fire retardance is a combination of free radical quenching and inhibition of the rate of devolatilisation of the timber due to char formation. Lewin, whilst at the Israel Fiber Institute in Jerusalem investigated the bromate-bromide process and found that this method was capable of achieving a high level of fire retardance [32]. The wood treated in this study was Southern Yellow Pine and Spruce, and the process involved the direct bromination of the lignin with an acidified bromate-bromide solution. The resultant wood was stable to leaching and resistant to fire and fungal decay. Lewin reported that the structural strength of the wood was not unduly affected, and that this treatment in fact improved the water repellency and swelling. In addition, the author used a proposed ASTM soil block standard for determining the decay resistance [33], to demonstrate that the wood treated by the bromate-bromide process yielded less than 5% weight loss when exposed to a range of fungi. The fire performance of wood treated by the bromate-bromide process was demonstrated using well-established methods such as the French Inflammability Test [34], the fire tube test (1950 – formally known as ASTM E6) [20] and the British Spread of Flame Test [35]. The author found that at bromine levels of less than 10%, it was possible to achieve a Class 2 rating according to the French standard, a Class 1 rating according to the British standard and less than 40% weight loss in the fire tube test.

Similarly, Lee et al. [36] showed that phosphorus pentoxide and amines were able to react within Loblolly Pine and Sweetgum to produce phosphoramides *in situ*; giving rise to a modified wood chemical structure which imbued the material with both decay and thermal resistance. Using Fourier transform infra-red (FTIR) spectroscopy and electron microscopy, the authors demonstrated that the reaction of the additives with the wood essentially modified the wood structure. The fungal decay resistance was determined using a later version (1986) of the soil block standard [8] used by Lewin, whilst the thermal stability was determined using differential scanning calorimetry (DSC) and thermogravimetric analysis (TGA). Whilst these authors provided no fire testing results, it was inferred from the data that this material would have enhanced fire retardant properties because of the increased char yield of 300–700% under combustion conditions, decreased heat flow in the range of 20–50% and decreased heat of combustion of up to 30% with respect to the untreated wood [37].

2.3 Conventional Preservatives and Fixing Thereof

Tsunoda [38] investigated the applicability of the vapour-boron treatment of wood and wood composites in terms of decay and termite resistance as well as fire performance. Wood preservative efficacy was determined using the relevant Japanese standards [39, 40] and the fire retardant performance was evaluated using the relevant fire standard [41]. The author found that a retention of 0.5% BAE in Japanese Cedar wood and wood composites, was high enough to control the decay fungi so that no mass was lost. This retention level was also able to control subterranean termites in the laboratory so that there was a 100% mortality rate. The above biocidal activity was evident regardless of whether the boron treatment was by vapour absorption under vacuum or by liquid impregnation. Further investigations were recommended by the author to evaluate the efficacy of this wood treatment under service conditions in the field. The author reported that a minimum of 10% BAE retention was necessary to achieve the required fire performance of a temperature–time area $\leq 350°C{\cdot}min$ and a fuming coefficient of $\leq 120\ C_A$ as called for in JIS A 1321. Importantly, there was no weathering component included in any of the tests to resolve the issue of leach resistance; hence the reason for the author's suggestion for further investigations.

Vinden and Romero [42] developed a process for the treatment of both softwoods and hardwoods, whereby the wood surface was treated via various methods, such as dipping, vacuum/pressure impregnation and brushing, with a boron-based preservative that reacted with the moisture in the wood to form a boron compound and alcohol. The wood was then subjected to a moisture free and enclosed environment in order for the preservative and the alcohol by-product to be absorbed into the wood structure. The authors claimed that this treatment imparted fire resistant properties to the wood as well as protection from termite attack and fungal decay. The treatment was not, however, leach resistant. The authors demonstrated a range of uptakes of boric acid equivalents (BAE), and various degrees of penetration of the different boron containing compounds. However, they provided no evidence, apart from that inferred by BAE, of anti-fungal or anti-termite efficacy. Although they claimed no direct fire retardant properties, they suggested that the boron compounds presented may optionally give the timber fire retardant enhancing properties. This is not however demonstrated in any of the examples provided. This work concurs with Tsunoda's research [38] and suggests that a minimum of 7% BAE is needed to provide wood based materials with fire retardancy. This is somewhat higher than the authors' recommended levels of 0.25% and 0.75% BAE for insect and fungal protection, respectively.

Kartal et al. chemically modified Japanese Cedar treated with disodium octoborate tetrahydrate (DOT), using allyl glycidyl ether (AGE) in combination with methyl methacrylate (MMA) to limit boron leaching [43]. The maximum treatment level of BAE used in this study was 1%. Co-polymerisation of the monomers in the borate treated wood was completed by catalytic heat treatment (4 h at 100°C). This process was performed in either a single step or sequentially. The authors used Japanese standard methods to determine the anti-termite [44] and anti-fungal efficacy [45], as well as the leach resistibility of the treated wood. It was demonstrated that the treatment was effective in limiting boron leachability from wood, as well as increasing the dimensional stability. It was also effective in increasing both the resistance to fungal decay with a 50–85% improvement, and resistance to termite attack with a 60–70% improvement, with respect to the untreated controls. The authors found that after leaching, the wood retained 0.5% of BAE, whilst wood treated with only DOT or DOT + MMA, retained *ca.* 0.1% and 0.2% BAE, respectively. The authors made no mention of the fire performance of the chemically modified wood; however, as implied by Tsunoda [38] and Vinden and Romero [42] the low treatment levels of BAE used in this study were unlikely to achieve a reasonable degree of fire retardancy. It was unclear from this work if there was any advantage in using a single step or a sequential chemical treatment.

Baysal et al. studied the physical restriction of water access in Douglas Fir by impregnating water repellent agents into the wood in order to limit the amount of leachate and water absorption after boron treatment [46]. The boron treatment included mixtures of boric acid and borax and the water repellents comprised the vinyl monomers styrene, methyl methacrylate and isocyanate. The timber was treated according to a 1976 version of the ASTM soil block standard [8], and the leaching regime followed was also outlined in this standard. The study found that secondary treatment of wood with a water repellent chemical following borate impregnation, reduced both the leaching of borates from wood in water as well as the water absorption of the modified wood. Styrene was the most effective monomer in terms of the immobility effect on borates and water absorption, i.e., water repellency.

2.4 Inorganic Modification of Wood

Saka et al. prepared wood-inorganic composites via a sol-gel process of alkoxysilanes to form silica gel within wood cell walls [47–52]. They treated Hinoki and Western Hemlock, and in some cases found that the alkoxysilane reacted with the wood hydroxyl groups, thus providing a degree of fixing of this treatment. The processes discussed by these authors were multi-step and included a heating step to complete the reaction. The alkoxysilanes were combined with either phosphorus pentoxide (P_2O_5) or boron oxide (B_2O_3) or a combination of the two in order to obtain the final binary or ternary composite. The fire performance of the modified wood was studied using the OI technique [28] and the termiticide efficacy was evaluated using a relevant Japanese standard [40]. It was found that the material displayed a greater resistance to burning compared to untreated wood with an improvement in the OI result of up to 65%. Further validation is required using the more common fire tests such as cone calorimetry. The authors have demonstrated that the relatively small amount of silica gel formed within the cell wall was effective against termite attack resulting in a 100% mortality rate. They used a 4-h water immersion technique to determine the fixability of the treatment and found that only SiO_2 gels were stable whilst those containing boron and phosphorus were not. They also found that the addition of trimethoxy silane fixing agents improved the leaching stability of the composites. It was shown that the treated wood had a greater thermal stability if the inorganic modification involved covalent bonding of the silica to the wood compared with hydrogen bonding. In fact they suggested that the covalently bonded case resulted in a high degree of cross-linking of wood with silica gels via a silane coupling agent. The authors demonstrated the flexibility of this sol–gel process by producing a ternary wood-inorganic composite made up of SiO_2–P_2O_5–B_2O_3, without the need for high temperatures normally required for synthesis of such a material.

Yamaguchi impregnated Japanese Cedar, Japanese Black Pine and Western Hemlock with a combination of colloidal or aqueous based monomeric silicic acid, and various concentrations of boric acid via a pressurisation process to form a silicic acid–boric acid complex within the timber [53, 54]. A curing or polymerisation process was then carried out at ambient temperature and pressure, and was controlled by solution pH. The author claimed that silicon from silicic acid was substituted by boron, and a boron element was built into the crystal lattice of the polymeric silicic acid, thus preventing leaching from the wood. The wood preservative efficacy was determined using relevant Japanese standards [39, 55] and combustion tests were performed using the relevant fire standard [56]. The silicic acid–boric acid complex demonstrated excellent resistance to fungal decay with a mass loss of less than 5% before and after leaching. Field stake tests showed that the treated wood exhibited a 100% mortality rate of termites after 14 days and the weight gain due to water ingress was reduced, thus indicating suitability of this treatment for outdoor applications. Combustion tests indicated that as the concentration of boric acid was increased, the volume of smoke was decreased along with the after-flaming and glowing combustion times.

Lenox et al. [57] developed an aqueous composition claimed to be useful for treating wood articles to provide resistance to fire and protection against fungi and insects. The composition was composed of a zinc compound, a boron compound, an amino acid, an alkali metal silicate and a source of alkalinity. The compositions were applied by vacuum and/or pressure treatment, or by dipping under atmospheric pressure. The authors found that the higher molar ratio of zinc to borate in the composition reduced the leaching of borate from the substrate and hence the activity of the preservative was retained for a longer time. The amino acid promoted the dissolution of zinc, and the source of alkalinity improved the solution stability of zinc and silicate. The authors also demonstrated that sufficient BAE was retained in the timber to ensure adequate anti-termite and anti-fungal properties. However, as previously mentioned by Tsunoda [38] and Vinden and Romero [42], the level of BAE needed to influence fire behaviour was around 7–10%. Using the numbers provided in the patent, and assuming a linear loss rate due to leaching, one would require a relatively high initial loading of 24–40% BAE to overcome the leaching and still retain an adequate level of fire retardancy. The authors have not provided evidence of biocidal resistance or fire performance apart from what is inferred from the level of BAE retained by the timber post leaching.

3 Commercially Available Combined Fire Retardant/ Preservative Products

A combined fire retardant and preservative treatment for wood is currently not available in Australia that meets the criteria set out in the Australian Bushfire and Wood Preservation Standards [3, 4]. There are however products which, according to marketing literature, offer protection to wood against fire, insects and fungi. At this time, there are no research details regarding these products in the public domain. The manufacturers do, however, make many claims as to the efficacy of their products with regards to termite and fungi resistance as well as fire performance.

4 Conclusions and Future Work

It seems that not much has changed since the review by White and Sweet [13]. The predominant approach is still one of formation of wood-inorganic composites, often using boron-based compounds to utilize its ability to act as both a wood preservative and fire retardant. The leaching issues associated with boron compounds is often overcome by use of a fixing process, rendering the boron inaccessible to water during the useful life of the timber. The exception to this is the work by Lewin where bromine is used to modify the wood.

Another creative approach is to synthesize a ceramic or glass type material by impregnating pre-ceramic compounds, such as silicic acid or silanes along with a source of phosphorus and boron, into the timber in a sol–gel type process and then complete the process by control of solution pH or by changing temperature conditions and subsequent drying at slightly elevated temperatures.

Some researchers have utilised the inherent chemical functionality of wood to assist in its modification and gone beyond a simple impregnation process, and have reacted fire retardant and wood preservative compounds with the available hydroxyl sites within the wood structure. Often the means of controlling the leaching of boron is by forming a water insoluble organic polymer around the boron.

The papers reviewed have shown a lack of consistency in terms of the performance testing of the timber with respect to wood preservation and fire retardancy. A more uniform approach using the same fire and preservative testing regime is suggested if this is an area to be further investigated.

The literature reviewed demonstrates that in general, to ensure that wood displays both fire retardancy and biocidal properties, one often needs complex reaction set-ups to perform the process. There is therefore a need for a single step process that utilizes existing wood preservation technology, i.e., a fire retardant additive that can be combined with a preservative in the conventional impregnation process, or a fire retardant that can be applied easily in series with the preservative (either before or after), in much the same way as the preservative is applied.

Since a great deal of the literature reviewed in this document is covered by patents, it is not clear whether these processes are accessible and in fact practical for general industry use. It is our proposal that a single step treatment (specifically for the Australian market), using an existing Australian approved H3 wood preservative in combination with a fire retardant, should be considered as a potential research option for future work as it has not been previously investigated.

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