Proceedings IRG Annual Meeting (ISSN 2000-8953)

IRG/WP 20-40910

THE INTERNATIONAL RESEARCH GROUP ON WOOD PROTECTION

Section 4 **Processes and properties**

Enhancing the durability of low durability *Eucalyptus* plantation species: a review of strategies

Kyra C Wood[1], Jeffrey J Morrell[2], William Leggate[3]

[1]Centre for Sustainable Architecture with Wood, University of Tasmania
School of Technology, Environments and Design
Locked Bag 1324, Launceston
7250, Tasmania, Australia

[2] National Centre for Timber Durability and Design Life, University of the Sunshine Coast
41 Boggo Road Ecosciences Precinct, Dutton Park
4102, Queensland, Australia

[3] Forest Products Innovation, Agri-Science Queensland, Department of Agriculture and Fisheries
Salisbury Research Facility, 50 Evans Road, Salisbury, Brisbane
4107, Queensland, Australia

Paper prepared for the IRG51 webinar on Wood Protection
10-11 June 2020

IRG SECRETARIAT
Box 5604
SE-114 86 Stockholm
Sweden
www.irg-wp.com

Enhancing the durability of low durability *Eucalyptus* plantation species: a review of strategies

Kyra C Wood[1], Jeffrey J Morrell[2], William Leggate[3]

[1]Centre for Sustainable Architecture with Wood, University of Tasmania,
School of Technology, Environments and Design, Locked Bag 1324, Launceston
7250, Tasmania, Australia, kyra.wood@utas.edu.au

[2]National Centre for Timber Durability and Design Life, University of the Sunshine Coast,
41 Boggo Road Ecosciences Precinct, Dutton Park, 4102, Queensland, Australia, jmorrell@usc.edu.au

[3]Forest Products Innovation, Agri-Science Queensland, Department of Agriculture and Fisheries,
Salisbury Research Facility, 50 Evans Road, Salisbury, Brisbane
4107, Queensland, Australia, william.leggate@daf.qld.gov.au

ABSTRACT

Eucalyptus species native to Australia have shown excellent growth rates, good physical properties and resistance to diseases. As a result, they are widely planted globally for a variety of uses. One negative aspect of many of these faster growing species is that they have a high percentage of low durability heartwood that resists preservative treatment. In Australia, large plantations of these species were established near the end of the 20th Century, primarily for paper production. However, shifting priorities have encouraged a re-examination of possible uses for these materials. Shining gum (*Eucalyptus nitens*) is an important plantation species in Tasmania. Among the possible uses for this species are those requiring enhanced durability. This paper reviews the options for enhancing the durability of Shining gum heartwood for structural and appearance product applications in both interior and exterior exposures.

Keywords: Shining gum, *Eucalyptus nitens*, durability, heartwood, refractory, incising, thermal modification, permeability

1. INTRODUCTION

Although members of the genus *Eucalyptus* are mainly native to Australia, they now have an almost worldwide distribution and have become a globally important plantation fibre source. Since the end of the 20th Century, sizable *Eucalyptus* plantations have been established in Australia, many of which were originally destined for the pulp and paper market. Tasmania alone has an estimated 208,000 hectares of Shining gum (*Eucalyptus nitens*), nearly 70% of the state's total plantation resource, that were planted to support a large domestic pulping industry (Downham and Gavran 2019). However, changing economics and market factors have prompted a re-examination of this resource for other, more value-added uses both in Australia and globally (Nolan *et al*. 2005, Wentzel *et al*. 2019).

Timber and veneer-based products can potentially create more value for Australia's *Eucalyptus* plantation resources than chips, but the characteristics of the wood resulting from certain biological traits, species provenance and plantation management strategies mean they may not be directly suitable for manufacture and production of structural or appearance wood products. In Australia, many *Eucalyptus* plantations are grown un-thinned, unpruned (fibre-managed), on short rotations to maximize output and reduce costs for paper chip production (Beadle *et al*. 2008). As a result, this timber contains high percentages of features (knots, limb trace, gum vein, etc.), juvenile wood and tension wood. Juvenile wood is a natural growth adaptation that allows the tip of the tree to flex as it grows upward, but it is typically weaker and prone to excessive longitudinal shrinkage (Maeglin 1987). The transition from juvenile to mature wood is gradual and can take from 6 to 15 or even 20 years depending on the species, meaning that trees grown in short rotation plantations contain very high percentages of this material. Tension wood has similar effects to juvenile wood, although it occurs as a result of trees bending or leaning in response to environmental stimuli such as wind or light (Washusen 2009). Forest management of plantation *Eucalyptus*, for example specific thinning and fertilising regimes, may help to reduce the likelihood of tension wood (Washusen 2009), but in Australia, the number of fibre-managed *Eucalyptus* plantations far exceeds the number of sawn-log managed plantations (Beadle *et al*. 2008). In addition, tree sizes and wood density can vary widely, even for trees with the same species origin, in the same age range and plantation (Potts *et al*. 2011), and this lack of uniformity, coupled with the propensity for collapse during drying and high percentages of features makes plantation eucalypts like Shining gum a complex and difficult material to fit into sawn log production criteria.

Extensive research is underway in the Australian timber industry to determine the best options for utilizing the *Eucalyptus* plantation resource for higher value wood products, despite its characteristic challenges. Possible applications include exterior uses such as cladding, decking, veneer-based products, mass timber elements, or even in-ground fences. However, the Australian Standard AS5604 classifies Shining gum as a Durability Class 3 timber for above ground applications and Class 4 for soil contact, equating to estimated service lives of 7 to 15 years above ground and 0 to 5 years in the soil, respectively. As a result, the timber of this species must be preservative treated or modified in some other way to provide acceptable performance for these applications.

Preservative treatment of Shining gum poses a major challenge. The sapwood zone of this species is relatively thin and treatable, but as is the case with most eucalypt species the heartwood is extremely resistant to conventional impregnation methods. This is a challenge which industry and researchers have been considering for many years. Cookson (2000) reviewed potential approaches to treating low durability eucalypts, with a focus on heartwood protection, including incising, pre-steaming/boiling, pressure variations, ammoniacal solutions, diffusion, and supercritical fluid treatments. The purpose of the current paper is to review and compare some of the above strategies that remain relevant, as well as discuss further options for this effort.

Development of contemporary alternative technologies for improving the performance of refractory, low durability plantation *Eucalyptus* species could enable value-enhanced opportunities for utilizing these materials. This would be of great benefit internationally given that there are now more than 20 million hectares of eucalypt plantations world-wide (Ferreira *et al*. 2019), and the vast majority of this resource has relatively low natural durability. Timber researchers at the University of Tasmania (UTAS) in Launceston and other industry and research collaborators are actively involved in a number of efforts to enhance the durability of Shining gum as well as other plantation, regrowth or regenerated *Eucalyptus* species. Research at UTAS is also focussing on wood modification for fire resistance and increasing the machineability and service-life of timber in non-exterior applications, but that is outside the scope of this paper.

This paper considers options for improving the durability of *Eucalyptus* heartwood, outlining some of the positive and negative attributes of each approach by reflecting on factors such as the repeatability and efficiency of the process, it's capacity for industry uptake as well as the commercial viability of the resulting product in terms of its appearance, anatomical and durability qualities. It will focus on seven different strategies including: enhancing the permeability of the wood by expanding pores; increasing the surface area and pathways for fluid movement by modifying the wood; reducing the need for preservative treatments by modifying the wood; altering the treatment fluid; altering the treatment process; creating surface barriers; and using thin sawn laminates or veneers.

2. STRATEGIES FOR IMPROVING TREATMENT OF *EUCALYPTUS* HEARTWOOD

As noted in the introduction, the heartwood (or true wood) of most *Eucalyptus* species, including Shining gum, is very resistant to conventional vacuum/pressure impregnation. Pressure treatment which is commonly used to treat softwood species often results in a thin shell of preservative treatment surrounding a largely untreated, decay and insect susceptible core. This type of thin barrier treatment will perform as long as the treatment envelope is not compromised by cutting or drilling, or by the development of checks that penetrate beyond the depth of the original treatment. In most built environments, it is impossible to control post occupancy modifications or alterations to timber building elements. Damage to the treatment envelope allows for the entry of fungal propagules or insects that can degrade the unprotected interior, leading to eventual failure. Altering pressure cycles can produce slight improvements in treatment results, but the effects are limited by the inherent resistance of the timber to fluid flow (Cobham and Vinden 1995).

The wood characteristics of Shining gum sharply limit the potential for effective preservative treatment to the current Australian/New Zealand Standard for Hazard Class 3 (weather exposed; above ground) that in sawn timber requires complete sapwood penetration as well as either 8mm of penetration of heartwood in timber >35mm thick or 5mm for timber <35mm thick (AS1604.1-2012). This seems relatively shallow but can be extremely hard to achieve with many *Eucalyptus* heartwoods, including Shining gum. An alternative requirement for Hazard Class 3 for sawn timber allows unpenetrated heartwood, but it cannot exceed 20% of the cross section nor extend more than halfway through a piece. However, the high proportion of heartwood and the typical sawing patterns adopted (e.g. Washusen *et al*. 2008, Washusen and Harwood 2011, Washusen 2013) leave only small percentages of sapwood on each board, making it difficult to achieve less than 20% unpenetrated heartwood. Even more challenging is the aim to treat Shining gum to Hazard Class 4 (in ground contact), which for sawn timber requires total sapwood penetration and not less than 10mm penetration of heartwood from any surface, regardless of the board’s dimensions. Unpenetrated heartwood may be permitted but with the same conditions as outlined for H3 above, and thus, faces similar problems.

Eucalyptus heartwood characteristics also affect the ability to use other treatment approaches such as resin impregnation, acetylation or any technologies that require liquid penetration into the timber. The options for improving treatment can take several forms including: enhancing the permeability of the wood by opening or removing the blocked pit membranes that restrict fluid flow, increasing the amount of cross section area exposed to fluid flow, modifying the treatment fluid, making the wood less susceptible to water ingress, or else focusing on the treatment of thin-sawn laminates or veneers for producing engineered wood products.

2.1 Enhancing permeability by expanding pores

Fluid flow in wood is largely dictated by the diameter of the smallest pores or openings at a cellular level (Nicholas and Siau 1973, Siau 1971). The cell structure of hardwoods is composed of vessels, fibres and parenchyma. Fluid flow occurs most easily through open vessels and becomes progressively more difficult through the fibres, while parenchyma cells mainly act as storage units. Eucalypts tend to have vessels uniformly distributed across the growth rings with fibres representing ~60% of the total section. Vessels can become occluded with tyloses that block flow and these are common in Shining gum heartwood. ‘Pits’ are generally the smallest openings in wood cells and they essentially act as a channel or conduit between different wood cell structures where fluid is stored or transported. Hardwood pits can become blocked by an accumulation of debris made up of extractives and other mineral deposits that restrict fluid flow.

2.1.1 Microwave treatments

Microwave treatments have been explored for increasing the permeability of both pine heartwood and *Eucalyptus* species (Vinden 1986, Torgovnikov and Vinden 2000 a, b, Xia et al. 2017). In essence, high intensity microwave energy is focussed on timber with a high moisture content to generate targeted steam pressure that causes pit membranes between cells, tyloses in vessels and ray cells to rupture thus enabling subsequent preservative treatment to flow through the wood cell structure more easily. Higher intensity microwaving can also create new voids or cavities in the wood on the radial and longitudinal planes which can significantly increase chemical uptake capacity. Aside from its ability to enhance permeability, microwaving can also potentially reduce drying times and decrease internal stress development that can lead to collapse in woods like Shining gum (Yang and Liu 2018).

Although microwave treatments have been shown to increase permeability, care must be taken to avoid overheating wet wood, which can lead to significant losses in physical or mechanical properties (Torgovnikov and Vinden 2009). Microwave treatment can also markedly change the appearance of the wood as clearly demonstrated by a photograph of Torgovnikov and Vinden's patented product 'Torgvin' (2009, p.88). Both these effects potentially limit the usefulness of microwaves for certain applications in the built environment. The most immediate application for microwave treatment is for enhancing the pulping process rather than enhancing sawn timber products, but Torgovnikov and Vinden also developed 'Vintorg', a composite product made by modifying wood through high intensity microwave treatment followed by soaking in resin, before the material is compressed and cured. The process counteracts the potential physical and mechanical effects of microwave treatment and reduces the highly porous surface appearance. However, this type of product clearly requires the addition of multiple, potentially costly steps into the timber manufacturing process. Capital and energy costs are an additional factor, although Torgovnikov and Vinden (2009) suggested that the operational costs were modest and were not a deterrent to industry uptake for a product with superior durability. However, this process is not commercially used.

Microwave treatment does have promise for enhancing the permeability of refractory species such as Shining gum especially if more nuanced, species-specific treatment parameters that minimize negative effects on strength can be developed.

2.1.2 Ponding

Although it is not used for improving permeability, long term ponding of logs has been used to limit checking prior to sawing. However, ponding for long periods under water has also been shown to result in substantial bacterial degradation of the pits and should improve permeability (Elwood and Ecklund 1959). However, the process is slow, taking months to years or even centuries and would require substantial volumes of both water and land area.

2.1.3 Fungal inoculation or biological incision

An alternative approach to altering permeability is to inoculate the wood with fungi. Most fungi preferentially move between cells by growing through and thus opening the pits. Inoculating southern pine and Douglas-fir poles and posts with *Trichoderma* spp. improved permeability, but the effect was variable across the stem and did not affect the heartwood (Archer 1983, Graham 1954, Lindgren 1952). Fungal growth was further enhanced by pre-treatment with sodium fluoride, which inhibited the growth of competing fungi, allowing *Trichoderma* to dominate in the sapwood.

While some *Trichoderma* species are marginal soft rotters, the overall effect on wood properties would be minimal in comparison with the gains in sapwood treatment. However, fluoride is no longer widely used for wood protection and its use in an industrial setting might be problematic.

Decay fungi have also been explored for opening pits and increasing permeability. Rosner and colleagues used two white rot fungi *Phanaerochete chrysosporium* and *Dichomitus squalens* to improve permeability (Rosner *et al*. 1998, Schwarze and Schubert 2009, Tucker *et al.* 1998). They found improved permeability but noted that care needed to be taken to ensure that the fungal exposure did not extend to the point where decay adversely affected mechanical and physical properties (Messner *et al*. 2003). While so-called 'biological incising' has shown promise under controlled conditions it has not fared well in field trials (Dale *et al*. 2019, Lehringer 2011) where conditions are more variable and other fungi can out-compete the test organisms, which limits its commercial applicability.

2.1.4 Chemical Additives

Another approach that can be used to enhance wood treatability is the incorporation of additives to the preservative formulation to improve preservative penetration. The additives can be used alone or in combination and include wood swelling agents; resin or extractive dispersing or dissolving chemicals; surfactants and wetting agents. These compounds are generally applied at low concentrations (i.e. < 5% m/v) mainly because of adverse effects, such as interference with the functioning of the other preservative formulation ingredients if the concentration is too high and also due to cost factors. Most additives produce slight improvements in penetration, ranging from 1 to 3 or 4 mm, but recent studies using various amines such as buffered amine oxides suggest that they can help enhance fluid movement (Ross 2015).

One of the most common tools for improving the penetration of preservative formulations is the addition of ammonia (Morrell and Morris 2002). Ammonia is used to solubilize copper, but also appears to substantially improve penetration in wood via a combination of dissolution of encrustations on pits and swelling of cell structure (Rak 1975, Gjovik 1983). Ammoniacal-based preservatives tend to provide improved penetration into seasoned refractory timbers on both a microscopic and macroscopic level (Cookson 2000). Ammoniacal-based systems have found a number of niche markets for treatment of refractory woods. The disadvantage of these systems is their tendency to darken the wood and their strong odours. Amines have been substituted for solubilising copper because they are less expensive and lack the ammonia odour, but the enhanced penetration associated with the ammonia is also lost.

2.2 Increasing permeable surface area and pathways for fluid by modifying wood

2.2.1 Incising

Incising is the practice of driving metal teeth into the radial or tangential faces of timber to increase the amount of cross-sectional area exposed to fluid flow. Since longitudinal flow can be orders of magnitude greater than either radial or tangential flow, the process increases the depth of preservative treatment to a zone just beyond the depth of the incisions (Morrell and Winandy 1987, Anderson *et al.* 1997, Chandler and Morrell 1999). While preservative penetration around each incision is limited, high density incising can produce uniform treatment to the depth of the incision (Smith and Morrell 1991, Lebow and Morrell 1993). Incising is required in North America for treatment of many timber species and was used in Australia for treatment of railway sleepers (AWPA 2019, Cookson 2000). It is also still used in Australia to a limited extent for aiding the treatment of softwood landscaping timbers. The process is simple and rapid and has been available for almost a century. Incising can also help to create more even drying checks in large timbers as it relieves drying stress near the surface that can lead to deeper checks (Henry 1973). This process is commonly used prior to air-seasoning of railway sleepers in North America.

While incising does improve preservative penetration, it is not without drawbacks. The most notable drawback is a loss in flexural properties (Morrell *et al*. 1998, Winandy and Morrell 1998, Winandy *et al*. 2018). Incising reduces the effective cross-sectional area of the timber. The effect is most noticeable on smaller dimension timbers and decreases with thickness. Changes in flexural properties can be predicted based upon loss of cross-sectional area. There is a definite trade-off between decreases in flexural properties and improved performance against biological deterioration. Numerous studies have shown that incising enhances preservative penetration and improves product performance. Another notable drawback of incising is that it negatively affects the surface appearance of the final product. Many architects routinely drop the incising requirement in North America for this reason. However, incising technology has improved markedly with the use of much finer incisor teeth, the use of needles instead of teeth and, finally, laser incising (Goodell *et al.* 1991, Islam *et al.* 2007, Morris *et al*. 1994, Suttie 1996, Yakuwa *et al.* 2018). Despite these advances, conventional high-density incising remains the predominant method for improving treatment. Incising could be feasible for enhancing the treatment of Shining gum for applications such as decking, posts and other products where the incising marks were acceptable. The marks could potentially be hidden by profiling the surface, or for example, the development of novel incising technology using photogrammetry, patterned incisions and application-specific CNC routing for designed exterior applications.

2.2.2 Compression

A number of researchers have explored the use of compression processes to improve durability (Cech and Huffman 1971, Sanders *et al*. 2000). At its simplest, wet wood is compressed in the radial or tangential direction prior to seasoning and treatment. The process ruptures cells creating additional pathways for fluid flow. The process is performed in the green condition while the cell walls are still saturated which minimizes potential effects on strength. Compression treatments can be taken further by heating the wood and then compressing the timber in the viscoelastic thermal compression (VTC) process. The VTC process was originally developed to densify lighter woods such as poplar. The combination of heating and a small amount of compression might enhance subsequent preservative treatment. The primary issue for this process would be the added cost. It is also worth noting that heating the wood causes a change in the appearance of the wood.

2.3 Reducing the need for preservatives by modifying wood

2.3.1 Thermal modification

There is an increasing global aversion to synthetic chemicals including those used to protect timber (Fell *et al*. 2006). Such concerns are especially prevalent in Europe, where major regulatory changes have markedly altered the markets for traditional wood preservatives (Sandberg and Kutnar 2016). These changes have fostered the development of alternative strategies for increasing durability that avoid the use of chemicals altogether and among these is thermal modification.

At its simplest, thermal modification involves heating dry timbers to temperatures of about 150℃ to 260℃ for varying periods of time. Exposure to elevated temperatures affects the three primary wood polymers differently, with the hemicelluloses being most susceptible to thermal degradation, followed by cellulose and finally lignin. Hemicelluloses play a number of roles in the lignocellulose matrix, including acting as a bridge between cellulose and lignin, and their non-uniform polymeric structure makes them among the first polymers to be degraded by many wood decay fungi (Winandy and Morrell 1993). Thermal modification attacks the hemicelluloses and alters the wood/moisture relationships. As a result, the wood wets more slowly rendering it potentially less susceptible to degradation because the conditions for decay are less suitable. There are an infinite range of conditions for thermal modification and a number of processes such as Thermowood, OHT, and Plato have been commercialised (Militz 2002). The processes are not new, but the potential for creating a more durable material with no synthetic chemicals has attracted interest. Thermally modified wood is primarily used in Europe, but there is increasing interest in this material outside Europe (Sandberg and Kutnar 2016), including in the Australian timber industry.

Thermal modification is an attractive option for increasing the durability of Shining gum because it is not affected by challenges related to low heartwood permeability that affect traditional preservative treatments. Instead, the process is dependent on heat transfer. Along with increased resistance to moisture uptake, the process changes some of the anatomical and visible qualities of the wood, including darkening its colour, increasing dimensional stability, reducing gluability and perhaps most significantly, decreasing its impact bending strength (Militz 2002). Even so, a reduced modulus of elasticity (MOE) may not be that problematic for certain building applications, for example wall cladding, and other changes could potentially be worked around or used to advantage by timber processors, builders and designers. In addition, while there is likely to be some increase in brittleness, a recent study suggests that the mechanical and anatomical properties of Shining gum may be less affected in an open versus a closed thermal modification system (Wentzel 2018 Wentzel *et al*. 2019), although potential commercial, environmental (e.g. odour during production) and operational pros and cons of open versus closed systems remain to be determined.

While thermal modification of Shining gum is possible, the primary limitation of this process is its ability to produce truly decay and insect resistant materials (Esteves and Pereira 2009, Hill 2006, pp. 99-126). Most thermally modified materials have been employed in Europe, which has a much lower decay risk than many areas in Australia where this species would be used. Thermally modified wood appears to be performing well in above-ground applications such as cladding where the wood is somewhat protected from continuous wetting, but these materials have not performed as well in traditional decay tests (Knapic *et al*. 2018, Vidrine *et al*. 2007). A further drawback for thermal modification is that it has little or no effect on termites, which are endemic to all of mainland Australia. Thus, thermally modified timbers would need supplemental treatment with some type of termiticide. There is already one light organic solvent preservative (LOSP) treated, thermally modified, radiata pine material on the market, which would potentially outcompete a Shining gum alternative. Potential problems with surface barrier treatments are discussed further in section 2.6 below.

2.4 Altering the treatment fluid

The other approach to improve treatment is to modify the solvent, generally by reducing the viscosity (Siau 1971). However, reduced viscosity has only limited effects on fluid movement which is still heavily influenced by pore size of the wood's cell structures. As a result, the use of more volatile solvents may produce slight improvements in treatment, but the benefits are minimal without concurrent treatment to increase permeability.

2.4.1 Gas phase treatment

Gas phase treatments can penetrate relatively refractory woods and gaseous fumigants have long been used for treating timbers to kill pests for quarantine purposes and for limiting internal decay in utility poles (Morrell and Corden 1986). These treatments are generally short term and highly toxic to non-target organisms. The one gaseous process that did show promise for timber in service was vapour phase boron. Developed nearly simultaneously in the UK and New Zealand, the process drew a vacuum over the wood and introduced trimethylborate (Burton *et al*. 1990, Turner *et al*. 1990). The trimethylborate volatilized and diffused through the wood, reacting with moisture to form boric acid and methanol. The methanol could be recovered leaving the boron in the wood. This process worked best in very dry wood and was especially suited for composites. Boron, however, is susceptible to leaching, so this treatment was more appropriate for termite and insect protection of finished panels in interior applications. A second process, using vapour copper was also explored but never commercialized (He *et al*. 1997). Vapour treatments were not explored for refractory species, but the primary limitations would be the cost of the chemicals, the need to dry wood to low moisture contents (<6 %), and the times required for the actives to diffuse through the timber at effective levels.

2.4.2 Supercritical Carbon Fluids

The ultimate fluid change approach would be to explore supercritical carbon dioxide impregnation. First explored for wood treatment in Japan, supercritical fluids (SCF) can move through already seasoned timbers like a gas, but also have solvating properties approaching those of liquids (Kayihan 1992, Krukonis 1988). Thus, a SCF can move through a refractory timber like Shining gum carrying enough biocide to provide protection against fungal and insect attack. Carbon dioxide is a preferred carrier because it has a relatively low critical temperature (31.1℃) and pressure (7.39 MPa) and minimal toxicity. Extensive testing on refractory heartwood of softwoods showed that a variety of fungicides could be delivered into the wood at effective levels and there is one commercial facility using supercritical carbon dioxide in Denmark (Kjellow *et al.* 2012, 2013, Kjellow and Henriksen 2009). The primary limitation to using this process is the initial start-up cost. High pressure pumps, vessels and fittings are costly and training and building expertise would take some time. However, the operating costs for SCF could be quite low because the carrier can be recovered and recompressed. The other issue that may affect SCF treatment of Shining gum is the ability to effectively relieve pressure differentials at the beginning and end of the process. Elevated pressures can cause crushing if the differences between the surface and interior exceed the material properties of the timber. Similarly, failure to relieve excessive pressure inside the timber at the end of the process can result in the timber cracking (Kjellow and Henriksen 2009, Smith *et al.* 1993), and this may be particularly problematic for a collapse-prone, lower density hardwood like Shining gum. However, these problems could potentially be addressed by careful selection of treatment parameters. The main benefits of this approach include that SCFs are able to permeate seasoned timber, which can subsequently be sold or machined directly, as well as the fact that the system can use low levels of low toxicity chemicals and is closed loop, which has advantages for worker and environmental safety. Although the process has been around for many decades, and evaluated on a small scale using Messmate (*Eucalyptus obliqua*) (Cookson 2009) it's unclear if it has yet been tried on Shining gum.

Kennedy *et al*. (2007), also explored hydrofluoroalkanes as alternative fluids. These refrigerants could readily move through refractory woods as gases and were easily recovered by recompression. The process, however, was not commercialized but it shows that there may be other fluids that could overcome the inherent resistance of timber to fluids.

2.5 Altering the treatment process

Treatment methods that don't involve vacuum pressure impregnation may include various methods of spraying, dipping or soaking timber in preservative fluid. In particular, dip/diffusion treatments have been used for decades to protect timbers in low decay risk environments or to provide surface protection against insects.

2.5.1 Boron pre-treatment

The most commonly used long term dip/diffusion process was boron treatment of framing timber in New Zealand. Although no longer widely used, the process provided protection against lyctid attack in framing and, coincidentally protection against fungal attack if the framing was wetted. Boron treatments are also still used Australia, although mainly to protect sapwood from lyctid attack in various Hazard Class 1 environments (i.e. inside, above ground) (Cookson *et al*. 1998).

Boron has a number of attractive features for wood protection (Obanda *et al*. 2008). It is effective against fungi and insects, it has low toxicity to non-target organisms and, most importantly, it is capable of diffusing into refractory woods with moisture. Another positive attribute of boron is that it is also an effective fire retardant and is a common ingredient in several commercially available fire retardants for interior use. Unfortunately, boron will also diffuse or leach out of the timber under high moisture regimes. Thus, boron alone is not a suitable treatment for using Shining gum in exterior exposures in Hazard Classes 3 or 4 by Australian/New Zealand Standards AS/NZ1604.

2.5.2 Boron pre-treatment with supplemental preservative overcoat

Although dip/diffusion with boron alone is not suitable for exterior applications, there may be a way to take advantage of the process. Boron pre-treatments are widely used in North America for protecting railway sleepers from decay during air seasoning. The process was first proposed by T. L. Amburgey (Amburgey and Sanders 2007), at Mississippi State University who showed that ties dipped in a boron solution prior to air-seasoning experienced much less decay than untreated ties. Amburgey also followed this up by over-treating boron treated ties with creosote and having these placed in the track (Amburgey and Sanders 2007, 2009). Field tests showed that the boron continued to protect the ties from internal decay for over 20 years. The creosote treatment apparently helped to retain the boron, limiting the potential for internal decay and prolonging tie service life. As a result, boron pre-treatment is now widely used in North America for railway sleepers.

Boron pre-treatment may also be feasible for Shining gum, although creosote treatment would have limited application or acceptability in Australia. Instead, over-treatment with light organic solvents (LOSPs) might help retain the boron. LOSPs are assumed to evaporate from the timber, but some residue remains that may be able to help retain the boron in the wood. This would need to be evaluated or other oil systems might be explored, along with a feasibility study for commercial/operational logistics in the Australian timber industrial setting.

2.5.3 Microwave with cold dipping

Hot and cold bath preservative treatment of wood has been around since 1867 when it was first patented by Seely (Wilkinson 1979). It involves immersing wood in successive baths of hot and cold preservatives. During the hot baths, the air expands in the timbers. When the wood is moved to the cold bath a partial vacuum is created within the cell lumens, causing the preservative to be drawn into the wood (Wilkinson 1979). Due to the longer treatment periods, this method finds little use in the commercial wood preservation industry except for thermal treatment of thin-sapwood western redcedar in North America. However, a recent variation of this approach is to use microwaves to rapidly heat the wood before it is immersed in a cold preservative solution. This can assist in achieving rapid treatment of the wood, although it may have limitations in terms of suitable wood dimensions and also commercial feasibility.

2.6 Creating surface barriers

Many attempts have been made to develop coatings or barriers to protect wood. An ideal coating would need to be thick enough to resist physical abrasion and biological attack, remain flexible for long periods of time and limit moisture uptake that would lead to dimensional instability and checking. These are major challenges especially because timber is often cut or drilled on site during construction, thereby compromising the barrier.

An excellent example of the limited effects of barriers can be shown with polyurea coatings (Konkler *et al*. 2019). These coatings can be sprayed on dry timber to a desired thickness and can be formulated to provide protection from ultraviolet light. Field exposures of otherwise untreated, polyurea coated Douglas-fir timbers at a high decay hazard test site near Hilo, Hawaii showed that termites rapidly tunnelled through coated, but non-treated Douglas-fir timbers while avoiding similarly coated preservative treated samples. Decay fungi were also able to penetrate the coatings to degrade the untreated wood inside although it took several years for this process to occur. Coatings will only work if fungi or insects cannot penetrate and the wood underneath does not shrink or swell to the point where the coating fails. Alternatively, preservative coatings used in combination with boron diffusion treatments might be useful for protecting against fungal attack since the coating would help retain the boron and the boron would be available should the coating fail.

2.7 Creating smaller-dimensioned sawn laminates or veneers

Most of the strategies in this paper relate to enhancing the durability of conventional sawn products and dimensions. One option that could be explored further to overcome the challenges of treating *Eucalyptus* heartwood is to use thinner sawn dimensions or veneers as the feedstock for treatment and subsequent gluing to create larger timber elements. While these processes do not alter wood permeability, the smaller dimensions of the individual pieces are more likely to result in a much higher percentage of the piece receiving acceptable preservative treatment. Veneers are particularly easier to treat compared with sawn timber because of the smaller dimensions (e.g. 2 or 3mm thick veneers compared to >19mm thickness sawn boards) as well as the presence of lathe checks that facilitate liquid penetration. Thin sawn and/or veneer laminates can then be glued to produce engineered wood products such as plywood, laminated veneer lumber (LVL), glulam and cross laminated timber. It might also be possible to achieve satisfactory durability performance by using glueline treatments for products using thinner veneers that incorporate insecticides and fungicides (Standards Australia 2012, Siraa *et al*. 2018).

Research has already highlighted the potential to produce engineered wood products such as plywood and LVL from fibre-managed Shining gum; for example, Blackburn *et al*. (2018) explored the potential for using fibre-managed Shining gum for structural plywood. However, these studies did not focus on preservative treatment. Some factors that would need to be considered before pursuing this approach would include the feasibility of gluing preservative treated *Eucalyptus* veneers and sawn laminates; the feasibility of using glueline treatments to achieve satisfactory durability performance; and the economic viability of, and market demand for, engineered wood products manufactured from treated *Eucalyptus* veneers and sawn laminates. In addition, the initial set-up for a commercial hardwood veneering/peeling operation is costly, and retrofitting existing facilities to accommodate plantation timber characteristics would also be required.

3. SUMMARY

Table 1: Summary of reviewed strategies and authors' preference for testing

Treatment type	Advantages	Disadvantages	Author preference (1 = high, 14 = low)
Microwave[a]	Increases permeability in *Eucalyptus*, potentially cost effective	Sensitive to variability in timber/process parameters, significant mechanical and appearance degrade, no commercial uptake as yet	9
Ponding	Increases permeability, may limit checking	Slow process, requires significant water/space, variable outcomes	11

Fungal inoculation	Increases permeability without mechanical losses	Variable outcomes when upscaled from lab to field trials, potential for mechanical degrade	12
Chemical adjuvants	Increases permeability without mechanical or appearance degrade, commercially viable	Process not refined yet, potentially high additional material and process costs	1
Incising	Increases surface penetration depth and area, new technology has potential to enable more aesthetic outcomes	Appearance degrade, some mechanical degrade	4
Compression	May increase permeability, (also improves dimensional stability, machineability)	Additional cost to process	8
Thermal	Can increase resistance to decay in certain applications by reducing hygroscopicity, no or low toxicity, can be used on refractory species, (also improves dimensional stability, machineability)	Does not improve termite resistance and resistance to decay in certain applications/environments remains unproven, can cause brittleness/mechanical degrade	7
Gas phase	Moves through refractory wood more easily than liquid	High toxicity to non-target organisms, takes a long time, requires very dry wood (less than 6% MC)	13
Supercritical fluids	Full permeation possible, closed loop system, uses seasoned timber which can be sold or machined directly after treatment	Costly set-up, potential crushing	3
Boron dip/diffusion[b]	Can permeate green wood, relatively simple set up, some fire-retardant capacity	Leaches out in high moisture regimes	14
Boron dip/diffusion[c]	As above, but leaching is less likely	Additional coating step adds some cost, commercial scale logistics and feasibility needs to be evaluated	5
Microwave[d]	Potentially increases uptake of chemicals, speeds up the hot/cold treatment method	Potential limitations on sawn timber sizes, commercial viability and effect on mechanical properties not known	6
Surface barrier	Can protect wood for short periods again decay and insects	Not decay or insect resistant in long term, or if surface barrier is penetrated in any way	10
LVLs/veneers	Smaller thicknesses much easier to treat to required % (also increases stability, machinability, mechanical strength, and broadens commercial applicability of plantation resource)	Costly set-up (for veneering/peeling operation), feasibility of gluing treated wood and glueline treatments not clear	2

[a]To increase permeability by rupturing pores, [b]Pre-treatment, [c]Pre-treatment with hard preservative overcoat, [d]To heat wood followed by direct dip into cold solution

While many of the methods for improving timber durability described above have produced mixed results, it is clear that some have the potential to enhance the durability of low durability *Eucalyptus* in specific applications. The inherent variability of the timber between trees, along the tree length and across the cross section makes it difficult to identify a single strategy for enhancing durability. Differences in growth rates, tree age, and even site differences further complicate the effort. As noted in the introduction, another consideration for this research, is that young plantation trees grown for pulp, potentially have very different characteristics to those older, larger trees that were most likely included in the research on which the Australian Standards and early durability and treatment research were based. For example, WoodSolutions, a website run by the Forest and Wood Products Association (FWPA 2020), which is dedicated to the dissemination of timber research and knowledge, suggests that seasoned Shining gum has a density of approximately 680 - 700kg/m^3, and describes the tree as reaching 70m height and 1-2m diameter. However, young, fibre-managed plantation trees harvested today are typically much smaller and less dense. Any assumptions about the characteristics of Shining gum or other *Eucalyptus* species really need to be re-evaluated in line with the current resource.

It is also important to note that many of these strategies remain awkwardly between academic research and commercial realities. For example, many wood modification or treatment options outlined have narrow research parameters requiring homogenous or uniform timber samples and controlled conditions in order to achieve repeatable and positive results. This is rare in a commercial scenario, meaning that treatments with highly sensitive parameters, like microwaving, tend to become less viable when upscaled to a commercial setting. Other factors, such as market forces and competition, for example from well-established softwood processors, also influence industry focus and willingness to pursue novel treatment options for plantation *Eucalyptus*.

The challenges should not prevent or deter further research into any of the potential strategies outlined above. As noted in the introduction, the aim of this paper was to review current durability treatments and treatment processes for refractory timber to gain insights or inspiration for possible pathways to enhance the durability and potential value of Tasmania’s primary plantation resource.

4. ACKNOWLEDGEMENTS

The authors would like to thank Michael Lee, senior technical advisor at the Centre for Sustainable Architecture with Wood, University of Tasmania, and various industry partners involved in the National Institute for Forest Products Innovation (NIFPI) funded research projects, for their input and discussion.

5. REFERENCES

Amburgey, T L, Sanders, M G (2009): Tie dual treatments with Timbor and creosote or copper naphthenate. *Crossties, Nov/Dec*, Railway Tie Association, Georgia, USA, 20-21.

Amburgey, T L, Sanders, M G (2007): Borate pre-treated crossties… a 20-year field test. *Proceedings American Wood Protection Association,* **103**, 109-111.

Anderson M, Morrell J J, Winandy J E (1997). Effect of incising depth and density on treatability of Douglas-fir, Hem-Fir, and Spruce-Pine-Fir lumber with ACZA, CCA, or ACQ. *Proceedings IRG Annual Meeting*, IRG/WP 97-40093, 8 pp.

AS1604.1 – 2012 (Reissued: 2017): Australian Standard Specification for preservative treatment, Part 1: Sawn and round timber. Standards Australia Limited, NSW, Australia.

Archer K J (1983). Studies on the biological improvement of permeability in New Zealand grown Douglas-fir. *Proceedings IRG Annual Meeting,* IRG/WP 3231, 10 pp.

AWPA (2019): 2019 Annual Book of Standards. *American Wood Protection Association*, Birmingham, Alabama.

Beadle, C, Volker, P, Bird, T, Mohammed, C, Barry, K, Pinkard, L, Wiseman, D, Harwood, C, Washusen, R, Wardlaw, T, Nolan, G (2008): Solid-wood production from temperate eucalypt plantations: a Tasmanian case study. *Southern Forests 2008*, **70**(1), 45-57.

Blackburn, D, Vega, M, Yong, R, Britton, D, Nolan, G (2018): Factors influencing the production of structural plywood in Tasmania, Australia from *Eucalyptus nitens* rotary peeled veneer. *Southern Forests: a Journal of Forest Science*, **80**(4), 319-328.

Burton R, Bergervoet A, Nasheri K, Vinden P, Page DR (1990). Gaseous preservative treatment of wood. *Proceedings IRG Annual Meeting*, IRG/WP 3631, 8 pp.

Cech, M Y, Huffman, D R (1971): Dynamic compression results in greatly increased creosote retention in spruce heartwood. *Forest Products Journal*, **22**(4), 21-25.

Chandler, W S, Morrell, J J (1999): Effect of incising on the strength of green Douglas-fir lumber. *Forest Products Journal*, **49**(9), 55-58.

Cobham P R S, Vinden P (1995). The use of pressure cycling to improve heartwood permeability in Pinus radiata (D. Don). *Proceedings IRG Annual Meeting*, IRG/WP 95-40050, 8 pp.

Cookson, L J (2009): Treatment of timber with permethrin in supercritical carbon dioxide to control termites. *The Journal of Supercritical Fluids*, **49**(2), 203-208.

Cookson, L J (2000): The Preservation of Eucalypts. In: *The Future of Eucalypts for Wood Products, Proceedings of an IUFRO Conference*. Launceston, Australia, 248-255.

Cookson, L J, Scown, D K, McCarthy, K (1998): Boron treatment methods for lyctid susceptible hardwoods growing in Tasmania. *Proceedings IRG Annual Meeting*, IRG/WP 98-30168, 12 pp.

Dale, A, Morris, P I, Uzunovic, A, Symons, P, Stirling, R (2019): Biological incising of lodgepole pine and white spruce lumber with *Dichomitus squalens*. *European Journal of Wood Products*, **77**, 1161-1176.

Downham, R, Gavran, M (2019): Australian plantation statistics 2019 update. *Australian Bureau of Agricultural and Resource Economics and Sciences (Technical Report 19.2),* Canberra, ACT. ISSN 189-3128, 23 pp.

Elwood, EL, Ecklund, BA (1959): Bacterial attack of pine logs in pond storage. *Forest Products Journal*, **9**, 283-292.

Esteves, B M, Pereira, H M (2009): Wood modification by heat: A review. *Bioresources* **4**(1), 370-404.

Fell, D R, Thomas, J, Hansen, E N (2006): Evolving consumer preferences for residential decking materials. *The Forestry Chronicle,* **82**, 253-258.

Ferreira, V, Boyero, L, Calvo, C, Correa, F, Figueroa, R, Gonçalves Jr, J F, Goyenola, G, Graça, M A S, Hepp, L U, Kariuki, S, López-Rodríguez, A, Mazzeo, N, M'Erimba, C, Monroy, S, Peil, A, Pozo, J, Rezende, R, Teixeira-de-Mello, F (2019): A Global Assessment of the Effects of *Eucalyptus* Plantations on Stream Ecosystem Functioning. *Ecosystems*, **22,** 629–64.

FWPA (2020): *WoodSolutions [online]*, Forest and Wood Products Australia, Victoria, Australia. Date accessed: 28/02/2020. https://www.woodsolutions.com.au/wood-species/gum-shining.

Gjovik, L R (1983): Treatability of southern pine, Douglas-fir and Engelmann spruce heartwood with ammoniacal copper arsenate and chromated copper arsenate. *Proceedings American Wood Preservers Association*, **79**, 18-30.

Goodell B S, Kamke F A, Liu J (1991). Laser incising of spruce lumber improves preservative penetration. *Proceedings IRG Annual Meeting*, IRG/WP 3646, 15pp.

Graham, R D (1954): The preservative treatment of Douglas-fir post sections infected with Trichoderma mold. *Forest Products Journal*, **4**, 164-166.

He, W, Simonsen, J, Morrell, J J (1997): Investigation of Bis-[1-dimethylamino)-2-propanolato] copper (II) as a wood preservative. *Forest Products Journal*, **47**(11/12), 69-74.

Henry, W T (1973): Treating processes and equipment. In: *Wood Deterioration and its Prevention by Preservative Treatment Volume II (DD Nicholas, Ed.),* Syracuse University Press, Syracuse, NY, 279-298.

Hill, C (2006): Wood modification: chemical, thermal and other processes. *Wiley Series in Renewable Resources*, J. Wiley & Sons, Ltd.

Islam M N, Ando K, Yamauchi H, Kobayashi Y, Hattori N (2007). Comparative study of full cell and passive impregnation of wood preservatives for laser incised Douglas-fir lumber. *Proceedings IRG Annual Meeting*, IRG/WP 07-40359, 8 pp.

Kayihan, F, (1992): Method of perfusing a porous workpiece with a chemical composition using cosolvents, *U.S. patent US 5,094,892*.

Kennedy M J, Walker B, Erskine C (2007). Hydrofluoroalkanes as carrier solvents for timber preservation. *Proceedings IRG Annual Meeting*, IRG/WP 07-40463, 11 pp.

Knapic, S, Santos, J, Santos J, Pereira, H (2018): Natural durability assessment of thermo-modified young wood of *Eucalyptus*. *Ciencia y tecnologia*, Universidad del Bio-Bio, Maderas, **20**(3), 489-498.

Konkler, M J, Cappellazzi, J, Morrell, J J (2019): Performance of polyurea-coated Douglas-fir timbers exposed in Hilo Hawaii. *International Wood Products Journal*, DOI: 10.1080/20426445.2019.1601825.

Krukonis, V J, (1988): Processing with supercritical fluids: overview and applications. *ACS Symposium Series*, American Chemical Society, Washington D.C., **366**, 27-43.

Kjellow A, Henriksen O (2009). Interactions between wood and propiconazole in supercritical carbon dioxide. *Proceedings IRG Annual Meeting*, IRG/WP 09-40461, 7 pp.

Kjellow A, Imsgard F, Fernandes J, Wagner R, Delis J (2013). Field performance of wood impregnated with siloxanes using supercritical carbon dioxide. *Proceedings IRG Annual Meeting*, IRG/WP 13-40632, 12 pp.

Kjellow A, Imsgard F, Fernandes J, Henriksen O, Klaassen E, Wagner R, Delis J (2012). Supercritical impregnation of wood with siloxane. *Proceedings IRG Annual Meeting*, IRG/WP 12-30595, 11 pp.

Lebow S T, Morrell J J (1993). A comparison between high and conventional incision densities for improving preservative treatment of Douglas-fir heartwood lumber. *Proceedings IRG Annual Meeting,* IRG/WP 93-40009, 9 pp.

Lehringer, C (2011): Permeability improvement of Norway Spruce wood with the white rot fungus *Physisporinus vitreus*. PhD Thesis. *Faculty of Forest Sciences and Forest Ecology, Georg-August University of Göttingen,* Germany, 136 pp.

Lindgren, R M (1952): Permeability of southern pine as affected by mold and other fungus infection. *Proceedings American Wood Preservers' Association,* **48**, 158-174.

Maeglin, R R (1987): Juvenile wood, tension wood, and growth stress effects on processing hardwoods. In: Applying the latest research to hardwood problems. *Proceedings 15th annual hardwood symposium of the Harwood Research Council*. Memphis, USA, 100-108.

Militz H (2002). Thermal treatment of wood: European processes and their background. *Proceedings IRG Annual Meeting,* IRG/WP 02-40241, 20 pp.

Messner, K, Bruce, A, Bongers, F (2003): Treatability of refractory wood species after fungal pre-treatment. *Proceedings European Conference on Wood Modification,* 389-401.

Morris P I, Morrell J J, Ruddick J N R (1994). A review of incising as a means to treat refractory wood species. *Proceedings IRG Annual Meeting,* IRG/WP 94-40019, 25 pp.

Morrell J J, Morris P I (2002). Methods for improving preservative penetration into wood: a review. *Proceedings IRG Annual Meeting,* Document No. IRG/WP 02-40227, 17 pp.

Morrell, J J, Gupta, R, Winandy, J E, Riyanto D S (1998): Effect of incising and preservative treatment on shear strength of nominal 2-inch lumber. *Wood and Fiber Science*, **30**, 374-381.

Morrell, J J, Winandy, J E (1987): Incising practices used to improve preservative treatment in western wood species: a preliminary survey. In: *Proceedings, American Wood Preservers' Association*, **83**, 400-404.

Morrell, J J, Corden, M E (1986): Controlling wood deterioration with fumigants: a review. *Forest Products Journal,* **36**(10), 26-34.

Nicholas, D D, Siau, J F (1973): Factors influencing treatability. In: *Wood Deterioration and its Prevention by Preservative Treatments (DD Nicholas, Ed.) Vol II,* Syracuse University Press, Syracuse, NY, 299-343.

Nolan, G, Greaves, B, Washusen, R, Parsons, M, Jennings, S (2005): Eucalypt plantations for solid wood products in Australia - a review 'If you don't prune it, we can't use it'. *Forest & Wood Products Research & Development Corporation*, Victoria, Australia, 138 pp.

Obanda, D N, Schupe, T F, Barnes, H M (2008): Reducing leaching of boron-based wood preservatives – a review of research. Bioresource Technology, **99**, 7312-7322.

Potts, B, Hamilton, M, Blackburn, D (2011): Genetics of Eucalypts: traps and opportunities. In: *Proceedings, Developing a Eucalypt Resource: learning from Australia and elsewhere*, Wood Technology Research Centre, New Zealand, 1-26.

Rak, J R (1975): Penetration by and stability of copper-chrome-arsenic wood preservatives. *Information report OPX, Environment Canada*, Forest Service, Eastern Forest Products Laboratory, Canada.

Rosner B, Messner K, Tucker E J B, Bruce A (1998). Improved preservative penetration of spruce after pre-treatment with selected fungi. I. Fungal pre-treatment of pole sections. *Proceedings IRG Annual Meeting Document No.* IRG/WP 98-40117, 15pp.

Ross, A (2015): The use of buffered Amine Oxides for wood preservative treatments. In: *Proceedings of the Canadian Wood Preservers Association 36th Annual Meeting*, Ottawa, Ontario, 123-127.

Sandberg, D, Kutnar, A (2016): Thermally modified timber: recent developments in Europe and North America. *Wood and Fiber Science*, **48**(2015 Convention, Special Issue), 28-39.

Sanders M G, Amburgey T L, Barnes H M (2000). Innovations in the treatment of Southern pine heartwood. *Proceedings IRG Annual Meeting*, IRG/WP 00-40172, 7 pp.

Schwarze F W M R, Schubert M (2009). Enhanced uptake of wood modification agents in a bioincised wood. *Proceedings IRG Annual Meeting*, IRG/WP 09-40445, 8 pp.

Siau, J F (1971): *Flow in wood*. Syracuse University Press, Syracuse, NY.

Siraa A, Day D, Kibby B (2018). Glueline fungicides in veneer based engineered wood products: updated results from laboratory work for the H1.2 hazard class in New Zealand. *Proceedings IRG Annual Meeting*, IRG/WP/18-30726, 7 pp.

Smith, S M, and Morrell, J J (1991): Measuring distribution of chromated copper arsenate around incisions in Douglas-fir heartwood by direct-scan x-ray techniques. *Wood Protection*, **1**(1), 31-37.

Smith, S M, Sahle-Demessie, E, Morrell, J J, Levien, K L, Ng, H (1993): Supercritical fluid (SCF) treatment: its effect on bending strength and stiffness of ponderosa pine sapwood. *Wood and Fiber Science*, **25**(2), 119-123.

Suttie E D (1996). In-ground contact field trial results of preservative treated incised and unincised spruce. *Proceedings IRG Annual Meeting*, IRG/WP 96-40076, 12 pp.

Torgovnikov G, Vinden P (2000a). Microwave modification of wood properties: improvements in wood permeability. *Proceedings IRG Annual Meeting*, IRG/WP 00-40181, 10 pp.

Torgovnikov, G, Vinden, P (2000b). Microwave modification of yellow stringybark (*Eucalyptus mulleriana*) posts for impregnation with chromated copper arsenate preservative - improvement in wood permeability. *Proceedings IRG Annual Meeting*, IRG/WP 00-40185, 7 pp.

Torgovnikov, G, Vinden, P (2009): High-intensity microwave wood modification for increasing permeability. *Forest Products Journal*, **59**(4), 84-92.

Tucker E J B, Bruce A, Staines H J, Rosner B, Messner K (1998). Improved preservative penetration of spruce after pre-treatment with selected fungi. II. Creosote treatment, analysis and strength testing. *Proceedings IRG Annual Meeting,* IRG/WP 98-40117, 18 pp.

Turner P, Murphy R J, Dickinson D J (1990). Treatment of wood-based panel products with volatile borate. *Proceedings IRG Annual Meeting*, IRG/WP 3616, 14 pp.

Vidrine C, Freitag C, Nicholson J, Morrell J J (2007). Effects of heat treatments on decay resistance and material properties of ponderosa pine and yellow poplar. *Proceedings IRG Annual Meeting,* IRG/WP 07-40374, 11 pp.

Vinden P (1986). Resin bleed after light organic solvent preservative treatment - the effects of drying method and process type. *Proceedings IRG Annual Meeting,* IRG/WP 3378, 5 pp.

Washusen, R (2009): The influence of plantation silviculture on tension wood formation. In: *Proceedings Revisiting Eucalypts 2009,* University of Canterbury, NZ, 91-100.

Washusen, R (2013): Processing methods for production of solid wood products from plantation-grown *Eucalyptus* species of importance to Australia. In: *Processing, Report (project number: PNB291-1112A),* Forest and Wood Products Australia, Victoria, Australia.

Washusen, R, Morrow, A, Ngo, D, Northway, R, Bojadzic, M (2008): *Eucalpytus nitens* thinning trial: solid wood quality and processing performance using conventional processing strategies. In: *Resource Characterisation and Improvement (project number: PN07.3019),* Forest and Wood Products Australia, Victoria, Australia.

Washusen, R, Harwood, C (2011): Processing plantation-grown eucalypt sawlogs: modelling costs and log prices for mills optimised for the Tasmanian plantation resource (Technical Report 211). *Researching sustainable forest landscapes*, Cooperative Research Centre for Forestry, Hobart, Tasmania, Australia.

Wentzel, M (2018): Process optimization of thermal modification of Chilean *Eucalyptus nitens* plantation wood. PhD Thesis. *Faculty of Forest Sciences and Forest Ecology, Georg-August University of Göttingen*, Germany, 188pp.

Wentzel, M, Fleckenstein, M, Hofmann, T, and Militz, H (2019): Relation of chemical and mechanical properties of *Eucalyptus nitens* wood thermally modified in open and closed systems. *Wood Material Science and Engineering*, **14**(3), 165-173.

Wilkinson, J G (1979) *Industrial timber preservation*. Associated Business Press. London.

Winandy, J E, Morrell, J J, and Cheung, K C K (2018): Review of revisions to incising-effect adjustment factors (Ci) in the 2018 National Design Specification for Wood Construction. *Wood Design Focus*, **28**(1), 11-17.

Winandy, J E, Morrell, J J (1998): Effects of incising on lumber strength and stiffness; relationships between incision density and depth; species and MSR grade. *Wood and Fiber Science*, **30**(2), 185-197.

Winandy, J E, Morrell, J J (1993): Relationship between incipient decay, strength, and chemical composition of Douglas-fir heartwood. *Wood and Fiber Science,* **25**(3), 278-288.

Xia H, Li X, Xie J, Xiong X (2017). Permeability of Eucalyptus wood improved by microwave treatment. *Proceedings IRG Annual Meeting*, IRG/WP/17-40773, 10 pp.

Yakuwa A, Endoh H, Mori M, Doi S (1995). A prototype needle incisor for refractory timber. *Proceedings IRG Annual Meeting,* IRG/WP 95-40041, 9 pp.

Yang, L, Liu, H (2018): A Review of *Eucalyptus* Wood Collapse and its Control during Drying. *BioResources*, **13**(1), 2171-2181.