Final Report
Project NT014

NATIONAL INSTITUTE FOR FOREST PRODUCTS INNOVATION

Increasing the durability, and other material characteristics of Tasmanian hardwoods

2023

Launceston Centre

Funded by the Australian Government, Tasmanian Government & Industry Partners.

nifpi.org.au

NATIONAL INSTITUTE FOR
FOREST PRODUCTS INNOVATION
LAUNCESTON

Increasing the durability, and other material characteristics of Tasmanian hardwoods

Prepared for

National Institute for Forest Products Innovation

Launceston

by

Kyra C. Wood
William Leggate
Rhianna Robinson
Stuart Meldrum
Benoit Belleville
Felix Wiesner
Ros S. B. M. Ghani

in consultation with:

Jeffrey J. Morrell, Babar Hassan,
Jack Norton, Malcolm Liehr,
Wenxuan Wu, Daniel Field, Tony Dakin

Publication: Increasing the durability, and other material characteristics of Tasmanian hardwoods

Project No: NIF078-1819 [NT014]

IMPORTANT NOTICE

ISBN: 978-1-922718-22-8

Researcher/s:

Dr Kyra C. Wood (Principal Researcher), Mr Stuart Meldrum, Ms Ros S.B.M. Ghani,
University of Tasmania, T40B Newnham Campus, Newnham TASMANIA 7248 (Corresponding author: kyra.wood@utas.edu.au
Dr William Leggate, Ms Rhianna Robinson, Queensland Department of Agriculture and Fisheries, Salisbury Research Facility, 50 Evans Road, Salisbury QLD 4107
Dr Benoit Belleville, University of Melbourne, 500 Yarra Boulevard, Richmond VIC 3121
Dr Felix Wiesner, (Formerly: University of Queensland, now: University of British Columbia)

This work is supported by funding provided to Forest and Wood Products Australia (FWPA) to administer the **National Institute for Forest Products Innovation** program by the Australian Government Department of Agriculture, Fisheries and Forestryand the Tasmanian Government.

Australian Government
Department of Agriculture, Fisheries and Forestry

Tasmanian Government

Forest and Wood Products Australia
Level 11, 10-16 Queen St, Melbourne, Victoria, 3000
T +61 3 9927 3200 F +61 3 9927 3288
E info@nifpi.org.au
W www.nifpi.org.au

Executive Summary

This report outlines the overarching aims, methodology, and results from the National Institute for Forest Products Innovation (NIFPI) project titled: 'Increasing the durability, and other material characteristics of Tasmanian hardwoods' (NT014/NIF078-1819).[1] This national research project was co-funded by the Australian and Tasmanian Governments, with cash and in-kind contributions from various timber industry and research collaborators. The project was led by Britton Timbers, with the University of Tasmania as the principal researcher.

The primary objective of this project was to research, develop, test, and evaluate practical methods of preservative and fire-retardant treatments or modifications for refractory Tasmanian hardwood species. Specifically, the aim was to improve Tasmanian hardwood:

- durability, for use in exterior cladding applications (outside, above ground), or H3 compliance according to AS 1604.1:2021; and
- bushfire-resistance, for use in zones with risk of bushfire attack (BAL-29), according to AS 3959:2018

A secondary aim was to research and develop treatment or modification systems for interior linings in terms of improving durability, fire performance, and dimensional stability.

The research methodology included background literature review and development of a series of strategic experimental trials conducted by collaborative research teams at the University of Tasmania, the Queensland Department of Agriculture and Fisheries, the University of Melbourne, and the University of Queensland.

The materials under investigation in each trial were primarily Tasmanian 26-year-old thinned and pruned plantation shining gum (*Eucalyptus nitens)* and 60-80 year old regrowth Tasmanian oak (*Eucalyptus spp. [3],* including: *E. obliqua, E. regnans* and *E. delegatensis*). Some other species (e.g. Tasmanian blue gum [*E. globulus*], spotted gum [*C. maculata*], blackbutt [*E. pilularis*], and radiata pine [*P. radiata*]) were included as comparators or controls but were not the primary focus of the research.

The above-mentioned species (except spotted gum and blackbutt) are not naturally durable or fire resistant. The heartwood (or true wood) of the Tasmanian species is also refractory, meaning that it is extremely difficult to treat using conventional treatment methods and chemicals. To overcome these challenges, the following strategies were trialled:

- Trial 1 Dual treatment system
- Trial 2 Vacuum pressure impregnation
- Trial 3 Pre-treatment with vacuum pressure impregnation
- Trial 4 Non-chemical
- Trial 5 Fire retardants

Significant outcomes from the research include:

[1] The research relates directly to a second NIFPI project titled 'New methods of reliably demonstrating species durability in commercially relevant time frames' (NT047/NIF108-1819). Some of the preservative treatment work and analysis conducted as part of NIF108 is of direct relevance to the aims and outcomes of this project. It is advised that the final reports be read together.

- Successful preservative treatment of Tasmanian oak veneer-based products that meet the requirements for H3 compliance according to AS1604.1:2021 using vacuum pressure impregnation with optimised pressures and scheduling combining commercially available preservative chemicals with commercially available adjuvant additives
    - Further work using additional species, e.g. Tasmanian plantation shining gum and blue gum veneer-based products is recommended
    - Further research on thinner dimensioned laminated elements (e.g. LVLs, GLT) and potential glue line treatment is recommended
    - Further work including larger sample sizes, sample numbers and analysed retention results is recommended
- Successful fire-retardant treatment of Tasmanian oak and spotted gum plywood and veneer materials that meet the requirements for Group 1 (interior) and BAL 29 (exterior) compliance using vacuum pressure impregnation with commercially available fire retardants
    - Further work using Tasmanian plantation shining gum and blue gum veneers is recommended
    - Further work to optimise the solution strengths and VPI pressures and schedule lengths for sawn shining gum boards is also recommended
    - Further work including larger sample sizes and sample numbers is recommended
- Successful, novel method for treating seasoned sawn plantation Tasmanian hardwood boards suitable for exterior wall cladding that met the penetration requirements for H3 compliance according to AS1604.1:2021
    - The method used a rolling compression pre-treatment system to increase the pathways for fluid flow within each board, followed by a vacuum pressure impregnation treatment using an optimised charge (schedule lengths and pressures) and combining a known preservative chemical with a commercially available penetration enhancing adjuvant additive
    - Using this optimised treatment method, 15/15 seasoned Tasmanian oak samples and 14/15 shining gum samples achieved total cross section penetration, high uptakes and theoretical retentions that pass the requirements outlined in AS1604.1:2021
    - Further work including longer length samples and analysed retention is recommended
    - Further R&D is planned to refine the design of the pre-treatment system
- Over 50% of samples passing the penetration requirements when treated using vacuum pressure impregnation with optimised pressures and longer scheduling and a combination of adjuvant additives and conventional preservative chemicals (ACQ and MCA)
    - With further refinement to optimise the solution strengths and schedule lengths, this method could eventually eliminate the need for a rolling compression pre-treatment to achieve H3 compliance according to AS1604.1:2021
    - Further R&D is recommended
- Significant findings on the controllability of spring back, set recovery, colour change, adhesion, and ability to glue thermo-mechanically densified plantation shining gum and native regrowth Tasmanian oak, with further research already underway
- Significant steps towards development of a predictive model for boron diffusion rates through select barriers in support of a boron-based dual treatment system in plantation shining gum and native regrowth Tasmanian oak

Because the research resulted in some successful and some promising outcomes for both durability treatments and fire-retardant treatments in Tasmanian hardwoods, the following report includes a summary of the major research projects, with selected key information redacted in consideration of potential commercial opportunities. Each of the trials have also been tabulated on pages 72-75 to provide a quick guide to the key opportunities and suggestions for industry resulting from this research.

Industry/research partners:
Britton Timbers (project lead)
Sustainable Timber Tasmania (STT)
Koppers Performance Chemicals (KPC)
Ta Ann Tasmania
Neville Smith Forest Products (NSFP)
Tasmanian Timber Promotion Board (TTPB)
University of Tasmania (UTAS)
Queensland Department of Agriculture and Fisheries (DAF)
University of Melbourne (UM)

Launceston NIFPI Steering Committee representative:
Ms Suzette Weeding, STT

Primary research team:
UTAS:
Dr Kyra Wood (principal researcher)
Mr Stuart Meldrum
Ms Ros Ghani (PhD candidate)
DAF:
Dr William Leggate
Ms Rhianna Robinson
UM:
Dr Benoit Belleville
University of British Columbia (formerly University of Queensland):
Dr Felix Wiesner

And in collaboration with:
University of the Sunshine Coast (USC):
Professor Jeffrey Morrell
UTAS
Malcolm Liehr
University of Queensland:
Mr Wenxuan Wu
DAF:
Dr Babar Hassan (formerly USC)
Mr Jack Norton
Mr Daniel Field
Mr Tony Dakin

Standards referred to in this report

AS 1604:2021 - Australian and New Zealand Standard for Preservative-treated wood-based products inclusive of Part 1: Products and treatment, Part 2: Verification requirements and Part 3: Test methods
AS 3959:2018 - Construction of buildings in bushfire-prone areas
AS/NZS 3837:1998 - Method of test for heat and smoke release rates for materials and products using an oxygen consumption cone calorimeter
ASTM D2898 - Accelerated weathering of fire-retardant-treated wood for fire testing.
AS 5637.1.2015 - Determination of fire hazard properties
AS ISO9705.2016 - Fire tests - Full-scale room test for surface products
AS/NZS 3837.1998 - Method of Test for Heat and Smoke Release Rates for Materials and Products Using an Oxygen Consumption Calorimeter
NCC 2019 – National Construction Code, Australia
AS/NZS 1080:2012 – Methods of test for moisture content determination
ASTM D2395 – Standard test methods for density and specific gravity
AWPA - American Wood Protection Association, annual book of standards
AWPC – Australasian Wood Preservation Committee / Protocols for assessment of wood preservatives

Glossary

ACQ - alkaline copper quaternary
Adjuvant (Adj) - a substance that is added to a pesticide product or pesticide spray mixture to enhance the pesticide's performance
ASET – available safe egress time
BAL – bush fire attack level
BAE – boric acid equivalent
Blackbutt – *Eucalyptus pilularis*
Blue Gum – *Eucalyptus globulus*
Boron – generally used in this document to refer to disodium octoborate tetrahydrate (DOT), or interchangeably used to refer to a boron-based preservative treatment
CLT – cross laminated timber
Cone calorimeter - used to assess fire performance of timber
CSAW – Centre for Sustainable Architecture with Wood
DAF – Department of Agriculture and Fisheries
GLT – glued laminated timber
GOS – green off saw
Group number – interior fire performance rating (e.g. Group 1)
HRR – heat release rate
LOSP – light organic solvent preservative
LVL – laminated veneer lumber
Kop-Coat – a commercially available tank blend solution of Approved-Water-Based-Azole+permethrin with typical process chemicals and small amounts of a boron tracer
Koppers – Koppers Performance Chemicals
MCA – micronized copper azole
NCC – national construction code
NIFPI – National Institute for Forest Products Innovation
NT014/NIF078 – short-hand reference number for this project
NT047/NIF108 – short-hand reference number for an affiliated project on durability titled: New methods of reliably demonstrating species durability in commercially relevant timeframes
PAN – preservative indicator 1- (2-pyridylazo)-2-napthol

Radiata pine – *Pinus radiata*
RSET – required safe egress time
UM – University of Melbourne
UQ – University of Queensland
UTAS – University of Tasmania
Schedule/Charge/Cycle – all refer to the combination of vacuum and pressure cycles totalling to the length of time required in a treatment cylinder. These terms are used interchangeably.
Set-recovery – a type of swelling deformation that occurs after densified timber is exposed to and absorbs moisture
Shining gum – *Eucalyptus Nitens*
Spotted gum – *Corymbia spp.*
Spring back – immediate recovery (swelling) in timber after the release of pressure in plattens following densification
SRF – Salisbury Research Facility
Tasmanian oak – collective term for three species: *Eucalyptus regnans, Eucalyptus delegatensis* and *Eucalyptus obliqua*
TM – thermo-mechanical densification
VPI – vacuum pressure impregnation

List of figures

List of tables

Table of Contents

Introduction

Australian *Eucalyptus* species commonly grown in Tasmania, including shining gum (*E. nitens* H. Deane and Maiden), blue gum (*E. globulus* J. Labillardiere) and Tasmanian oak (three species: *E. obliqua* L'Hér, *E. regnans* F. Muell, *E. delegatensis* L'Hér), are fast growing and have good physical and aesthetic properties for use as building materials. They are an important source of timber both for export and domestic markets. Currently, the timber industry is mostly limited to selling these species either for woodchip production or for indoor applications. One of the reasons for this is that they are not naturally resistant to fungi or insects, and do not exhibit natural fire retardant properties. To expand the market potential for these timber species to exterior built environment applications, they must be preservative treated according to strict criteria outlined by relevant Australian and New Zealand standards.

However, the heartwood (also called true wood) of these Tasmanian hardwood species is extremely resistant to fluid chemical treatments that are commonly used in other low-durability timbers like pine. Most sawn boards have a high percentage of refractory heartwood, which presents a challenge to producers who wish to expand their product range into exterior appearance-grade applications like wall cladding.

With a focus on the needs and practicalities of timber industry processing and capacity in Tasmania, this research project investigated preservative treatment methods to improve the durability and bushfire-resistance of Tasmanian hardwoods so that they may be safely used as exterior claddings. A secondary aim was to improve the material for use as interior linings or for other indoor applications.

Background challenges and strategies for wood preservation

Australia is renowned for its aggressive decay fungi, insects, and bushfires, making it one of the world's most challenging environments for building with wood. Wood preservation generally involves protecting timber from such destructive hazards to increase its longevity in service as a building material. Risk level can vary significantly depending on the environmental and climatic context where the timber is exposed. There are many different species of fungus including various types of mould fungi, which tend to generate relatively superficial and appearance-based damage, and decay fungi which tend to cause more problematic structural damage in timber. A commonality is that most fungi require oxygen, and moist organic matter as a food source to flourish (e.g. timber, at around 25%-30% moisture content or more). Different fungi are likely to attack different species of timber and some of the most aggressive decay fungi occur in the top 250mm of soil. Like decay fungi, insects such as termites generally attack from the ground up and prefer to eat moist wood as well, although some will also cause damage under dry conditions, and certain species can fly. With sufficient oxygen and heat, timber acts as an excellent fuel source for fire (Zabel and Morrell, 2020).

Some trees have heartwood that is resistant to both bushfire and biological organisms that cause deterioration (Australian Standard AS 3959:2018; Australian Standard 5604:2005). Natural durability is commonly the result of a combination of naturally occurring extractives that are toxic to fungi and insects, and low permeability (Archer and Lebow, 2006), while fire performance is often correlated with the density of the timber (AS 3959:2018). Some non-Australian native hardwoods, like teak or merbau, are naturally resistant (more so to decay fungi than fire) but environmental and economic realities including diminishing supply of rainforest and native resources, relatively unknowable forest practices standards in other countries, carbon mileage, and unreliable and often high importation costs, means they are less desirable to use than certain Australian hardwoods. Some Australian hardwoods like spotted gum and blackbutt are also considered naturally resistant to decay fungi and bushfire, but again, old growth native forest resources are less and less obtainable. There is also increasing evidence to suggest that plantation timber of the same species, harvested around 16-30 years old, do not necessarily have the same durability or fire performance characteristics (Beadle, et al., 2008; Francis, 2022) as material which is much older at the time of harvest.

Unfortunately, the heartwood of some of the most abundant and fast-growing Australian hardwood species like shining gum, blue gum and Tasmanian oak have no natural fire resistance and very low natural durability.

In Australia, the natural durability of different species of timber are classified in the Australian Standard AS 5604:2005 by their probable life expectancy in different exposures. AS 5604 rates shining gum (*E. nitens*) as a Class 3 timber for above ground applications and Class 4 for soil contact, equating to an estimated service life of 7 to 15 years above ground and 0 to 5 years in the soil. Southern blue gum (*E. globulus*) is classified as a Class 2 timber for above ground (15 – 40 years) and Class 3 in-ground (5 - 15 years). Tasmanian oak comprises three different species, which rate differently to each other, with *E. regnans* and *E. delegatensis* classified as Class 3 above ground and Class 4 in-ground, and *E. obliqua* classified as Class 3 above ground and Class 3 in-ground.

Given their low durability ratings these Australian hardwood species need to be preservative treated or modified in some way to provide acceptable longevity for most building applications. The Australian Standard AS1604.1:2021 identifies six primary hazard classes for timber and outlines different levels of chemical preservative treatment required for the heartwood and sapwood of hardwood and softwood in each hazard class. Exterior cladding (the focus of this research project) falls into hazard class 3 (H3) a relatively broad category that also includes fencing material, decking, soffit linings, and anything else that is to be used outside but not in contact with the soil. The Australian Standard wood protection requirements for hardwood sawn timber in an H3 exposure include complete sapwood penetration and either 8mm of penetration of heartwood in timber >35mm thick or 5mm for timber <35mm thick (AS 1604.1:2021). Alternatively, unpenetrated heartwood may be allowed, but it cannot exceed 20% of the cross section nor extend more than halfway through the sawn board, nor exceed 50% of the width of the surface on which it occurs.

In terms of fire, the Australian Standard AS 3959:2018 fulfils a dual purpose: (1) it defines the potential risk and severity of a bushfire at a building site, based on the local climate or fire danger index, vegetation, and topographical conditions; and (2) it specifies construction requirements according to the expected bushfire severity on a building site. The bushfire severity is classified by Bushfire Attack Level (BAL), which contains, BAL-LOW (no requirements for building elements), BAL-12.5, BAL-19, BAL-29, BAL-40 and BAL-FZ (flame zone). Each BAL is associated with the maximum expected exposure heat flux risk that a structural element might experience during a bushfire (i.e. BAL-29 anticipates a maximum exposure heat flux of 29 kW/m^2). In addition, higher BALs also anticipate the accumulation of embers or contact with flames.

Although interiors were not the primary focus of this research project, acceptable safety of occupants inside buildings is achieved through the provision of sufficient egress times. The governing principle is that the available safe egress time (ASET) is larger than the required safe egress time (RSET). The former is defined by the time to reach untenable conditions due to smoke and fire, while the latter is defined by building geometry and occupant group. The choice of interior materials can influence the fire growth and therefore influences ASET. Group Numbers ranging from 1 (highest performing, non-combustible) to 4 (poorest performing) are one of multiple methods to classify building materials to regulate their acceptable use in terms of the fire performance of buildings.

To be able to utilise some of the abundant, low durability and low bushfire resisting Australian hardwood timber in a broader range of applications, some form of preservative and fire-retardant treatment is needed. However, preservative and fire-retardant treatment of the species outlined above is an ongoing challenge which the timber industry and various researchers have been trying to address for many years with varying degrees of success. The most common method for protecting wood is to apply a coating or paint that protects the wood from excessive moisture uptake, thus limiting the likelihood of decay fungi causing damage. Similarly, various intumescent or other fire-retardant coatings are promoted to improve fire performance. However, coatings alone do not offer sufficient protection from decay fungi and insect attack, and are only useful so long as they remain intact. Lack of maintenance, weathering, and human interference (e.g. building contractors drilling, cutting or rip sawing timber elements on a construction site) can quickly render coatings redundant.

Other methods that penetrate the wood more deeply than a coating, like using vacuum pressure to impregnate the wood with a fluid chemical preservative (discussed further in Trial 2 below), are the most effective means of preserving timber in the long-term. However, conventional treatment processes do not work consistently with the *Eucalyptus* species that form the focus of this research. The challenge with treating *Eucalyptus* to improve its durability and fire resistance mostly lies in the structure of the wood at a microscopic level. Wood et al., (2020) outline the problem with regard to a representative *Eucalyptus* species (shining gum) as follows:

> '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.'

Many methods have been trialled to enhance the treatability of low durability eucalypts using preservative chemicals, including incising, pre-steaming/boiling, pressure variations in vacuum pressure impregnation, ammoniacal solutions, diffusion, and supercritical fluid treatments (Cookson 2000). However, so far, the literature has not revealed any treatments for Australian hardwoods that are able to properly satisfy the requirements for H3 applications that are outlined in AS 1604.1:2021.

Research design and progression

What cannot be overstated about this research project, is that it was a national, collaborative effort involving multiple partners. The project was directly linked to another Launceston-based NIFPI research project which aimed to shorten the testing timeframes for durability analysis, using the material generated from this project.

Work began with a collaborative research planning meeting and subsequent literature review co-authored by the lead researchers across both projects, and this helped establish the most viable potential strategies to achieve the project goals (Wood, et. al., 2020). The project research team collaboratively established a series of strategic trials that were then undertaken at the University of Tasmania, the Queensland Department of Agriculture and Fisheries, and the University of Melbourne, with subsequent durability analysis commenced by the University of Tasmania and the University of the Sunshine Coast.

Due to changes in staffing and capacity at UTAS, DAF, Koppers, and UM, and the onset of the COVID-19 pandemic, the project was initially beset by variations to the overall research strategy and slow sub-contract negotiations which significantly delayed the start of the research. Major research trials began approximately a year and a half behind schedule. Ongoing challenges caused delays throughout the project, including interstate travel restrictions, health-related absences of key researchers, and short and often delayed supply of timber, along with untimely disruption to CSAW's research operations caused by a relocation to Newnham because of the Northern Transformation Program at UTAS.

Despite the delays and initial challenges, the research trials have produced some significant successes and outputs. Project teams met regularly to discuss progress and decide on next steps for the research as the iterative trials revealed new challenges and opportunities over the course of the project. Progress was also reported back to industry partners through a series of milestone meetings, during which financial obligations were also reported on and signed off.

Document structure

This document is a compilation of work by various research teams. Final reports detailing methods and results were provided by each research team who collaborated on the project and these reports can be made available on request. Shorter summaries of the associated work are provided in the body of this report. Some segments of the writing from collaborator reports have been directly extracted and included in the main body of this report, and the authors/contributors are properly acknowledged as primary co-authors of this document in full.

Strategic research trials: methodologies, methods, results and discussions

This research project involved literature review, collaborative research design with national research teams, and large-scale replicated scientific experimentation. At initial planning meetings the strategies discussed included: trialling green-off-saw (GOS) and seasoned material of various Tasmanian timbers; veneer-based products and sawn boards; physically preconditioning or pre-treating the timber to increase pathways for preservative fluid flow via methods like incision, compression rolling, microwaving, and heating the wood followed by dipping into a cold solution; adding penetration enhancing adjuvants to the standard chemical vacuum pressure impregnation (VPI) process; iteratively improving the suitability of VPI treatment cycles for Tasmanian hardwoods by changing the pressures, times and chemicals used; using a boron dip and diffusion process followed by a hard preservative overcoat to stop leaching; thermo-mechanical densification; and using VPI for fire retardant treatments.

Following the research planning discussions held at the collaborative start-up meeting, strategies outlined by Wood, et al. (2020), and the results from some initial preservative VPI treatment trials that were done in the affiliated NIFPI project (refer to NT047/NIF108 final report for more detail) five major research trials were established for this project each with its own subset of research trials which involved systematic experiments with thousands of samples being tested and analysed across the project overall.

The efficacy of treatments or modifications trialled in this project were evaluated against Australian Standard criteria as much as possible. Where the research was dealing with novel methods that have no Australian benchmark, international standards or theoretical measures were used. In most cases, treated or modified material generated by this project has subsequently been included in durability analysis trials in the affiliated NIFPI project (NT047/NIF108), however many of the results from that analysis are still pending given the lengthy time frames required to produce data. Some complementary preservative treatment trials were also conducted as part of the NT047/NIF108 project, and the results of those trials are discussed in the final report for that project.

The following sections and subsections of this document provide a summary of each of the major research trials and sub-trial components that were conducted under the auspices of the NIF078 project. Each summary outlines the primary concept, aims, methods, and results, and provides a brief discussion of the potential benefits for industry with some suggestions for what still needs to be done or areas for further research and development.

Trial 1 Dual Treatment System: boron-based dip-diffusion with leach-preventing overcoat

Boron-based timber treatments are cheap, readily available, and have excellent fungicidal and insecticidal properties (Findlay, 1985; Archer and Lebow, 2006, p.g. 317; Cookson et al., 1998). Borates diffuse easily into wood, even refractory heartwood, when it is wet (unseasoned), and do not alter the appearance of the timber surface. They are also a known chemical component in many fire-retardant treatments (LeVan and Tran, 1990) and boron-based treatments often include a chlorinated phenol to help control mould fungi during timber air-drying. The key challenge with boron-based treatments is that whilst they are relatively easy to get into refractory timber and significantly improve its durability, they leach out just as easily when the timber is exposed to water over time.

To overcome the leaching issue, this trial investigated a dual treatment, dip-diffusion with a vacuum pressure impregnated (VPI) coating system. Dipping wood in a boron solution for a few minutes when it is green and allowing it to diffuse through the wood as it air dries over a period of months, is a simple and feasible way to get boron into wood (Tamblyn, 1985; Findlay, 1985). This research aimed to test whether a thin, vacuum pressure impregnated (VPI) envelope or other coating system using a second preservative type may be enough to stop the boron leaching out and simultaneously satisfy the Australian requirements for an H3 suitable timber application.

Similar dual treatment dip-diffusion methods have been proposed by various researchers and effectively employed in the United States in 1985 (Amburgey and Sanders, 2007; 2009) to treat railway crossties made from non-durable refractory timber (white oak, red oak and gum) by dipping boards in different commercially available borate solutions for one minute, allowing them to diffuse for four weeks and then air-dry, followed by an overcoat treatment with two different oil-borne preservatives (creosote and copper napthenate). Although oil-borne creosote and copper napthenate will protect timber in H3 exposures, they are not available for use in domestic applications in Australia due to concerns about toxicity. However, copper napthenate is sometimes used in a light organic solvent-borne preservative solution, and this or other VPI preservative types may be able to provide enough of a barrier to prevent leaching.

Canadian wood scientists at FPInnovations also investigated the use of VPI boron-treated timber elements with brushed-on or sprayed-on transparent coatings to prevent leaching. After being subjected to accelerated artificial weathering tests, a water-based two-part, two-step film was found to be the most effective at preventing leaching of borates from the wood (Morris et al., 2008). This research was followed by a long-term field trial, and results from eight years of exposure indicated that whereas untreated control samples were experiencing moderate to advanced levels of decay, the borate-treated material with a simple overcoat appeared to remain sound after six years and only showed a very small amount of decay at eight years exposure (Ingram and Morris, 2015).

These promising results indicate that a similar dual-treatment system may be a suitable and effective way to treat refractory Australian hardwoods. The sub-set of trials discussed below, aimed to develop various aspects of this approach.

The research for Trial 1 was primarily undertaken by a PhD candidate and other researchers and technical staff at the University of Tasmania, using the laboratory equipment at the Centre for Sustainable Architecture with Wood's T40 facility, and with support from and access to facilities withing the University of Tasmania's Chemistry department. Note that the research for this trial is incomplete for two reasons: due the length of the PhD candidacy; and due to unforeseen delays caused by an ongoing and serious health condition experienced by the PhD candidate.

Boron-based treatments used in this trial were provided by KPC and Arxsada AG (formerly Lonza Specialty Ingredients), and reagents were purchased from Ace Chemical Company.

Trial 1.1 Treatability of *Eucalyptus* via boron-based dip-diffusion

Concept: Boron-based preservative treatments are already used in various *Eucalyptus* species, but commonly the process aims to treat the non-refractory sapwood of species with naturally durable heartwood, like spotted gum or blackbutt for H1 or H2 applications. Cookson et al., (1998) describe treating refractory Tasmanian hardwoods (blackwood and messmate) with boron-based chemicals via both Bethell VPI and dip-diffusion, but the treatment was intended to protect the sapwood against lyctid beetles, and no mention is made of the effectiveness of the treatment in heartwood. There is a gap in the knowledge regarding the effectiveness of using dip-diffusion to treat refractory *Eucalyptus* heartwood, using the dip-diffusion method. There has been little need for a test that looks specifically at how to treat the refractory heartwood of shining gum or other *Eucalyptus* species because the Australian Standards do not consider boron-based preservative treatments suitable for exterior (H3+) applications. A premise for the dual treatment hypothesis, is that a simple boron-based dip-diffusion treatment is an effective way to treat the heartwood of Australian hardwoods, but little is known about the most appropriate dipping times, solution concentrations, drying times, etc., for the species under investigation.

Aims: To test the efficacy of treating green-off-saw (GOS) Tasmanian hardwood species via dip-diffusion with a boron-based preservative, and establish the appropriate dipping times, solution strengths, and diffusion periods for different thicknesses of timber.

Materials and methods: GOS Tasmanian plantation shining gum and regrowth Tasmanian oak samples of varying thickness were used for this experiment (see Table 1 for dimensions). Initial moisture content and density was assessed by cutting a 20mm biscuit from five boards of each thickness and weighing the samples before and after oven drying following the methods outlined in AS1080.1:2012 and ASTM Standard D2395. A test to determine the average percentage of heartwood vs sapwood for each species was also undertaken before the treatment, by spraying a methyl orange solution on a cross sections of GOS and dried wood. A separate pilot trial was also undertaken to establish the optimal dipping time for the samples in the boron-based solution, by establishing net water uptake at different dipping intervals. In the pilot trial, GOS shining gum and Tasmanian oak samples were immersed in water and extracted at one

Figure 1. Samples being dipped in a boron-based preservative solution. Photo: Ros Ghani

minute, two minutes, three minutes, four minutes, five minutes, ten minutes, one hour, three hours, six hours and twenty-four hours and the preservative uptake measured at each point. From statistical analysis, dipping at three minutes was considered sufficient to have significant water uptake for both wood species. (Dipping for one hour or more significantly increased the uptake, but as this project aimed to remain relevant for industrial timber processing, longer periods were ruled out.)

After these initial characterisation tests to establish a method, samples were dipped (Figure 1) for three minutes into one of two different commercially available boron-based preservatives (Timbor and Diffusol) at two different concentrations (10% BAE and 15% BAE). Rather than block stacking and covering with a plastic wrap as per a typical diffusion process (Tamblyn, 1985; Archer and Lebow, 2006), samples were arranged with spacers (rack sticks) between each layer to mimic a typical yard drying rack configuration that allows airflow between the boards as is likely to occur in an Australian hardwood drying process. Samples were extracted from the 'mini-rack' at four intervals throughout the drying period, to assess the degree of boron penetration.

Assessment was done by calculating the boric acid equivalent (BAE), net boron uptake (l/m^3), and theoretical retention using the following formulae:

$$Net\ boron\ uptake\ (l/m3)\ =\ \frac{(Weight\ after - Weight\ before)}{(Board\ dimensions\ before\ /\ 1000000)}$$

$$Theoretical\ retention\ (Kgs\ preservative\ actives/m3)\ =\ Concentration\ (Kgs\ preservative\ actives/l)\ x\ Uptake/Absorption\ (l/m3)$$

$$BAE\ (\%\ m/m) = \frac{(Uptake\ x\ Solution\ strength)}{Density}$$

Penetration was visually assessed using a curcumin-based indicator spray on sample cross-sections. Statistical analysis was performed using the open-source statistical package which is RStudio. The statistical analyses that were carried out were: (1) analysis of variance (ANOVA) – to determine the overall significance of the data and (2) Tukey's post hoc test – to find the specific group of the significant means.

Table 1. Boron-based preservative treatment of Tasmanian oak and shining gum of varying thicknesses

Species	Treatment	Solution Concentration	No. of samples 100 x 22 x 300mm (WxHxL)	No. of samples 100 x 28 x 300mm (WxHxL)	No. of samples 100 x 42 x 300mm (WxHXL)
Shining gum (*E. nitens*)	Diffusol	10%	5	5	5
		15%	5	5	5
	Timbor	10%	5	5	5
		15%	5	5	5
Tasmanian oak (mixed spp. *E. obliqua, E. regnans, E. delegatensis)*	Diffusol	10%	5	5	5
		15%	5	5	5
	Timbor	10%	5	5	5
		15%	5	5	5
		Total samples:			120

Results: the detailed results are not provided here as a publication by the PhD student on this subject is currently in draft, however, in summary, a short dipping time of three minutes was found to result in a suitable concentration of boron within the heartwood of 22 mm shining gum boards following a ten-week diffusion period. Boron retention was still low in the other shining gum thicknesses and in Tasmanian oak boards, but increasing the solution strength could result in significantly higher retentions. Visual assessment revealed that most 22 mm boards showed complete penetration through the cross section. Although 28 mm and 42 mm boards were not completely penetrated, they also had not yet reached fibre saturation point (FSP) by the end of the ten-week diffusion period, meaning that boron would continue to diffuse through the cross section as the board continued to dry. In summary, the results from this trial indicate that it is possible to achieve good retention and penetration in the heartwood of refractory Tasmanian hardwoods using a boron-based dip-diffusion method. Further research to refine the solution strengths suitable for the proposed application is needed.

Trial 1.2 Maximum retention of boron at high concentrations

Concept: Currently, the Australian standard only allows boron-based treatments for interior applications due to the leaching issue (mentioned above). As such, there is no Australian standard outlining the retention amount that would be required for boron to be used as a fungicide or insecticide in exterior applications. Interior applications (H1-H2, inside above ground) in Australia require a respective retention amount of 0.047% and 0.35% m/m, (AS1604.1:2021). It is likely that for exterior applications a higher retention amount would be required due to the greater risks posed by aggressive fungi or termites, and to allow for potential losses in chemical concentration that might occur during the production process. As noted in trial 1.1 above, to improve retention results, the concentration of a chemical solution can be increased, but boron tends to crystalise at high concentrations which could prevent it from properly penetrating the surface or diffusing through the wood. The American Wood Preservers Association (AWPA) Standard U1-20 for sawn timber and crossties provides a useful non-Australian benchmark for the use of a boron-based timber pre-treatment (followed by overcoat of some kind) in an exterior application, suggesting that a minimum of 2.7kg/m^3 is needed. Findlay et al., (1985, pg. 68) recommend that the average retention of boric acid equivalent (BAE) that is needed to effectively protect timber is 0.4% m/m based on the dry weight of the wood, with 0.1% m/m concentration in the core of the board. Before refining the process to better understand what an appropriate concentration level of boron should be in Australian *Eucalyptus*, we first needed to know how high we could push the concentration of the (unheated) solution before causing crystallisation.

Figure 2. Samples being weighed after dipping. Photo: Ros Ghani

Aim: To establish the highest possible concentration of boron that can be retained in Tasmanian hardwood species.

Materials and methods: GOS plantation shining gum boards 100 mm x 25 mm x 250 mm were selected as a representative refractory Tasmanian hardwood and dipped into an unheated boron-based solution at different concentrations, increasing from 15% BAE to 30% BAE in 1% increments (four samples were used for each level concentration). Samples were end sealed, and weighed (Figure 2) before and directly after dipping to determine gross retentions. Theoretical retention was calculated and converted from % m/m to kg/m^3 for easy comparison with other standards using the following formula:

$$Retention\ (kg/m3) = \frac{retention\ (\%\ m/m)x\ oven\ dry\ timber\ density\ (kg/m3)}{100}$$

Following treatment, samples were then stacked and left to air dry to allow diffusion to occur, and further tests will be carried out in due course to ascertain penetration through the cross section. A subset will be analysed for actual retention.

Results: The detailed results are not provided here as a publication by the PhD student on this subject is still pending, however, in summary, the highest theoretical retention achieved at a concentration of 30% was around 0.6% m/m or 3.30kg/m^3 assuming an average density of 550kg/m^3 for the shining gum. This is greater than the amount required by the Australian Standard for H2 applications (0.35% m/m) and is also much higher than the amount required in the AWPA U1-20 for a dual treatment approach in railway cross-ties (2.7kg/m^3). Further research is needed to determine analysed retention of selected boards, but these retention amounts are promising for the proposed dual treatment approach.

Trial 1.3 Predicting the diffusion rate of boron-based preservative treatments through different species and selected barrier systems

Concept: To support the hypothesis that a boron-based dual treatment system may be an effective way to treat refractory *Eucalyptus* heartwood, we first needed to understand the rate at which boron-based preservatives move (or leach) through different materials under high moisture regimes. The rate at which boron-based preservatives move through untreated and barrier treated Tasmanian hardwoods, or the diffusion coefficient (Ra, et al., 2001), may be able to be mathematically quantified if data can be collected that establishes how long it takes for boron to move through saturated wood (i.e. steady-state diffusion, according to Fick's first law of diffusion). This can be done experimentally using a diffusion cup method (Tarmian et al., 2020). A diffusion cup is designed to accommodate two solutions in two chambers: for example, a boron-based preservative solution in one end; and distilled water in the other end.

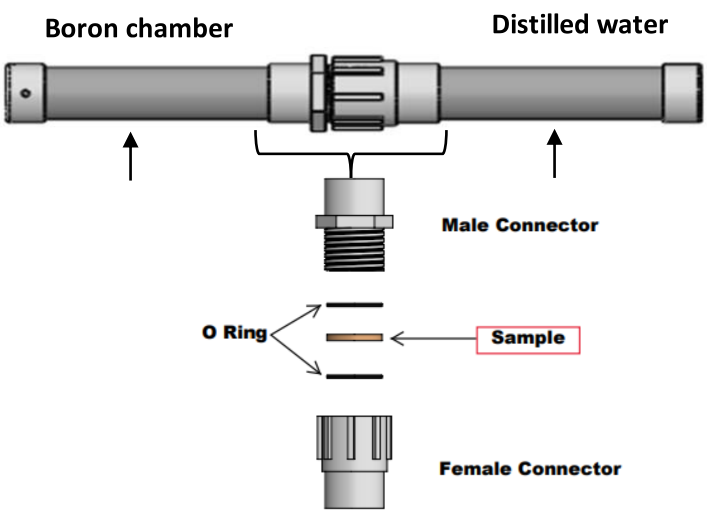


Figure 3. Diffusion cup apparatus schematic.

The two chambers are separated by a piece of wood so that any solution movement from the high concentration chamber (boron) to the low concentration chamber (distilled water) must go through the wood piece (i.e. a process that mimics leaching). Samples are regularly collected from the distilled water chamber and tested for the boron concentration, and this process continues until the boron concentration in distilled water side reaches a steady state.

Aims: To collect diffusion-rate data for boron-movement through untreated Tasmanian hardwoods and Tasmanian hardwoods coated with selected preservative barriers and to develop a predictive model for leaching rates over time.

Materials and methods: The full description of materials and methods of this experimental diffusion cup set up are not provided here as they form part of an ongoing PhD investigation which will be published in due course. However, in summary, small discs of seasoned Tasmanian oak and shining gum were prepared to fit into a PVC pipe apparatus, with two chambers at either end joined by a male/female connector (Figures 3 & 4). The timber discs were either dry or soaked prior to installation in the diffusion cup apparatus. Some discs were untreated, while others were treated with selected preservative barriers (e.g. vacuum pressure impregnated ACQ or LOSP, hot dipped paraffin wax, etc.,). In the diffusion cup apparatus, one chamber was filled with distilled water and the other chamber with a boron-based preservative solution. A small access point at the distilled water end was used to extract a 2ml sample every few days and replaced with an equivalent amount of distilled water. The samples of solution were then analysed for boron concentration using the AWPA A65-21 standard method using a UV spectrophotometer, and Azomethine-H reagent (Figure 5). This extraction and analysis process will continue until the boron concentration in the distilled water end of the diffusion cup reaches a steady state. In total (so far) seventy diffusion cups have been installed.

Figure 4. Diffusion cup apparatus. Photo: Kyra Wood.

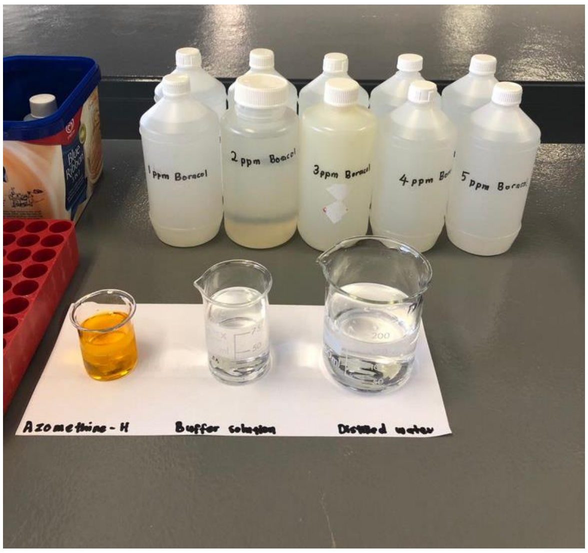


Figure 5. Solution used for boron content determination test. Photo: Ros Ghani.

Results: the detailed results are not provided here as the data collection is ongoing. A publication by the PhD student on this subject will follow.

Trial 1.4 Treatability of *Eucalyptus* via boron-based dip-diffusion: *UPSCALED*

Concept: Industry drying practices and processing of Tasmanian hardwoods involve several stages that may undermine the viability of a boron-based treatment option. For example, the inclusion of a process whereby freshly sawn, racked timber is subsequently block stacked and covered for a period of 3-4 weeks (a critical step according to most diffusion theory, see Findlay et al., 1985, p.g. 53) before being separated with rack-sticks for the air-drying period is a double-handling that is unlikely to be well-received in the Australian hardwood drying industry. Testing the proposed dual treatment system at a larger scale and simulating certain stages of timber production may help to establish whether this process is viable.

Figure 6. Unsheltered rack of boron treated shining gum boards air drying at T40, with leachate collection set up underneath. Photo: Kyra Wood.

Aims: To test and evaluate the boron-based treatment approach outlined in Trial 1.1, using a larger sample size and scale, and simulating and considering industry standard practices like air drying racks of timber spaced with rack sticks (sheltered and unsheltered). The timber will then be reconditioning and dried as per industry practice, then dressed and the waste recovered for preservative analysis and disposal as per regulatory requirements.

Materials and methods: This trial used thinned and pruned 26-year-old plantation shining gum dipped in a commercially available boron-based treatment. Work (so far) has included: dipping larger sample sizes (1500 mm x 100 mm x 25 mm) and quantities (~1.5m^3) following the times and solution concentrations outlined in Trial 1.1; weighing to determine uptakes; racking and air drying in the yard at T40 (covered and semi-sheltered, Figures 6); collecting leachate from under the air-drying timber to establish whether unsheltered air drying and exposure to the elements significantly affects the amount of boron in the wood; and checking the sapwood vs heartwood content of boards to establish the effect of sapwood content on uptake amounts. Further tests will include: reconditioning the wood in a commercial reconditioning process; dressing and finishing the wood before VPI or hot wax dip as per the best performing barriers shown by the PhD research outlined in Trial 1.3; and finally testing the durability of the proposed system with weathering tests, field trial and laboratory decay analysis.

Results: This component of the research is ongoing, however initial results indicate good penetration and diffusion through the board cross sections in both sheltered and unsheltered racks during the nine-month drying period (Figure 7). At the time of reporting, the boards are being reconditioned and dried by an industry partner. A publication on this subject will follow.

Benefits for industry?

If a boron-based preservative treatment solution can be reliably prevented from leaching using an overcoat or envelope barrier treatment, it could provide one of the most effective, simple, environmentally responsible, and economically feasible preservative treatments for refractory Tasmanian hardwoods.

At this stage, the research is ongoing. It is a relatively theoretical project with modelling of the diffusion-rate data of boron through selected barriers as the primary focus of the research. However, when combined with the more practical research focus in Trial 1.4, the results from this long-term trial could prove extremely useful to the timber industry.

What still needs to be done?

This project requires a lot more research and development before the proposed system may be considered appropriate for commercialisation or industry-uptake. It is also unlikely that the proposed system would meet the Australian requirements for preservative treatment without changes to the Australian Standards, so if the approach is successful it would likely require an alternative form of certification to be deemed fit for purpose, for example using Codemark[2] certification.

[2] To know more about Codemark certification you can read about it here: https://www.abcb.gov.au/about-codemark; or here: https://saiassurance.com.au/codemark-certification-scheme;

Trial 2 Vacuum pressure impregnation (VPI)

The simplest and most readily available preservative treatment systems in Australia use vacuum and pressure in large cylinders to impregnate whole packs of timber with either water-borne or oil-borne chemicals that are toxic to decay fungi and insects. The Bethell (full cell) method (Findlay, 1985) is widely used to treat softwood species like plantation pine, which have a high ratio of permeable sapwood in each board. Timber is commonly block stacked and rolled into the treatment cylinder on a carriage. Depending on the requirements of the intended application, different chemicals are then forced into the timber using either water or oil as a carrier and solvent. Using vacuum to draw the air out of the cylinder and out of the wood, a preservative solution is drawn into the cylinder and hydraulic pressure is applied for varying periods of time. After treatment, the solution is drained from the cylinder and stored. The capital costs of setting up a VPI treatment cylinder are reasonably high, but some timber producers in Australia have already invested in this infrastructure, while others can send their product to be treated by specialist preservative treatment companies in most parts of Australia.

The major drawback when using a standard hardwood vacuum pressure impregnation cycle and solution strength is the amount of preservative retained in the refractory Eucalyptus heartwood is usually far less than what is required by the Australian Standards and the preservative penetration is also limited. This has been shown by the research in this project and in the affiliated NIFPI project (see final report for NT047/NIF108). Another drawback is that timber is normally already seasoned before treatment, but the treatment process often involves significant rewetting of the wood especially in water-based formulations as fluids are used to transport the biocides. For many Australian hardwoods, drying is not a simple matter of putting the timber in a kiln as the high temperatures and air flow can result in drying-related defects like collapse, checking and splitting that cause major losses. Properly drying VPI treated timber without defect potentially requires a double-handling that may make the process unfeasible.

The research in Trial 2 was subcontracted to the Queensland Department of Agriculture and Fisheries primarily undertaken by researchers at Salisbury Research Facility using their laboratory-based semi-commercial scale treatment cylinders, with some additional treatment and analytic work done at I-treat, QLD, and AgriSolutions. The research in Trial 2 extended a preliminary VPI trial that was carried out by researchers on the affiliated NIFPI project (see NT047/NIF108 final report for more detail).

In the NT047/NIF108 preliminary VPI trial, treatment schedules were identified that led to adequate copper penetration in more than 50% of shining gum timber samples as per the penetration requirements of AS1604. Trial 2 in this project further refined those treatment schedules with a focus on reducing the schedule length to make the treatments more commercially viable, although some longer schedule times were investigated after previous trials indicated penetration improvements with longer schedules. Most commercial treatment schedules run for a maximum of 2 hours and the initial trial treatment schedule aimed to match a commercial schedule. Trial 2 also explored the addition of off-the-shelf adjuvants to common preservatives. Alkaline copper quaternary (ACQ), micronized copper azole (MCA) and a ready-to-use light organic solvent preservative (LOSP) solution were supplied by Koppers Performance Chemicals (KPC). Finally, Kop-Coat, a commercially available, tank blend solution of APVMA Approved Water Based Azole + permethrin with typical process chemicals and small amounts of a boron-based tracer was also included in the trial.

Trial 2.1 Adjuvants

Concept: Adjuvants are compounds traditionally used in the agriculture industry to enhance dispersion of insecticides and herbicides and have been trialled in the timber industry to aid preservative penetration in refractory (hard to treat) hardwoods. These penetration enhancing agents effectively alter the wood permeability through a combination of dissolving encrustations that block fluid movement in the wood at a cellular level, and also swelling the cell structure (Wood et al., 2020). Using vacuum pressure impregnation (VPI) and combining adjuvants with known preservative chemicals may improve preservative uptake and retention for Tasmanian hardwoods.

Aims: To assess and improve the preservative uptake in seasoned and green-off-saw (GOS) shining gum; to test certain commercially available preservative treatments, combined with three differing treatment schedules and three different commercially available adjuvants; to refine the methods for subsequent use with pre-treatments (Trial 3.1); and to establish a 'best bet' treatment option based on these iterations (Trial 3.2)

Materials and methods: Large scale iterative trials were undertaken in a VPI treatment cylinder at DAF (Figures 9 and 10) to ascertain the best performing combinations of two known waterborne preservatives (micronized copper azole, MCA [0.65%] and alkaline copper quaternary, ACQ [1.0%]) using standard commercial solution strengths. Three adjuvant additives were trialled (deidentified and named as B, S, and V). Three different charges were trialled (100 mins, 130 mins, 190 mins) were trialled (Table 2).

Table 2. Vacuum and pressure schedules

Charge	Initial Vac	Time	Hold Vac	Time	Pressure	Time	Final Vac	Time	Total schedule
1 (commercial)	-85kPa	30			+1400kPa	60	-85kPA	10	100 mins
2	-85kPa	60			+1400kPa	60	-85kPA	10	130 mins
3	-85kPa	60	-70kPA	60	+1400kPa	60	-85kPA	10	190 mins

GOS and seasoned plantation shining gum were trialled. All samples across Trial 2 were cut from matched parent boards (19mm x 100mm), using two cut patterns (Figure 8). Shining gum was selected as a representative species of Tasmanian hardwood, while regrowth/native Tasmanian oak was only included in the final 'best bet' trial (Trial 3.4) and veneer-based trials (Trial 2.4) to reduce unnecessary waste. In total, over 1300 samples were treated (including the LOSP and Kop-Coat trials outlined in sections 2.2 and 2.3 below). A full report detailing precise methods, results and discussion from this trial is available on request. After treatment all individual samples were weighed and measured to determine the solution uptake. After the treated samples were partially air dried (Figure 11), they were cut in half and conditioned to 12% EMC in a constant environment chamber. A 10 mm wide biscuit was cut for penetration testing from the centre cross section of every treated sample and oven dried.

300mm	300mm	300mm	300mm	300mm	300mm	300mm	300mm	300mm	300mm
ACQ	ACQ + Adj1	ACQ + Adj 2	ACQ + Adj 3	MCA	MCA + Adj 1	MCA + Adj 2	MCA + Adj 3	Kop-Coat	LOSP

300mm	300mm	300mm	300mm	300mm	300mm	300mm	300mm
ACQ	ACQ + Adj 1	ACQ + Adj 2	ACQ + Adj 3	MCA	MCA + Adj 1	MCA + Adj 2	MCA + Adj 3

Figure 8. Parent board cut patterns for charge 1 (top) and charges 2 and 3 (bottom).

Figure 9. Samples awaiting treatment in the VPI cylinder at the Salisbury Research Facility. Photo: Rhianna Robinson.

Figure 10. Samples before treatment (left) and after treatment (right). Photo: Stuart Meldrum.

Figure 11. Samples air-drying following treatment. Photo: Rhianna Robinson.

Table 3. Seasoned and GOS shining gum average treatment uptakes (l/m³)

Shining gum (15 samples per treatment)								
Seasoned	Charge 1	Charge 2	Charge 3		Seasoned	Charge 1	Charge 2	Charge 3
MCA	140	192	231		ACQ	200	206	200
MCA + B	187	176	231		ACQ + B	194	198	215
MCA + S	187	204	239		ACQ + S	169	196	240
MCA + V	223	226	261		ACQ + V	186	217	213
*Green highlighted is the commercial charge and preservative that was selected for the pre-treatment trial, blue highlighted is slightly longer charge and preservative that was later selected for the 'best bet' trial.								
GOS	Charge 1	Charge 2	Charge 3		GOS	Charge 1	Charge 2	Charge 3
MCA	107	104	107		ACQ	107	104	107
MCA + B	108	102	106		ACQ + B	108	102	106
MCA + S	97	138	141		ACQ + S	97	102	65
MCA + V	123	114	141		ACQ + V	107	115	111

Figure 12. Penetration images of treated shining gum from charge 3+ACQ+adjuvants, left to right, showing copper penetration of ACQ, ACQ + B, ACQ + S and ACQ + V. Photo: Stuart Meldrum.

Table 4. Seasoned shining gum charge 3 + ACQ + Adjuvants								
Percentage of penetration*					Theoretical retention as % m/m**			
ACQ	ACQ + B	ACQ + S	ACQ + V		ACQ	ACQ + B	ACQ + S	ACQ + V
77	80	80	75		0.41	0.40	0.39	0.28
69	77	75	68		0.35	0.39	0.42	0.34
70	76	76	86		0.39	0.45	0.52	0.47
36	40	50	49		0.24	0.26	0.35	0.37
92	92	89	89		0.62	0.55	0.61	0.51
24	19	21	29		0.19	0.16	0.15	0.17
82	90	98	95		0.50	0.54	0.80	0.67
70	80	77	83		0.23	0.32	0.36	0.34
45	45	39	37		0.14	0.20	0.19	0.19
92	90	88	87		0.44	0.43	0.49	0.35
76	81	76	79		0.42	0.48	0.48	0.37
42	43	40	36		0.23	0.22	0.21	0.20
90	90	89	90		0.60	0.64	0.69	0.67
76	90	88	85		0.37	0.51	0.51	0.46
75	80	81	88		0.34	0.30	0.44	0.38
68	72	71	72	←Avg→	0.37	0.39	0.44	0.38
0 pass	0 pass	1 pass	0 pass		7 pass	9 pass	10 pass	5 pass

*Minimum 5 mm penetration for timber <35 mm thick. Alternatively, unpenetrated heartwood may be allowed, but it cannot exceed 20% of the cross section nor extend more than halfway through the sawn board, nor exceed 50% of the width of the surface on which it occurs.
**Minimum requirement for ACQ is 0.39% and MCA is 0.229% for H3 in AS 1604 Table 4.3(A).
Highlighted cells indicate a pass against relevant requirements outlined in AS 1604.

Figure 13. Penetration images of treated shining gum from charge 3+MCA+adjuvants, left to right, showing copper penetration of MCA, MCA + B, MCA + S and MCA + V. Photo: Stuart Meldrum.

Table 5. Seasoned shining gum charge 3 + MCA + Adjuvants								
Percentage of penetration*					Theoretical retention as % m/m**			
MCA	MCA + B	MCA + S	MCA + V		MCA	MCA + B	MCA + S	MCA + V
56	60	52	68		0.13	0.13	0.12	0.13
48	39	45	81		0.13	0.12	0.17	0.25
67	79	63	61		0.25	0.27	0.20	0.24
49	46	45	40		0.21	0.14	0.13	0.14
86	90	95	98		0.30	0.29	0.31	0.32
5	30	15	25		0.07	0.08	0.07	0.08
94	94	90	92		0.30	0.29	0.26	0.29
55	50	40	54		0.14	0.12	0.11	0.13
10	56	49	55		0.09	0.14	0.12	0.17
68	77	64	96		0.15	0.15	0.27	0.30
50	71	85	83		0.17	0.18	0.26	0.24
25	58	40	54		0.09	0.17	0.11	0.15
81	82	83	92		0.31	0.27	0.31	0.32
77	81	75	81		0.24	0.25	0.26	0.23
85	75	81	90		0.19	0.19	0.22	0.21
57	66	71	62	←Avg→	0.18	0.19	0.20	0.21
0 pass	0 pass	0 pass	1 pass		5 pass	5 pass	6 pass	8 pass
*Minimum 5 mm penetration for timber <35 mm thick. Alternatively, unpenetrated heartwood may be allowed, but it cannot exceed 20% of the cross section nor extend more than halfway through the sawn board, nor exceed 50% of the width of the surface on which it occurs. **Minimum requirement for ACQ is 0.39% and MCA is 0.229% for H3 in AS 1604 Table 4.3(A). Highlighted cells indicate a pass against relevant requirements outlined in AS 1604.								

Figure 7. Samples selected from the unsheltered stack at the end of the outdoor drying period and sprayed with a boron-reactive indicator showing good penetration and diffusion through the cross section. Photo: Stuart Meldrum.

Penetration assessments were completed on the cross-sectional biscuits using the preservative indicator PAN (1- (2-pyridylazo)-2-napthol) to confirm the presence of copper to AS/NZ 1604.3:2021 (Figures 12 and 13). Individual biscuits were evaluated for penetration using a grid analysis (or ImageJ software) and assessed against penetration criteria outlined in AS1604. Using the uptake results, sample density and solution strength, theoretical retention was able to be calculated for each sample. Whilst theoretical retention is different from calculated/analysed retention, it can be used as a predictive tool to scope the success of a treatment and aid in determining required solution strengths.

Results: This method did not result in a reliable successful H3 treatment, but findings from the trial provided critical knowledge and procedural refinement towards making the use of VPI with refractory Tasmanian hardwood species an effective treatment option that meets the Australian Standard criteria.

Increases in average uptakes were observed as the charge length increased for all treatments for both GOS and seasoned shining gum (Table 3). MCA + V charge 3 recorded the highest average uptake of all for seasoned timber at 261 L/m^3. ACQ + S charge 3 recorded the highest uptake for (ACQ treated) seasoned timber at 240 L/m^3. Increasing charge length and adjuvant addition made visible improvements to penetration for both MCA and ACQ based treatments but only two seasoned samples met the penetration requirements outlined in AS1604 being samples from MCA + V charge 3 and ACQ + S charge 3 (Tables 4 and 5).

In terms of theoretical retention, seasoned timber with adjuvant S + ACQ + charge 3 recorded 10 out of 15 passes; and seasoned timber with adjuvant V + MCA + charge 3 recorded 8 out of 15 passes for theoretical retention (Tables 4 and 5). MCA was deemed to have better environmental credentials, cause less change in colour after treatment, and is slightly cheaper than ACQ, so it was selected for further testing with veneer-based products, pre-treatments and for the ‘best bet’ trial, however both MCA and ACQ performed similarly.

MCA + V and MCA + S charge 3 had the highest uptake of all for GOS timber at 140 L/m^3. ACQ + V schedule 2 had the highest uptake for (ACQ treated) GOS timber at 115 L/m^3. No penetration passes were recorded for GOS ACQ. In general, GOS material did not perform well (i.e. seasoned shining gum recorded higher average uptakes in comparison to GOS for both ACQ, MCA and GOS material significantly deformed while it was drying) so it was not pursued in the final iterations nor subsequently for the ‘best-bet’ trial (Trial 3.2) or the fire-retardants trial (Trials 5.1 and 5.2).

The samples used in this study were relatively short in length (approx. 200-300mm) when compared with actual board lengths that range up to 5.5-6m in length, but all samples were end sealed before treatment to better represent ‘longer length’ timber treatment. Most of the material that was seasoned before it was VPI treated did not collapse or deform during post-treatment drying, but questions remain as to how the post-treatment drying phase would affect larger-scale timber elements.

Benefits for industry?

If conventional and readily available equipment and chemicals with known preservative capability can be used to effectively treat Tasmanian hardwoods, this could be one of the simplest options for industry to take up. Some Tasmanian softwood sawmills already operate their own VPI treatment cylinders, but capital costs for setting up equipment would likely be expensive for smaller scaled operations. However, there are also existing commercial treatment plants and providers within Australia where material could either be sold, or sent for treatment.

What still needs to be done?
Investigating the effectiveness of longer schedule lengths and altering solution strengths could see further improvements in uptakes and penetration and negate the need for the pre-treatments which were used to successfully reach the H3 benchmark in sawn boards (see Trial 3.2 below). A study of the economic feasibility of longer schedules and different solution strengths would also be advisable, and a trial using full scale boards would be of interest. A further consideration is that timber treated with waterborne chemical preservatives requires time following treatment for air or kiln drying and this has the potential to result in drying-related defects if not done in ways that are suitable for the individual species.

Some further refinement of this approach by a treatment company in collaboration with an interested timber industry partner is highly recommended.

Trial 2.2 Light organic solvent preservatives (LOSP)

Concept: Light organic solvent preservative (LOSP) treatment via vacuum pressure impregnation, is a solvent-borne, low-uptake treatment process. As it does not introduce excess moisture to the wood through the pressure impregnation process, little to no drying time is required after treatment. It is commonly used to treat non-refractory species like *Pinus radiata,* generally for H3 applications.

Aims: To treat refractory Tasmanian hardwood samples using LOSP via VPI according to the required benchmarks set out in the Australian Standard criteria.

Materials and methods: Sample sizes and species were the same as for Trial 2.1. Treatment was performed at DAF in a modified set up using a wet vacuum-vacuum only and a ready-to-use solution of LOSP. Limited information was provided on the required schedule and solution strength, so calculating theoretical retention wasn't possible, but the preservative contained trace amounts of copper so that penetration assessment could be done using the copper reactive PAN indicator spray on sample cross sections.

Penetration assessments were completed on the biscuits (oven dried) using the preservative indicator PAN (1- (2-pyridylazo)-2-napthol) (Figure 14). Individual biscuits were evaluated for penetration using a grid analysis and assessed against penetration criteria outlined in AS1604.

The LOSP solution used for treatment was a ready to use solution supplied by Koppers Performance Chemicals (KPC). Copper and zinc are common tracers added to LOSP to enable penetration testing. Zinc tracers can be more difficult to detect than copper with typical indicator sprays, therefore copper naphthenate was selected. Copper naphthenate was added at 0.5% to the LOSP solution.

Results: LOSP treated samples recorded very low uptakes, with seasoned samples recording

Table 6. LOSP uptakes for seasoned and GOS shining gum

Uptake l/m³		
Seasoned	**GOS**	
14.5	22.8	
5.3	19.1	
7.5	26.2	
10.0	28.7	
13.6	36.3	
8.1	44.8	
9.3	20.8	
7.2	20.0	
7.9	17.0	
8.3	34.8	
10.3	15.8	
7.4	13.2	
5.5	14.4	
7.3	29.8	
10.8	21.9	
8.87	**24.37**	←Avg

Figure 14. Penetration images of LOSP treated shining gum (LHS seasoned), (RHS GOS). Photo: Stuart Meldrum.

an average uptake of 8.87 l/m^3 (Table 6). The typical targeted uptake when treating with LOSP for softwood is 35 – 40 l/m^3. Shining gum has a higher density than softwood so an uptake between 40 – 45 l/m^3 is theorised to meet the H3 requirement.

GOS samples recorded significantly higher uptakes (24.37 l/m^3) in comparison to seasoned samples. KPC did not provide the solution strength however to meet retention requirements a minimum uptake of 35 l/m^3 is required (based on a softwood comparison).

Penetration assessment on sample cross-sections demonstrated almost no visible penetration in LOSP-treated samples (Figure 14). These samples would not pass penetration or retention requirements outlined in AS 1604.

Benefits for industry?
If this process could be improved LOSPs would offer a treatment alternative that does not require a drying period for the timber after treatment. Given the known difficulties of drying certain *Eucalyptus* species without collapse or other distortions, this could be of great benefit to the industry. It would also potentially impart less colour than some of the waterborne chemicals (although most LOSP still leaves a slight greenish tinge to the wood). There is at least one local pine production company in Tasmania operating their own treatment cylinder

What still needs to be done?
Further research exploring different schedules and solution strengths might improve the performance of this treatment, so it should not be discredited. In addition, this treatment might work well with a rolling compression pre-treatment (described further in Trial 3.2 below).

Trial 2.3 Kop-Coat

Concept: Kop-Coat is a commercially available treatment that has been Codemark[3] certified for use with certain species of refractory Australian hardwoods (e.g. Victorian ash). If it can meet the Australian Standard requirements for H3 with Tasmanian hardwoods this has potential as a very simple, readily available and promising treatment option.

Aims: To test a commercially available preservative option that is already being used in Australia to treat refractory species of hardwood against the Australian Standard criteria.

Materials and methods: Sample sizes and species were the same as for Trial 2.1. Matched samples from the same parent boards used in Trials 2.1 and 2.2 were sent to I-Treat in Narangba, which is a commercial treatment facility. The Kop-Coat solution used for treatment was a tank blend solution of APVMA Approved Water Based Azole + permethrin with typical process chemicals and small amounts of a boron tracer. As Kop-Coat is a patented product no further details of the solution were provided. Following treatment, a subset of samples were sent to Agrisolutions, a GLP compliant testing lab in Brisbane, for preservative retention analysis courtesy of Kop-Coat (see Table 8).

Results: For the Kop-Coat samples, uptakes were known (Table 7). However, as there is no copper in the treatment it was impossible to visually assess the penetration results of the treatment using PAN or chrome azurol S indicator sprays. Theoretical retention was also unable to be calculated as the solution strength was unknown. Treated samples were penetration tested for boron using a boron reactive indicator spray (Figure 15) and showed a strong distribution of the boron tracer. Information provided by a Kop-Coat representative suggested the presence of the

Table 7. Kop-Coat uptakes for seasoned and GOS shining gum

Uptake L/m3		
Seasoned	**GOS**	
20.8	29.6 (4)	
22.7	23.9	
21.6	35.7	
27.4	38.7	
28.1 (1)	41.9 (5)	
19.7 (2)	46.9	
21.5	32.2	
23.0 (3)	27.1	
20.7	22.1	
20.3	32.2	
24.9	29.6	
27.1	22.0	
20.0	16.9	
7.3	40.7	
10.8	18.7 (6)	
18.73	**28.24**	**←Avg**

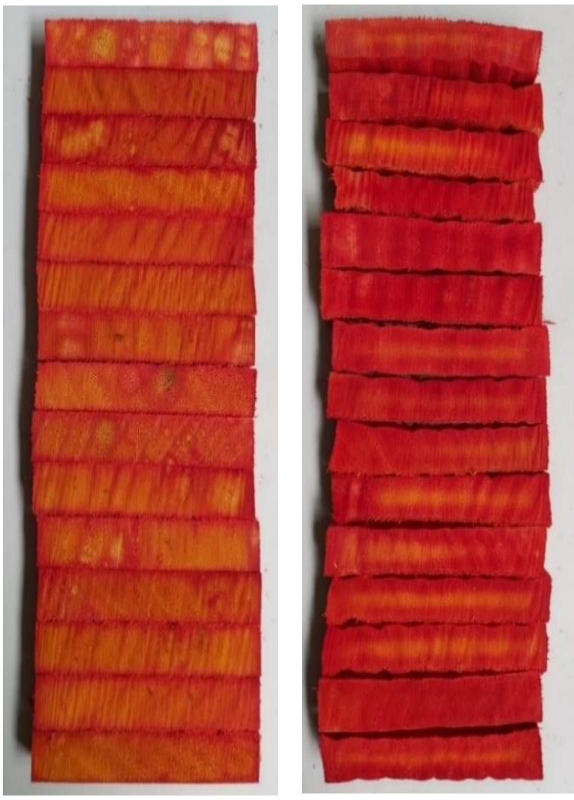


Figure 15. Penetration images of Kop-Coat treated shining gum (LHS seasoned; RHS GOS). Photo: Rhianna Robinson.

[3] To know more about Codemark certification you can read about it here: https://www.abcb.gov.au/about-codemark; or here: https://saiassurance.com.au/codemark-certification-scheme;

tracer relates to the preservative actives propiconazole, tebuconazole and permethrin.
The retention analysis showed that some GOS samples passed the required retention target as a % m/m per the requirements in AS 1604 for H3 (Table 8). Analytical results for Kop-Coat treated samples for seasoned and GOS samples is associated to the uptake of preservative. While these results are limited, there is potential for improved retention if uptake can be increased or if there is an increase in solution strength. GOS samples were highly distorted post treatment and despite promising results this distortion and collapse could make this option potentially unviable.

Table 8. Seasoned and GOS shining gum retention analysis Kop-Coat treatment: propiconazole, tebuconazole and permethrin.

Target retention: 0.08 % m/m) (*AS1604 H3 Hardwoods*)				
Sample type	0.030	0.030	0.020	Result
	PCZ	TBZ	Permethrin	
E nitens seasoned (1)	0.022	0.021	0.020	Fail
E nitens seasoned (2)	0.023	0.018	0.021	Fail
E nitens seasoned (3)	0.022	0.018	0.018	Fail
E nitens GOS (4)	0.031	0.032	0.021	Pass
E nitens GOS (5)	0.09	0.074	0.061	Pass
E nitens GOS (6)	0.029	0.028	0.022	Fail

Measurement uncertainty ±10%.
Highlighted cells indicate required retention against targeted %.

Benefits for industry?

This product has potential for industry as a simple and available treatment option with Codemark certification.

What still needs to be done?

Further research to improve the performance of this treatment option in Tasmanian hardwoods in terms of improving retention analysis and uptakes. Long term durability analysis in field trials (there are some already underway through the National Centre for Timber Durability and Design Life in QLD).

Trial 2.4 Veneer-based

Concept: To overcome the challenges of treating refractory *Eucalyptus* heartwood one option is to use thinner sawn dimensions or veneers as the feedstock for treatment. These can then be glued to create larger elements. While using thinner dimensioned boards or veneers does not alter wood permeability, it is more likely to result in a higher proportion of the timber element receiving acceptable amounts of preservative treatment.

Aims: The aim was to establish whether veneers or plywood could be treated successfully for use in H3 applications.

Materials and methods: A large, replicated trial was conducted at DAF using 300mm x 300mm Tasmanian oak veneers with spotted gum veneers for comparison. Veneers were either treated as single sheets and then glued to form a five lamella plywood, or glued into a five lamella ply and then treated as a whole timber element. A total of sixty samples were treated using the charge 1 + MCA + V combination (described in Trial 2.1 above). Samples were weighed before and after treatment to determine uptakes. Thirty untreated controls were included for the subsequent durability analysis.

Penetration assessments were completed on the biscuits (oven dried) using the preservative indicator PAN (1- (2-pyridylazo)-2-napthol) (Figure 17). Individual biscuits were evaluated for penetration using a grid analysis and assessed against penetration criteria outlined in AS 1604. Using the uptake results, sample density and solution strength, theoretical retention was able to be calculated for each sample. Whilst theoretical retention is different from calculated/analysed retention, it can be used as a predictive tool to scope the success of a treatment and aid in determining required solution strengths.

Results: This trial successfully developed a veneer-based H3 product for Tasmanian oak.

Tasmanian oak veneers recorded high uptakes averaging at 653.3 l/m3 (Figure 16, Table 9) and 15/15 penetration passes (Table 11). These samples also recorded an average theoretical retention of 0.423 % m/m (Table 9) and would pass the H3 penetration and retention requirements outlined in AS1604. Spotted gum veneers recorded relatively low uptakes averaging at 192.87 l/m3. Spotted gum average theoretical retention is 0.084 % m/m. These samples would pass the AS1604 requirement because they meet the natural durability requirements for H3.

Seasoned Tasmanian oak and spotted gum plywood samples were also treated with charge 1 + MCA + V. Tasmanian oak plywood recorded high uptakes averaging at 602.6 l/m3 (Figure 16, Table 10). These samples also recorded an average theoretical retention of 0.23 % m/m and half would pass the requirements outlined in AS 1604 (Table 10). Spotted gum plywood recorded uptakes averaging at 310.27 l/m3. Spotted gum average theoretical retention is 0.09 % m/m. These samples would pass the AS 1604 criteria because they meet the natural durability requirements for H3.

Veneer treated Tasmanian oak shows promise for commercial production as veneers treated with ease and with reliable retentions and penetrations that meet the requirements outlined in AS 1604. Veneers appeared to have successfully glued with a commercially available adhesive however it is recommended that bond quality assessments be performed before recommending this product.

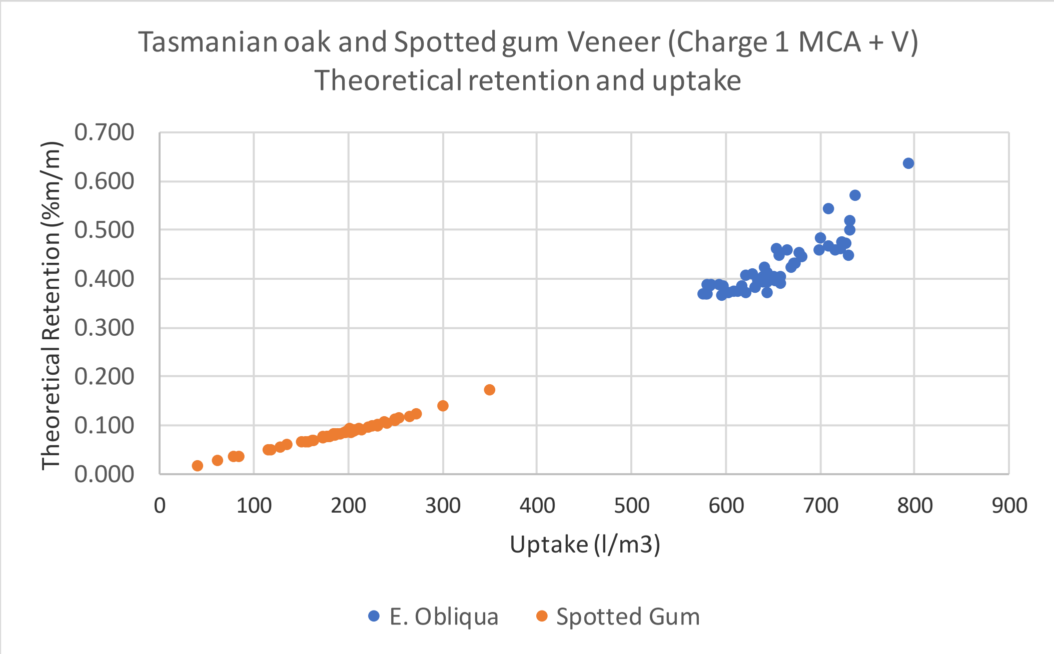


Figure 16. Veneer uptakes and theoretical retention following treatment with charge 1+MCA +V

Table 9. Tasmanian oak and spotted gum veneer average uptakes and theoretical retention				
Charge 1 + MCA + V. Retention % m/m as per the AS1604 requirement of 0.229% m/m H3 hardwood				
Tasmanian oak (55)		Veneer	Spotted gum (55)	
Uptake l/m3	Theoretical retention		Uptake l/m3	Theoretical retention
653.926	**0.423**	**← Avg→**	**192.866**	**0.084**
Highlighted cells indicate a pass against the relevant requirements outlined in AS 1604.				

Table 10. Tasmanian oak and spotted gum plywood average uptakes and theoretical retention				
Charge 1 + MCA + V. Retention % m/m as per the AS1604 requirement of 0.229% m/m H3 hardwood				
Tasmanian oak		Plywood	Spotted gum	
Uptake	Theoretical retention		Uptake	Theoretical retention
729.73	0.274		345.69	0.102
737.61	0.276		356.31	0.107
750.16	0.281		298.26	0.091
727.72	0.278		278.14	0.084
759.18	0.291		224.54	0.069
598.37	0.226		264.71	0.079
560.60	0.214		327.51	0.102
567.45	0.220		391.57	0.121
585.27	0.227		382.14	0.117
484.35	0.201		224.60	0.068
511.52	0.214		414.63	0.126
526.03	0.210		404.51	0.124
522.23	0.212		220.26	0.068
479.73	0.196		242.83	0.074
499.24	0.203		278.31	0.085
602.61	**0.23**	**←Avg→**	**310.27**	**0.09**
Highlighted cells indicate a pass against the relevant requirements outline in AS 1604.				

Table 11. Tasmanian oak and spotted gum veneer-based products penetration % Per criteria outlined in AS1604 for H3					
SPG – ply untreated control	SPG – plywood treated	SPG – veneer treated	Tas oak – ply untreated control	Tas oak - plywood treated	Tas oak – veneer treated
15/15 pass	15/15 pass	15/15 pass	0/15 pass	0/15 pass	15/15 pass

Figure 17. Penetration images of veneer-based samples following treatment with charge 1 + MCA + V spotted gum plywood; treated spotted gum plywood; veneer treated spotted gum; untreated Tasmanian oak plywood; treated Tasmanian oak plywood; and veneer treated shining gum. Photo: Rhianna Robinson.

Benefits for industry?

Veneer treated Tasmanian oak shows promise for commercial production as veneers treated with ease and with reliable retentions and penetrations that meet the requirements outlined in AS1604. Veneers appeared to have successfully glued with a commercially available adhesive.

What still needs to be done?

While this product meets the required retentions and penetrations, adhesive performance testing and bond quality assessments to relevant standards have not been explored. It is recommended that full size panels are manufactured, and NATA accredited bond quality assessments are performed to correctly classify how this product can be used. Additionally, exploring different adhesives fell outside the scope of this project. Work to investigate preservative, adjuvant and adhesive combinations on bond performance is recommended. This work was completed on Tasmanian oak, and the performance of shining gum remains unknown. It is recommended that this H3 trial is replicated on shining gum.

Trial 3 Pre-treatment with VPI (including 'best bet' trial)

Vacuum pressure impregnation (VPI) is an economically feasible and readily available preservative treatment option for softwoods in Australia and Tasmania. However, the results from Trial 2 demonstrated that despite marked improvements with the inclusion of additives and longer schedules, treatment of Tasmanian hardwoods using this method was unsuccessful, except in veneer-based products.

Trial 3 investigated the effectiveness of applying various pre-treatments to sawn boards, and combining this with subsequent VPI. Pre-treating timber essentially means modifying it in a physical way that will increase the uptake of preservative fluids in a VPI process. Three different pre-treatment methods were investigated: incision, microwaving, and compression.

Incision involves puncturing the surfaces of a timber element with lots of small holes, thus increasing the treatable surface area. Radial and tangential water movement in timber is significantly slower than longitudinal flow, so incising a board increases the preservative penetration depth (radially/tangentially) to just beyond the depth of the incision (Morrell and Winandy, 1987; Anderson et al., 1997; Chandler and Morrell, 1999). Preservative penetration around each incision is limited, however applying a high incision density treatment can create a uniform penetration that acts as an envelope or shell treatment around a potentially untreated core. The process is relatively simple, and this method is already used commercially in the USA and Australia primarily for treating softwood landscaping timbers. The main objection to using this method for something non-structural like cladding, is the appearance of the incisions, however there may be ways in which to overcome this drawback by employing newer technologies or good design (Wood et al., 2020).

Microwaving and compression both work by rupturing the internal structure of the timber, using force or high heat levels to generate micro-fine internal checking, which enables preservative fluids to flow more freely through the wood.

Microwaving has already been thoroughly trialled in a variety of timber species, including shining gum, through research that initially aimed to reduce drying times and drying-related collapse (Vinden, 1986; Torgovnikov and Vinden, 2000 a, b; Yang and Liu, 2018). In this pre-treatment approach, 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 which can significantly increase chemical uptake capacity during subsequent VPI treatment. The main drawbacks with this approach for cladding are that it can significantly change the appearance of the wood (Wood et al., 2020), the success of the process is highly sensitive to variability in the wood, particularly moisture content and density (Torgovnikov and Vinden, 2009), and the process is not yet commercially available.

Like microwaving, compression would normally be done on wet or unseasoned (green) timber, while the cell walls are still saturated to prevent structural deformation (Cech and Huffman, 1971; Sanders et al., 2000; Kumar, 2021) which is a drawback considering the complicated and invested nature of the hardwood timber drying process. Static compression is also limited by the potential associated set-up costs and the cost of slow production. However, if seasoned timber could be used instead of green, and a faster, industrial compression system were designed, this process would be an effective pre-treatment for VPI treatment of cladding materials.

The purpose of the 'best bet' trial was to trial the highest performing pre-treatment method in combination with the highest performing preservative, adjuvant and schedule. The treatment schedule, adjuvant, preservative and pre-treatment method were identified in previous replicated trials (Trial 2 above; and the affiliated NIFPI project, NT047/NIF108) and showed promise for improved uptake, penetration and theoretical retention. Additionally, thinner dimension samples were included in this trial, as a smaller cross section also showed promise for improving penetration. Finally matched samples of both shining gum and Tasmanian oak were treated with the Kop-Coat (water based azole + permethrin) system at I-treat, Narangba. Tasmanian oak veneers (both sliced and peeled) were included in the treatment charge for visual comparison and future durability assessments.

Research for Trial 3 was subcontracted to the Queensland Department of Agriculture and Fisheries and primarily conducted by researchers at the Salisbury Research Facility, with the blade incisions done at PSR Machining, laser incision outsourced to Verge Laser, and manufacture of the novel rolling compression system by local Queensland engineering and metal fabrication companies. Chemicals for the VPI treatment were provided by KPC, as in Trial 2.

Trial 3.1 Pre-treatment comparison trial

Trial 3.1.1 Incision

Concept: Incision is already used commercially in Australia to pre-treat certain timber landscaping materials, which are then VPI treated with a known preservative like copper-chromated-arsenic (CCA). Although this method is known to work with pine, questions remained around its potential effectiveness in Tasmanian hardwoods, and the effectiveness of using a lower toxicity chemical treatment suitable for cladding, was also unknown.

Aims: To establish the most efficient, effective, and aesthetic incision methods by investigating a range of suitable incision depths and spacing ratios, and to identify the optimal replication and treatments to pursue in the subsequent up-scaled trial. (Note: two commercial incision facilities were approached to incise the timber using their industrial equipment, but they were unable to accommodate the sample thicknesses being trialled in this research project on their industrial processing equipment)

Materials and methods: Five custom incision methods were trialled and compared using 300 mm x 100 mm x 19 mm seasoned and GOS shining gum boards. Methods included a blade incisor, a nail bed press plate, a spiked roller, a nail plate press, and the use of a laser. Samples were then treated using VPI charge 1 + MCA + adjuvant V following the methods established in Trial 2.1. The advantages and disadvantages of each incision method were tabulated, and the best performing systems (laser and nail bed press) were selected for the pre-treatment comparison VPI treatment (Trial 3.1.4).

Blade incisions were completed on a custom-built jig that can house up to 20 cutting knives (Figure 18). The blades were separated with spacers at approximately 1 mm apart. The jig fitted with the blades was mounted into a milling machine with an automated driving bed and the samples were incised as the bed moved. This system achieved a maximum 2 mm depth as the blades were prone to breakage. There are few machine designs capable of handling

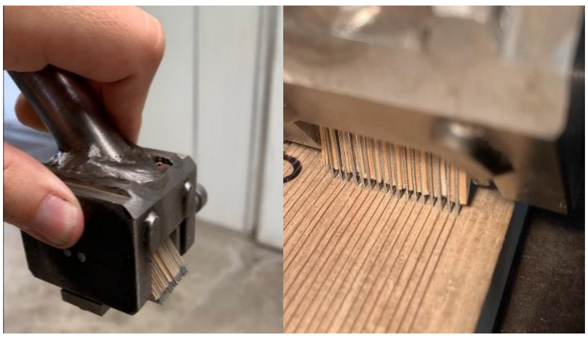


Figure 18. Blade incision set-up. Photo: Rhianna Robinson.

the dragging force and for this reason this incision method was not progressed into further trials.

The nail bed incisions were completed on a novel custom-built jig (Figure 19). The jig was designed to attach to a 10 ton Universal Testing machine (Shimadzu) where the depth and other parameters could be precisely monitored. The Shimadzu had the capacity to compress and withdraw the incision nails when the sample was stabilised. The system used concrete nails for their high stiffness properties and nails were arranged in a 10 mm square grid. The nails had a diameter of 2.5 mm and were pressed to a depth of 8 mm. This system was highly effective in achieving the intended incisions. Despite slight imperfections in appearance this method performed well during treatment and was selected to trial further. The nail bed square incision method was later modified to a 10 mm triangular pattern, and pursued in Trial 3.1.4.

Figure 19. Nail bed incision set-up. Photo: Rhianna Robinson.

Spiked roller incisions were performed using a rolling spiked wheel designed for perforating tyres in high performance racing (Figure 20). A number of methods and machinery were trialled to mount the roller however a custom-built piece of machinery with large hydraulic compressive force and an automatic driving bed would be required to automate this process. In this trial, the incisions were made manually whilst the samples were mounted in a frame. The spikes are positioned in a 6.5 mm square grid with a maximum depth of 4 mm. Whilst the incision density was desirable the depth of incision limited performance during treatment and for this reason this method was not selected to progress to further trials.

Figure 20. Spiked roller incision set-up. Photo: Rhianna Robinson.

Nail plate incisions were completed using a common nail plate (Multinail) attached to a novel jig (Figure 21). The jig and nail plate were pressed into the samples using a hydraulic press to a depth of 8 mm. The teeth were positioned in a pre-determined 10 mm triangular grid pattern. The nail plate and jig were then manually removed and the process was repeated along the length of the sample. This method was simple and effective for achieving incisions however the nail plate teeth become malleable after repeated incising and the plate needed to be

Figure 21. Nail plate incision set-up. Photo: Rhianna Robinson.

replaced frequently. Whilst it didn't occur, there was potential for fatigued 'teeth' to become embedded in the timber and for this reason the method was not selected to be progressed in further trials.

Finally, laser incisions were completed by Verge Laser, who specialise in laser engraving and cutting. The laser system used was a CO_2 laser. Two patterns of laser incising were trialled: a 10 mm square grid to a depth of 8 mm; and a 10 mm triangular grid to a depth of 8 mm (Figure 22). The square grid improved uptake and penetration but there were visible areas of untreated timber where there were no incisions present. The triangular grid staggered the incisions along the grain and a clear improvement in uptake and penetration was seen following treatment (Figures 23 and 24). A limitation of laser incising was the interaction between the laser and the variable properties of timber. A uniform depth was difficult to achieve based on the moisture content of the timber and the changes in density between the earlywood and latewood across the sample (up to 3-4 mm variation across the sample). Despite the cost and variation in depth, laser incising was the most visually attractive and performed well during initial VPI treatment tests (Figure 22), so it was chosen to progress in further trials.

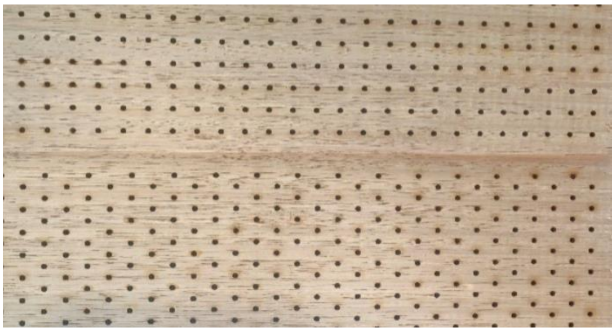


Figure 22. Laser incision patterns, square (top) and triangular (bottom). Photo: Rhianna Robinson.

Figure 23. Penetration images of laser incision patterns following treatment. Photo: Rhianna Robinson.

Figure 24. Penetration images of laser incision patterns following treatment. Photo: Rhianna Robinson.

Trial 3.1.2 Microwave

Concept: High intensity microwave energy can heat timber from the inside out, causing ray cells, vessels, and pit membranes to rupture, essentially causing micro-fine checking that increases pathways for fluid flow but does not drastically alter the appearance of the timber from the outside. This approach has already been trialled in other refractory species (Torgovnikov and Vinden, 2000 a, b; Torgovnikov and Vinden, 2009), although as noted above, primarily it was intended to help with drying the timber. Refining the approach for refractory *Eucalyptus* species in terms of the optimal timber moisture content, length of time to microwave, and intensity may result in improved permeability of the product without excessively damaging or changing its appearance.

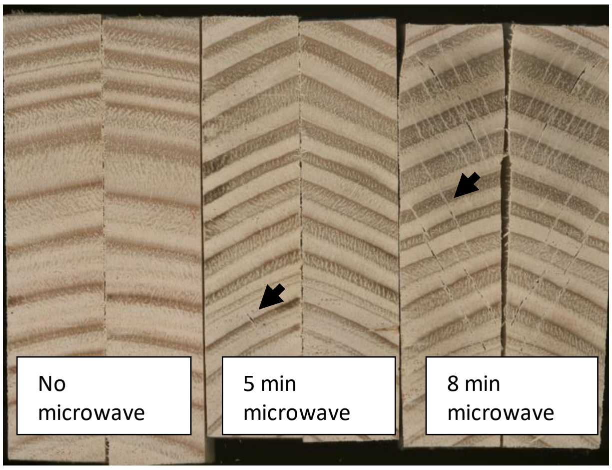


Figure 25. Internal checking in shining gum samples after different lengths of time under microwave. Photo: Rhianna Robinson.

Aims: To establish a method to investigate microwave pre-treatment of timber and how it might assist in increasing preservative penetration; and to assess the influence of the board temperature at the time of treatment on preservative uptakes.

Materials and methods: In preliminary work, matched seasoned and GOS shining gum samples were microwaved individually for either three, four, five, six, seven, and eight-minute durations (Figure 25) at varying power intensities. Samples were then cut in half to compare the amount of internal rupture, and five minutes with a medium power level was selected as the preferred amount of time. Subsequently, new samples were microwaved for five minutes in the time immediately preceding VPI treatment at a 'medium' power level. Matched microwaved samples were either kept in an oven at 100 ^{o}C (so that all samples entered the treatment cycle at the same temperature), microwaved then cooled to room temperature, or microwaved then immediately treated in comparison to non-microwaved unheated controls using VPI charge 1 + MCA + adjuvant V following the methods established in Trial 2.1.

Trial 3.1.3 Compression

Concept: Several researchers have investigated the potential of compressing wood to improve its permeability with promising results (Gunzerodt et al., 1986; Deng, 1990; Kumar, 2021). Kumar (2021) demonstrated significant improvements in southern pine preservative uptake as the static compression ratio increased and found that compression beyond 30% of the original dimensions caused rupturing and damage to the timber. However, the approach has not been commercialised yet, and its effectiveness on already seasoned Tasmanian hardwood is unknown. Static compression is unviable due to the significant force required to press large surface areas. The static compression approach also requires time to compress the timber which could make it unfeasible in industrial timber processing. A more efficient, rolling compression method with the potential to be applied to pre-existing systems used in industry would potentially improve the feasibility of this approach.

Aims: To investigate two forms of compression (static and rolling) and establish an appropriate method for seasoned Tasmanian hardwoods.

Materials and methods: Static compression (Figure 26) was completed using an accredited Shimadzu for both GOS and seasoned shining gum to a compression depth ratio of 28-30%. Static compression was applied at approximately 10 mm/min and held under full compression for 10 seconds (Figure 27). Samples were released slowly from compression. For a 300 mm x 100 mm x 19 mm sample length it took an average of 29 tons to compress the samples to a compression depth ratio of 30% of the original board. Static compressed samples were then treated using VPI charge 1 + MCA + adjuvant V following the methods established in Trial 2.1.

For the rolling compression, engineering and metal fabrication companies were consulted to construct a rolling compression system

Figure 26. Static compression tests. Photo: Rhianna Robinson.

Figure 27. Static compression set up. Photo: Rhianna Robinson.

Figure 28. Custom designed and built rolling compression set up. Photo: Rhianna Robinson.

Figure 29. Custom designed and built rolling compression set up. Photo: Rhianna Robinson.

that was designed and engineered by Rhianna Robinson for this project. The rolling compression system consisted of paired rollers with high dynamic load rated bushes that are pushed together via a dual hydraulic ram tension rig (Figures 28 and 29). The timber samples were pulled through using the traverse length of the tension rig system while the rollers remained stationary. After trialling and refining the methodology for compression rolling the matched samples were compressed at a rate of approx. 40 mm/min and then subsequently treated using VPI charge 1 + MCA + adjuvant V following the methods established in Trial 2.1.

3.1.4 Vacuum pressure impregnation of pre-treated boards

Aim: To compare the best performing pre-treatment methods with each other.

Materials and methods: Eight matched 300 mm x 100 mm x 19 mm samples were cut from fifteen boards of seasoned plantation shining gum (the same number of samples from GOS shining gum were also trialled, but the method and results are not presented here as they did not outperform seasoned material. After machining, all samples were end sealed then weighed and measured. The average moisture content of the samples was determined using the oven dry method from small samples cut from several parent boards. Samples were then pre-treated using the methods outlined above in trials 3.1.1 (nail bed incision and laser incision), 3.1.2 (microwaving) and 3.1.3 (static and rolling compression). Following pre-treatment, all pre-treated samples were included in a vacuum pressure treatment, using the commercial treatment methods described in Trial 2.1, charge 1 (the shortest treatment cycle) + MCA+ adjuvant V. Samples were weighed post treatment to determine uptakes, and a 20 mm biscuit was cut from the middle of each sample to evaluate penetration, and sprayed with PAN (1- (2-pyridylazo)-2-napthol) indicator (Figure 31). Individual biscuits were evaluated for penetration using a grid analysis and assessed against penetration criteria outlined in AS1604. Using the uptake results, sample density and solution strength, theoretical retention was able to be calculated for each sample. Whilst theoretical retention is different from calculated/analysed retention, it can be used as a predictive tool to scope the success of a treatment and aid in determining required solution strengths.

Table 12. Seasoned shining gum pre-treatment uptakes (l/m^3)

	Control 1	Control 2	Static Compression	Laser Incisions	Nail Plate Incisions	Microwaving	Rolling Compression	Control 3
1	324	282.1	449.5	301.6	300.8	361.7	249.6	241.2
2	293.5	233.9	393.3	257.3	345.1	409.1	387	229.8
3	147.8	139.3	227.2	202.8	205.5	219.7	322.5	117.6
4	156.5	157.8	294.4	202.6	212.1	107.2	239.2	124.1
5	326.8	277.8	423.1	331.7	317.4	472.6	360.4	223.1
6	96.5	90.3	113.8	119.5	139	103.4	211	71.8
7	143.7	139.6	297.9	162.7	164.6	125	236.9	114.8
8	135.3	118.7	167.4	133.9	121.1	196	228	122.1
9	156.8	106.8	205.6	124.2	257	217.4	228.1	112.6
10	119.5	66.8	227.4	108.1	152.1	87.9	229.5	112.7
11	431.3	373.2	566.7	436.2	416.5	443.6	443.4	294
12	164.7	161.8	161.5	195.8	188.7	252	246.4	134.7
13	116	95.1	157.7	139.9	148.5	138	369.5	213
14	162.5	136.5	351.2	198	206	123.1	322.2	159.7
15	218	197.3	273.3	214.3	225.8	156.4	272	160
Avg→	**199.5**	**171.8**	**287.3**	**208.6**	**226.7**	**227.5**	**289.7**	**162.1**

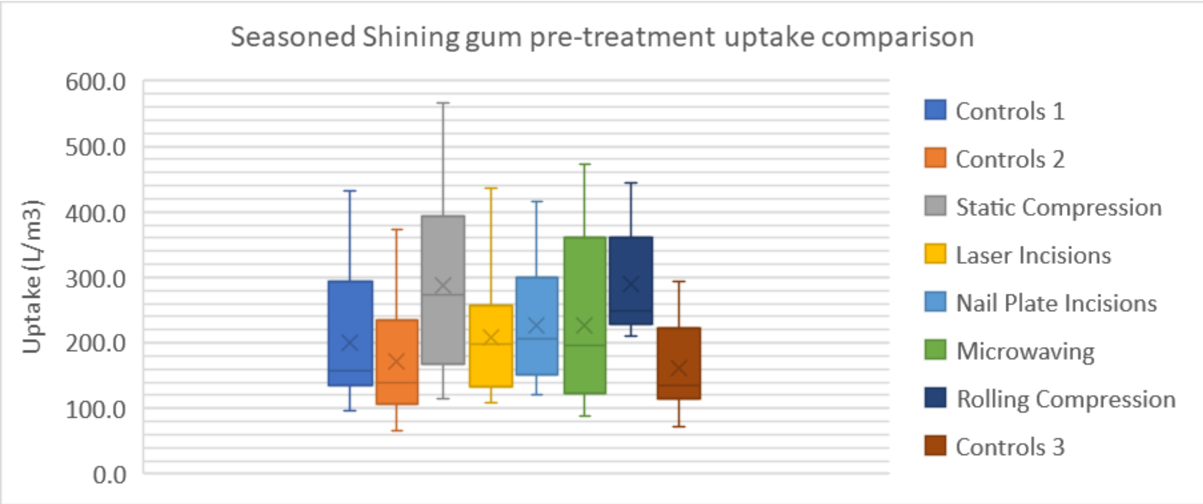


Figure 30. Comparative chart showing the range of uptakes for all pre-treatment options trialled.

Control 1 (no pre-treatment)	Control 2	Static Compression	Laser Incision	Nail Press Incision	Microwave	Rolling Compression	Control 3

Figure 31. Pre-treatment comparison penetration images for shining gum samples treated with charge 1 + MCA + V. Photo: Rhianna Robinson.

Table 13. Seasoned shining gum pre-treatment theoretical retention Min. 0.229% m/m as per the criteria outlined in AS1604 for H3 hardwood								
	Controls 1	Controls 2	Static Compression	Laser Incisions	Nail Plate Incisions	Microwaving	Rolling Compression	Controls 3
1	0.293	0.26	0.381	0.276	0.281	0.353	0.232	0.233
2	0.219	0.158	0.288	0.172	0.258	0.295	0.287	0.177
3	0.117	0.105	0.163	0.165	0.164	0.18	0.255	0.093
4	0.137	0.139	0.239	0.174	0.187	0.096	0.208	0.108
5	0.266	0.224	0.318	0.266	0.248	0.414	0.288	0.187
6	0.073	0.07	0.087	0.09	0.107	0.08	0.16	0.056
7	0.111	0.107	0.223	0.122	0.121	0.102	0.193	0.094
8	0.098	0.088	0.126	0.095	0.075	0.161	0.172	0.099
9	0.115	0.077	0.148	0.09	0.191	0.162	0.17	0.084
10	0.094	0.048	0.182	0.077	0.119	0.068	0.172	0.088
11	0.415	0.368	0.51	0.43	0.417	0.465	0.454	0.297
12	0.119	0.106	0.11	0.142	0.128	0.198	0.157	0.092
13	0.096	0.079	0.124	0.117	0.123	0.12	0.318	0.191
14	0.137	0.112	0.303	0.167	0.177	0.11	0.281	0.142
15	0.163	0.15	0.196	0.162	0.168	0.125	0.21	0.124
Avg→	**0.164**	**0.139**	**0.227**	**0.17**	**0.184**	**0.195**	**0.237**	**0.138**
	3 pass	**2 pass**	**6 pass**	**3 pass**	**4 pass**	**4 pass**	**7 pass**	**2 pass**
Highlighted cells indicate a pass against the requirements outlined in AS 1604.								

Table 14. Seasoned shining gum pre-treatment penetration % Per criteria outlined in AS1604 for H3 hardwood								
	Controls 1	Controls 2	Static Compression	Laser Incisions	Nail Plate Incisions	Microwaving	Rolling Compression	Controls 3
1	79	77	86	70	71	70	86	72
2	89	74	88	73	77	84	87	61
3	17	23	60	35	26	18	74	23
4	25	32	64	43	37	11	61	30
5	89	82	46	88	78	88	90	82
6	6	0	4	11	12	13	37	8
7	35	16	62	30	30	15	50	10
8	24	20	43	7	23	37	43	28
9	42	12	37	21	74	54	66	29
10	7	2	34	9	14	9	60	12
11	95	90	97	100	75	81	92	82
12	27	41	38	26	25	45	74	49
13	10	5	23	18	14	17	85	61
14	32	36	68	41	32	12	74	61
15	55	47	47	33	39	23	47	65
Avg→	**42.13**	**37.13**	**53.13**	**40.33**	**41.8**	**38.47**	**68.4**	**44.87**
	0 pass	**0 pass**	**1 pass**	**1 pass**	**0 pass**	**1 pass**	**3 pass**	**0 pass**

Results (incision): In the preliminary trial to establish effectiveness, 10 mm deep triangular pattern laser incised boards showed extremely promising uptake and penetration results following treatment (Figures 23 and 24), but the second trial was less convincing (Figures 30 and 31), which speaks to the potential sensitivity of the laser incision process to moisture content and density variations in the timber. The incisions were shallower and more variable in the second treatment, approx. 5-8 mm, which means that returning to a deeper incision depth could see improved performance like the results from the first iteration. A limitation of laser incising is the interaction between the laser and the variable properties of timber. A uniform depth is difficult to achieve based on the moisture content of the timber and the changes in density between the earlywood and latewood across the sample (up to 3-4 mm variation across the sample). Although laser incision was still a high performer in terms of uptakes, theoretical retention and penetration (Tables 12, 13 and 14), it was not selected for the 'best bet' trial because of the cost of the process. GOS samples recorded significantly lower uptakes and retention rates, and were too distorted after drying to be assessed for penetration, so they weren't pursued in the 'best bet' trial either.

Results (microwave): Performance improvements were seen in uptake and theoretical retention (Tables 12 and 13) however a large range was observed between the samples (Figure 30). Penetration samples showed treated areas or pockets immediately adjacent to untreated zones irrespective of earlywood and latewood bands. This is likely due to the moisture gradients within the timber that respond unpredictably when microwaved. Preliminary results indicated that the temperature and moisture loss was a greater contributor to preservative uptake than just microwaving.

Results (compression): As a pre-treatment option, static and rolling compression recorded the highest uptakes for seasoned shining gum with averages of 287.3 l/m^3 and 289.7 l/m^3 respectively (Table 12). This was an improvement of approximately 110 l/m^3 in comparison to controls. Theoretical retention was calculated for each sample and assessed against the % m/m requirement outlined in AS1604. Static compression and rolling compression had 7/15 pass theoretical retention (Table 13). The average theoretical retention for static compression and rolling compression are 0.227 and 0.237 respectively in comparison to controls (1,2, and 3) (0.164, 0.139 and 0.138 respectively). Despite relatively low penetration passes (Table 14) large increases in percentage penetration were observed when compared with controls (Table 14 and Figure 30), even though the shortest treatment charge was used for the VPI treatment. As noted in previous trials (Trial 2, and in the affiliated NIFPI project, NT047/NIF108) longer charges result in better uptakes, so with a longer charge the uptakes would likely improve considerably. Additionally, compressed penetration samples showed improved latewood treatment in comparison to controls and earlier treatments (Figure 31). Therefore, this is the pre-treatment method that was selected to progress to the 'best bet' trial (Trial 3.2).

Benefits for industry?
Incision is possibly one of the most commercially feasible pre-treatment approaches for wall claddings, because it is an approach that is already well understood and used in industrial settings. But getting the incision patterns to appear more uniform, designerly or intentional, for example by using lasers, proved costly even in the initial trial research and development. The benefits at this stage are knowing that particularly in the preliminary work, laser incised material (with a 10 mm incision depth) treated well, and with some refinement, it has definite potential as a dual treatment strategy for refractory timber.

The use of microwaving to dry refractory timber species has been well documented and although the method can be effective it has yet to be taken up by any commercial operators. Exploring the potential use of microwaving to improve preservative uptake is another step towards understanding the potential advantages of the microwaving process, but it appears to suffer from the same sensitivity to variability in the wood that makes it one of the less robust potential treatment options.

Static compression is currently commercially unviable due to the slow nature of the process and specialised equipment that is required to meet the significant loads. Rolling compression shows promise as a process that could be adopted into industrial production systems.

What still needs to be done?
Although this research may not be of immediate interest to industry, a longer-term more specific incision-focussed pre-treatment project that focuses on improving the design aesthetic, for example by increasing or changing the hole sizes or simplifying the incision process and equipment, has great potential.

If microwaving pre-treatment were to be pursued further, exploring mid to low range energy intensity levels for rupturing the wood without causing visible degradation would be of interest.

Further schedule refinement could improve penetration and retention in compressed boards. (This method was selected to investigate further as part of the ‘best bet’ trial).

Trial 3.2 'Best bet'

Concept: The 'best bet' trial combined the best performing chemicals and pre-treatment approaches with the best performing VPI charge as identified in the iterative replicated trials.

Aims: To see if a significant or successful H3 treatment for cladding could be achieved in shining gum and Tasmanian oak sawn boards by adopting the best performing approaches from all the VPI treatment trials.

Materials and methods: The trial included matched samples from fifteen parent boards each of seasoned shining gum and Tasmanian oak. Each board was cut to obtain two thinner dimensioned samples (5 mm thick), two controls (non-compressed), one rolling compression sample, and a sample for Kop-Coat treatment (Figure 32). Two 150 mm offcuts from each parent board were also cut from the same board and used to determine initial moisture content via the oven dry method. Each allocated treatment changed location on the parent board to avoid any potential influences of position. 200 mm from both ends of each board was trimmed and discarded to avoid any potential influence on treatment.

Offcut 1	P1	P2	P3	P4	P5	Offcut 2
MC%	Control 1	Rolling Compression	Thin (2 x 5 mm)	Kop-Coat	Control 2	MC%
150 mm	500 mm	800 mm	500 mm	500 mm	500 mm	150 mm
Final Dimensions	500 x 100 x 19	500 x 100 x 19	500 x 100 x 5 500 x 100 x 5	500 x 100 x 19	500 x 100 x 19	

Figure 32. Parent board cutting pattern for 'best bet' trial.

Samples were end sealed, weighed and labelled, then (except the Kop-Coat samples) subjected to a VPI process based on charge 3 + MCA + adjuvant V (see Trial 2.1). Samples were weighed post treatment and a penetration 'biscuit' (20 mm full cross section) was cut from the centre of each sample after air drying. Penetration assessments were completed on the biscuits (oven dried) using the preservative indicator PAN (1- (2-pyridylazo)-2-napthol) (Figures 35 and 36). Individual biscuits were evaluated for penetration using a grid analysis and assessed against penetration criteria outlined in AS 1604. Using the uptake results, sample density and solution strength, theoretical retention was able to be calculated for each sample. A subset of representative matched samples (boards 4 and 11) was assessed for preservative retention by an independent laboratory against requirements outlined in AS 1604. For the retention analysis two additional 'biscuits' were cut (20 mm full cross section) for each sample adjacent to the penetration sample to assess preservative retention in the penetration zone of the full cross section and in the inner 1/9th.

A final 'best bet' treatment was also done using the Kop-Coat treatment and method at I-treat, Narangba. For the Kop-Coat treatment evaluation, similar to trial 2.3, treated samples were penetration tested for boron using a boron indicator spray, and retention analysis performed by an independent laboratory on selected boards.

Results: This trial successfully developed an H3 sawn board product for shining gum and Tasmanian oak.

Rolling compression combined with charge 3 + MCA + adjuvant V significantly improved uptakes for both shining gum and Tasmanian oak (Figures 33 and 34). Penetration was also visibly improved with 14/15 shining gum and 15/15 Tasmanian oak samples meeting the requirements of AS 1604.1:2021 (Tables 15 and 16, Figures 35 and 36). In addition, 14/15 shining gum and 15/15 Tasmanian oak samples passed the theoretical retention evaluation (Tables 17 and 18).

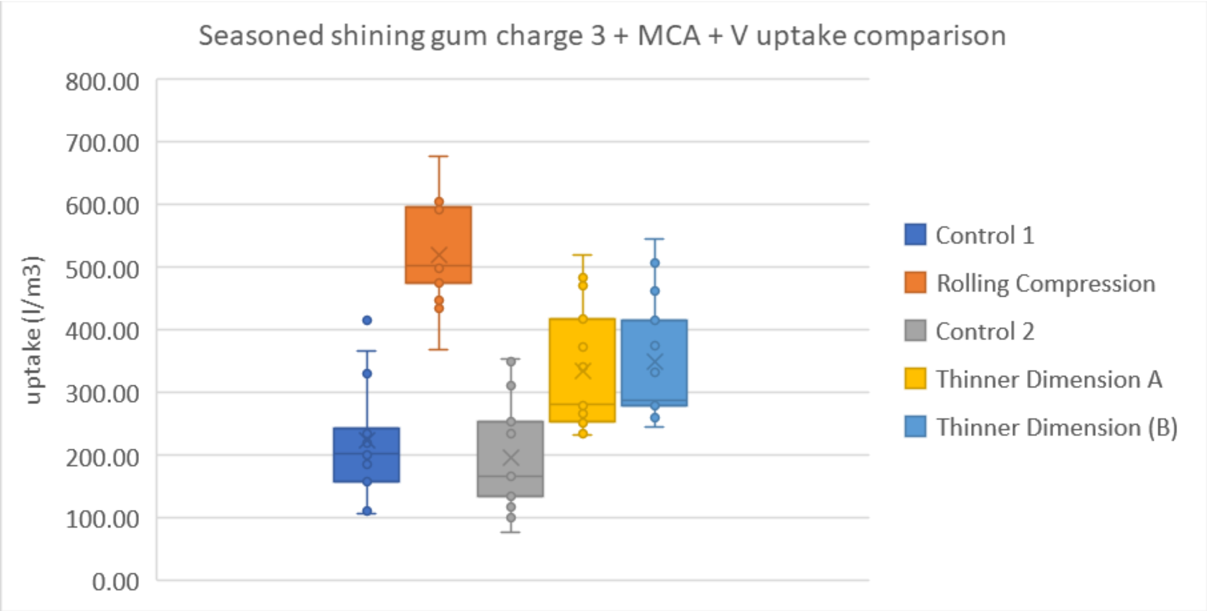


Figure 33. Uptake comparison for all shining gum 'best bet' samples treated using charge 3 + MCA + V.

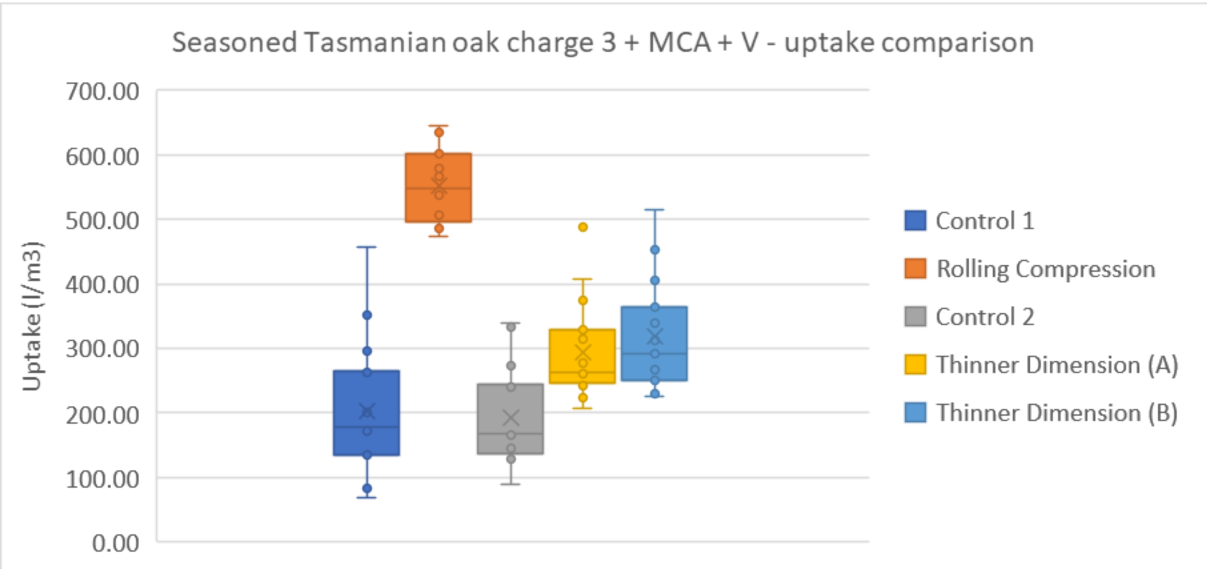


Figure 34. Uptake comparison for all Tasmanian oak 'best bet' samples treated using charge 3 + MCA + V.

Control 1	Rolling Compression	Control 2	Thinner Dimension A	Thinner Dimension (B)

Figure 35. 'Best bet' trial comparison penetration images for shining gum samples treated with charge 3 + MCA + V. Photo: Rhianna Robinson.

Control 1	Rolling Compression	Control 2	Thinner Dimension A	Thinner Dimension (B)

Figure 36. 'Best bet' trial comparison penetration images for Tasmanian oak samples treated with charge 3 + MCA + V. Photo: Rhianna Robinson.

Table 15. Seasoned shining gum 'best bet' trial penetration percentage Per criteria outlined in AS1604 for H3 hardwood					
	Control 1	Rolling Compression	Control 2	Thinner Dimension A	Thinner Dimension (B)
1	28.2	90	23.4	86.3	90.9
2	46.4	85	27	83.8	80.3
3	4.6	91.2	24.4	83.3	87.8
4	15.1	98.1	0	84.8	87.8
5	68.1	95	70.3	96.9	95.5
6	4.3	99.5	45.8	96.9	98.5
7	90	98.9	80.2	100	100
8	20.3	86.4	38.5	77.2	89.4
9	5.5	82	2.5	97	96.9
10	43.9	96	53.1	78.7	71.2
11	20.3	86	10.1	98.5	93.9
12	67.6	97	75.7	100	93.9
13	27	83.7	13	74.2	81.8
14	8.9	96.3	3.1	83.8	72.7
15	88	100	80.2	98.4	100
Avg→	**35.88**	**92.34**	**36.49**	**89.32**	**89.37**
	1 pass	**14 pass**	**0 pass**	**6 pass**	**6 pass**

Table 16. Seasoned Tasmanian oak 'best bet' trial penetration percentage Per criteria outlined in AS1604 for H3 hardwood					
	Control 1	Rolling Compression	Control 2	Thinner Dimension A	Thinner Dimension (B)
1	6	99.4	80	69.1	69.6
2	56.5	98.4	92.7	95.5	97
3	87.3	100	93.7	100	100
4	27.2	96.8	11.9	72	71.2
5	32.3	98.5	37.5	80	84.8
6	17.6	98.9	15.6	91.2	80.8
7	77.8	100	88	100	100
8	2	98.9	59.3	77.9	80.3
9	2.6	90.4	15.6	94.1	92.6
10	81.3	100	91.6	100	100
11	2.5	99.4	22.9	84.8	100
12	0	98.9	0	79.4	97
13	81.3	98.9	48.9	94.1	95.4
14	14.1	95.9	22.9	63.6	83.8
15	26.2	99.4	37.5	59	81.8
Avg→	**34.31**	**98.25**	**47.87**	**84.05**	**88.95**
	0 pass	**15 pass**	**0 pass**	**4 pass**	**6 pass**

Table 17. Seasoned shining gum 'best bet' trial theoretical retention (Target 0.229% m/m per AS1604 H3 hardwood)					
	Control 1	Rolling Compression	Control 2	Thinner Dimension A	Thinner Dimension (B)
1	0.195	0.360	0.108	0.212	0.202
2	0.181	0.324	0.124	0.209	0.205
3	0.087	0.330	0.102	0.198	0.214
4	0.181	0.400	0.088	0.205	0.217
5	0.298	0.413	0.248	0.394	0.346
6	0.161	0.440	0.204	0.340	0.332
7	0.333	0.428	0.281	0.394	0.404
8	0.147	0.303	0.139	0.216	0.200
9	0.064	0.207	0.043	0.239	0.272
10	0.147	0.308	0.173	0.167	0.195
11	0.121	0.309	0.130	0.274	0.252
12	0.163	0.307	0.196	0.285	0.319
13	0.152	0.341	0.120	0.190	0.223
14	0.127	0.365	0.088	0.213	0.198
15	0.407	0.430	0.246	0.386	0.267
Avg→	**0.184**	**0.351**	**0.153**	**0.261**	**0.256**
	3 pass	**14 pass**	**3 pass**	**7 pass**	**7 pass**
Highlighted cells indicate a pass against the requirements outlined in AS 1604.					

Table 18. Seasoned Tasmanian oak 'best bet' trial theoretical retention (Target 0.229% m/m per AS1604 H3 hardwood)					
	Control 1	Rolling Compression	Control 2	Thinner Dimension A	Thinner Dimension (B)
1	0.063	0.355	0.093	0.147	0.158
2	0.172	0.297	0.158	0.205	0.231
3	0.164	0.273	0.153	0.270	0.266
4	0.134	0.326	0.099	0.188	0.199
5	0.167	0.399	0.143	0.219	0.205
6	0.138	0.408	0.105	0.218	0.188
7	0.216	0.409	0.276	0.383	0.387
8	0.090	0.297	0.081	0.158	0.150
9	0.043	0.269	0.055	0.125	0.171
10	0.247	0.344	0.225	0.257	0.267
11	0.068	0.415	0.134	0.236	0.254
12	0.091	0.303	0.081	0.164	0.182
13	0.357	0.402	0.203	0.252	0.284
14	0.085	0.264	0.109	0.160	0.177
15	0.155	0.430	0.137	0.219	0.284
Avg→	**0.146**	**0.346**	**0.137**	**0.213**	**0.226**
	2 pass	**15 pass**	**1 pass**	**5 pass**	**7 pass**
Highlighted cells indicate a pass against the requirements outlined in AS 1604.					

Table 19. Seasoned shining gum 'best bet' trial analysed retention Target Retention (T_R) Level 0.229% m/m per AS1604.1 and AS1604.2 H3 Hardwoods						
Species	Sample	Board	Allocation	CuAZ	Result > T_R	Result >0.66 x T_R
Shining gum	Full Section	4	Thinner Dimension	0.082	Fail	No
Shining gum	Full Section	4	Control 1	0.05	Fail	No
Shining gum	Inner 1/9th	4	Control 1	0.028	Fail	No
Shining gum	Full Section	4	Rolling compression	0.221	Fail	Yes
Shining gum	Inner 1/9th	4	Rolling compression	0.235	Pass	Yes
Shining gum	Full Section	11	Thinner Dimension	0.132	Fail	No
Shining gum	Full Section	11	Control 1	0.062	Fail	No
Shining gum	Inner 1/9th	11	Control 1	0.042	Fail	No
Shining gum	Full Section	11	Rolling compression	0.188	Fail	Yes
Shining gum	Inner 1/9th	11	Rolling compression	0.19	Fail	Yes
Highlighted cells indicate a nominal pass against the requirements outlined in AS 1604.2, however sample sizes were too small to be truly representative or verified (a minimum of ten is required and only two were tested)						

Table 20. Seasoned Tasmanian oak 'best bet' trial analysed retention Target Retention (T_R) Level 0.229% m/m per AS1604.1 and AS1604.2 H3 Hardwoods						
Species	Sample	Board	Allocation	CuAZ	Result > T_R	Result >0.66 x T_R
Tas Oak	Full Section	4	Thinner Dimension	0.104	Fail	No
Tas Oak	Full Section	4	Control 1	0.052	Fail	No
Tas Oak	Inner 1/9th	4	Control 1	0.031	Fail	No
Tas Oak	Full Section	4	Rolling compression	0.192	Fail	Yes
Tas Oak	Inner 1/9th	4	Rolling compression	0.21	Fail	Yes
Tas Oak	Full Section	11	Thinner Dimension	0.107	Fail	No
Tas Oak	Full Section	11	Control 1	0.014	Fail	No
Tas Oak	Inner 1/9th	11	Control 1	0.038	Fail	No
Tas Oak	Full Section	11	Rolling compression	0.248	Pass	Yes
Tas Oak	Inner 1/9th	11	Rolling compression	0.211	Fail	Yes
Highlighted cells indicate a nominal pass against the requirements outlined in AS 1604.2, however sample sizes were too small to be truly representative or verified (a minimum of ten is required and only two were tested)						

For shining gum, two boards that were analysed for copper azole concentration/retention showed that one sample (inner 1/9th) of rolling compression met the AS1604 requirements of CuAz retention for H3 exposures, recording 0.235 % m/m (Table 19). Other rolling compression samples (both inner 1/9th and full cross sections) demonstrated retentions of 0.188 - 0.221 % m/m which is more than 66 % of the target retention. The number of samples used in this analysis was too small to draw any conclusions from this. In Tasmanian oak, one rolling compression sample (full section) met the requirements of CuAz retention recording 0.248 % m/m (Table 20). Other rolling compression samples (both inner 1/9th and full cross sections) demonstrated retentions of 0.192 - 0.2111 % m/m which is more than 66 % of the target retention. Again, the number of samples used in this analysis was too small to draw any conclusions from this. Retention analysis with a greater number of samples would help to strengthen these results.

Altering concentration strength fell outside the scope of the project as the primary aim was to improve penetration performance. If the solution strength was increased from 0.45 % to 0.6% all samples would confidently meet the retention requirements (calculated using analysed retention results), however, with an increase to 0.6 % solution strength to ensure that all samples meet the required retention targets as an H3 product there would also be a preservative cost increase.

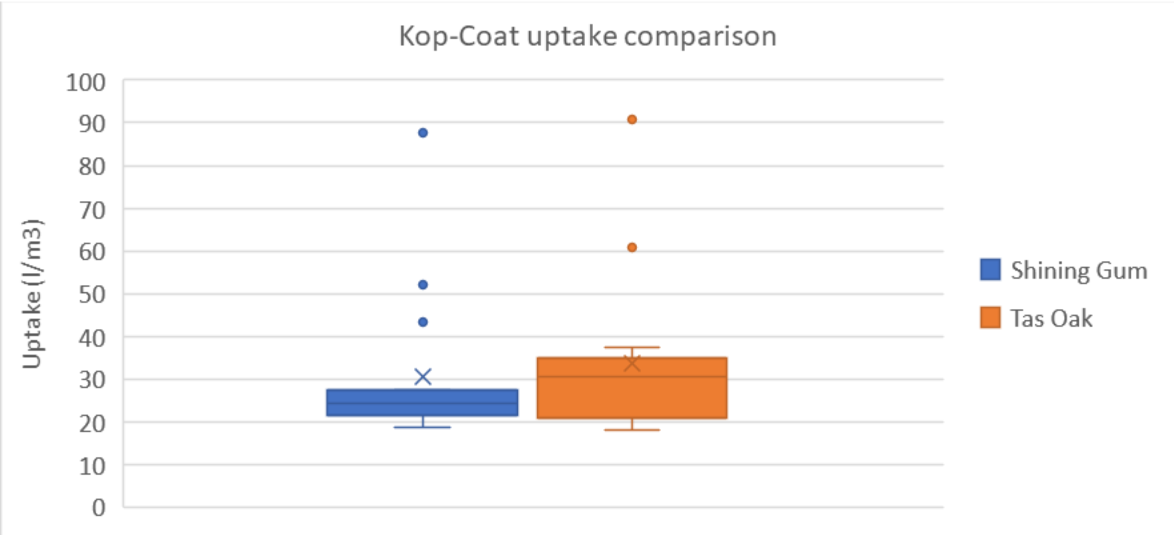
Shining gum thinner dimensioned samples did not perform as well as rolling compression samples, recording a combined average uptake of 342.31 l/m^3, which was higher than the controls which recorded an average uptake of 210 l/m^3. Thinner dimensions improved the average theoretical retention with 7/15 samples meeting the retention requirements in both treatment groups, however no samples passed the analysed retention requirements for CuAz. Similarly, Tasmanian oak thinner dimensioned samples recorded an average uptake of 306.87 l/m^3, and again this was higher than the uptakes in the controls, which averaged 196.0 l/m^3. Thinner dimensions improved the average theoretical retention, with 7/15 samples meeting the retention requirements when averaged across the two treatment groups. No samples passed the analysed CuAz retention requirement of 0.23% m/m for hardwood.

Figure 37. Penetration images for Kop-Coat 'best bet' trial samples sprayed with boron-reactive indicator spray (RHS shining gum; LHS Tasmanian oak). Photo: Rhianna Robinson.

For the Kop-Coat samples, uptakes were known (Figure 38), but as there is no copper in the treatment it was impossible to visually assess the penetration results of the treatment using PAN or chrome azurol S indicator sprays. Treated samples were penetration tested for boron using a boron reactive indicator spray (Figure 37) and showed a reasonable distribution of the boron tracer. Information provided by a Kop-Coat representative suggested the presence of the tracer relates to the preservative actives propiconazole, tebuconazole and permethrin.

Theoretical retention was also unable to be calculated due to the unknown solution strength of Kop-Coat. A subset of matched samples was analysed for propiconazole, tebuconazole and permethrin concentrations. Two Tasmanian oak samples (full cross sections only) met the requirements for retention however the paired and matched inner 1/9th did not meet the required retention (Table 21). Tasmanian oak samples recorded higher retention in comparison to shining gum. The full cross sections had consistently higher retentions than their paired and matched inner 1/9th counterparts indicating a gradient in retention from the outside of the board to the core (Figure 39). Other Kop-Coat Tasmanian oak samples ranged from 0.067-0.111% m/m with most samples achieving 66 % of the target retention. As noted for the shining gum and Tasmanian oak rolling compression treated material, the number of samples analysed was too small to be able to provide a verified result.

Table 21. Seasoned shining gum and Tasmanian oak 'best bet Kop-Coat analysed retention								
Target retention (T_R) total: 0.08 % m/m per *AS1604 H3 Hardwoods*				0.03	0.03	0.02	Result > T_R	Result >0.66 x T_R
Species	Sample	Board	Allocation	PCZ	TBZ	Permethrin		
Nitens	Full Section	4	Kop-Coat	0.019	0.02	0.016	Fail	Yes
Nitens	Inner 1/9th	4	Kop-Coat	0.015	0.016	0.012	Fail	No
Nitens	Full Section	11	Kop-Coat	0.028	0.032	0.025	Fail	Yes
Nitens	Inner 1/9th	11	Kop-Coat	0.02	0.022	0.016	Fail	Yes
Tas Oak	Full Section	4	Kop-Coat	0.033	0.037	0.029	Pass	Yes
Tas Oak	Inner 1/9th	4	Kop-Coat	0.023	0.025	0.019	Fail	Yes
Tas Oak	Full Section	11	Kop-Coat	0.036	0.041	0.034	Pass	Yes
Tas Oak	Inner 1/9th	11	Kop-Coat	0.026	0.029	0.023	Fail	Yes
Measurement uncertainty ±10%. Highlighted cells indicate a nominal pass against the requirements outlined in AS 1604.2, however sample sizes were too small to be truly representative (a minimum of ten is required and only two were tested for each species)								



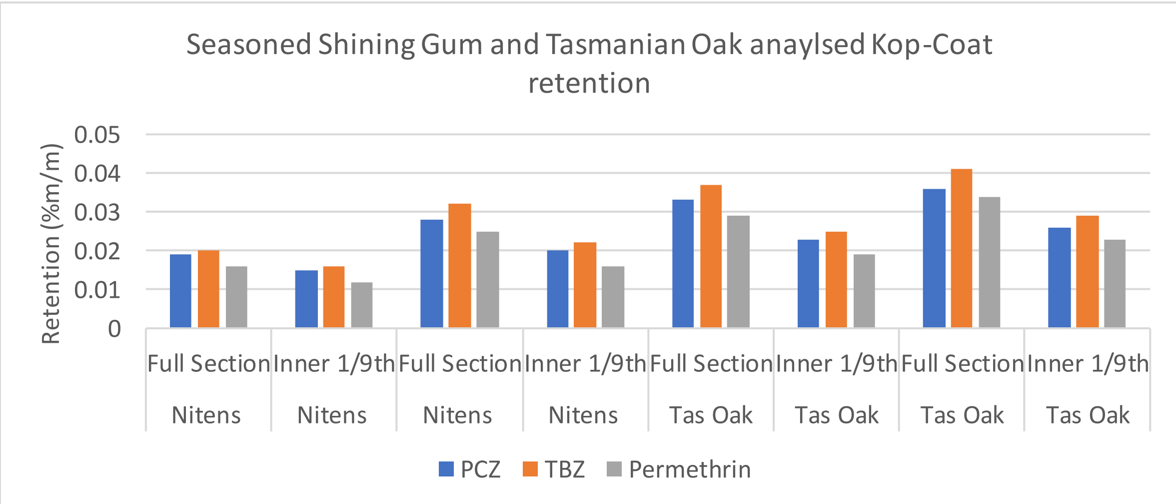


Figure 38 (top) and Figure 39 (bottom). Kop-Coat 'best bet' trial uptakes (top) and analysed retention (bottom).

The shining gum samples full section and inner 1/9th were all below the required amount. Retention analysis with a greater number of samples is recommended to provide a verifiable result. Proportions of propiconazole, tebuconazole and permethrin were highly consistent across all analysed samples so an increase in either solution strength or uptakes would likely see increased retention passes.

Benefits for industry?
The penetration, uptake and theoretical retention results from the rolling compression pre-treatment combined with VPI charge 3 + MCA + adjuvant V are exceptional and provide a significant step towards making H3 treatment a commercial option for refractory *Eucalyptus* species. Kop-Coat treatment also shows promise for shining gum and Tasmanian oak if retentions can be increased.

What still needs to be done?
While the results from the rolling compression pre-treatment with VPI charge 3 + MCA + adjuvant V are significant and show the most promise out of all the treatments trialled in this project, there is still a lot of research and development work that needs to be completed before this method can become a commercial reality. A cost-benefit analysis and further research and development on the design and engineering of the rolling compression system is needed to improve its suitability for an industrial process. In rolling compression pre-treated samples, analysed retention recorded concentrations slightly below the required levels, with the lowest concentration meeting 82% of requirements. Analysing a greater number of samples would help determine whether this treatment could nevertheless meet the requirements for a conditionally verified pass within a batch. Altering concentration strength fell outside the scope of the project, however if the solution strength was increased from 0.45 % to 0.6% all samples would confidently meet the retention requirements (calculated using analysed retention results). Trialling an increase to 0.6 % solution would likely see shining gum samples meeting all targets as a H3 product, but a feasibility study on this is recommended. Retention analysis on a larger number of samples is needed. Further work on the effect of the rupturing process on the mechanical properties of the wood should also be undertaken.

Trial 4 Non-chemical

Densification has been used since the early 1900s to make various low-density wood species stronger, harder and more resistant to surface abrasion, and thus more attractive as furniture or flooring material. In some cases, it has had the added benefit of also making the wood more resistant to fungal attack. It might also improve timber's fire performance as higher density species are associated with improved resistance (AS 3959:2018). Some abundant Tasmanian hardwoods, like plantation shining gum, have a relatively low-density profile when compared with other hardwoods, and increasing their density could open new market opportunities.

During the densification process, wood is softened and compressed, resulting in densification without fracturing the cell walls. Compression takes place in a hot press between 120 to 180 °C by carefully controlling the pressing conditions (Rautkari *et al.,* 2011). The moisture in cell walls induces a mechano-sorptive effect and further softens the wood, enabling mechanical compression of wood without cell wall fracture (Bao *et al.,* 2017). The degree of cell wall plasticization during compression is a key factor because, if adequately plasticized, wood cells can be compressed without fractures as they deform instead of breaking when buckled. For this reason, the compression step is mainly performed at temperatures exceeding the glass transition temperature (Tg) of wood constituents and reaching temperatures at which these constituents decompose (Navi and Sandberg, 2011).

If the deformations during the densification process are large, the result is the viscous buckling of cell walls without major fracture taking place and the strength and stiffness of the wood material are increased approximately in proportion to the increase in density (Kutnar *et al.,* 2008). The heat treatment can also improve resistance to decay (Huang *et al.,* 2012), decrease hygroscopicity (Metsa-Kortelainen *et al.,* 2006; Kariz *et al.*, 2017), and improve dimensional stability (Esteves *et al.,* 2007; Kariz *et al.,* 2017).

The main challenge associated with this type of densification is the fixation of the compressive deformation when the densified wood is exposed to moisture. Studies found that wood with the highest degree of compression shows the highest potential for compression deformation recovery or set-recovery (Blomberg *et al.,* 2006; Kutnar *et al.,* 2009). The set-recovery or thickness swelling effect occurs because internal stresses introduced during compression are relieved when the wood is exposed to moisture. Several approaches to fixing set-recovery of densified wood are viable, including impregnation with a synthetic resin, mechanical fixation, or thermo-hydro-mechanical (THM) treatments at high temperature and moisture (Navi and Heger, 2004). Another challenge is spring back, or immediate set-recovery following the release of pressure or load in the press. Higher temperature enables relaxation of the inner stress and even minor thermal degradation of the cell wall components takes place, leading to a more stable state after compression (Laine *et al.,* 2014). By contrast, with lower temperatures, there is very little stress relaxation, and thus, the deformation is mainly elastic. The elastic energy is stored in the cell walls, and as the load is removed, the stress is released, causing immediate spring-back deformation (Navi and Heger, 2004).

Most research regarding densification has been conducted on wood from coniferous species and in close systems, and scarcely on wood from hardwood species whose anatomical structures are more complex and have a greater influence on the result of the process (Navi and Heger, 2004). Although Tasmanian oak species have average hardwood densities, plantation shining gum is relatively low density for a hardwood. Given the potential additional benefits of improved abrasion resistance, durability and fire resistance that researchers have experienced with other species, the densification process may help to improve some of these characteristics in Tasmanian hardwoods. Balasso et al., (2020) tried densifying certain species of *Eucalyptus*, however the focus of their research was on the mechanical performance of small samples that had been compressed from 8mm to 5mm, and there was no additional refinement of the process to improve outcomes in relation to spring back or set recovery. This research extends their work, by investigating larger sample thicknesses, different compression ratios, and evaluating the effects of varying temperatures, compression times on various properties (outlined below) that may be relevant for outdoor or indoor cladding or lining applications.

The research for this trial subcontracted to the University of Melbourne was primarily conducted by researchers in the School of Ecosystem and Forest Sciences. (Full report available on request). An affiliated trial tested the durability and fire-performance of a small number of samples from this trial using laboratory decay tests and cone-calorimeter tests (see the final report from NT047/NIF108 for more detail).

Trial 4.1 Thermo-mechanical densification

Aims: This trial aimed to densify shining gum and Tasmanian oak using a thermo-mechanical densification process and evaluate the effects of varying temperatures, compression times and ratios on set-recovery/thickness swelling (including: immediate recovery after opening the press called 'spring back'; set recovery following a soaking and oven drying cycle; and set recovery following moisture cycling in a temperature and humidity chamber), colour change, machineability, coating adhesion, and delamination. The fire resistance and durability of densified material were also evaluated in a separate trial in the affiliated NIFPI project (see Final Report for NT047/NIF108).

Materials and methods: (Note: a preliminary trial was undertaking to establish the strategy for this upscaled trial method, and some of the methods and results from that trial are mentioned here but the majority of the methods and results discussed herein refer to the upscaled trial. (Full report on the preliminary trial available on request.)

Seasoned Tasmanian oak and shining gum boards were conditioned, then cut to size and compressed (Figure 40), perpendicular to the grain, with or without a steaming pre-treatment using a variety of parameters. The densification process consisted of three stages adapted from Tenorio and Moya (2021):

1) preheating at 150 °C or 175 °C for ten minutes;
2) compression perpendicular to the grain until reaching the target thickness of 12 mm (compression ratio: 25 % or 37 %) for ten or twenty minutes, at the temperature maintained in stage one;

Figure 40. Tasmanian hardwoods under compression. Photo: Benoit Belleville.

3) cooling where the lamellas were kept compressed but without heat (platens temperature < 60 °C) for an additional ten minutes.

Ten or five replicates per combination of parameters were prepared for shining gum and Tasmanian oak for a total of 120 densified lamellas. (Note, the three different species from the Tasmanian oak were identified by the suppliers, and a minimum of three replicates for each of the species composing Tasmanian oak were densified per combination of parameters).

The post-densification assessment of densified lamellas for the upscaled trial included: spring back (immediate recovery after opening the press); colour change; set recovery via direct exposure to water; set recovery via temperature and humidity changes; pull-off strength test to test adhesion of coatings; and delamination.

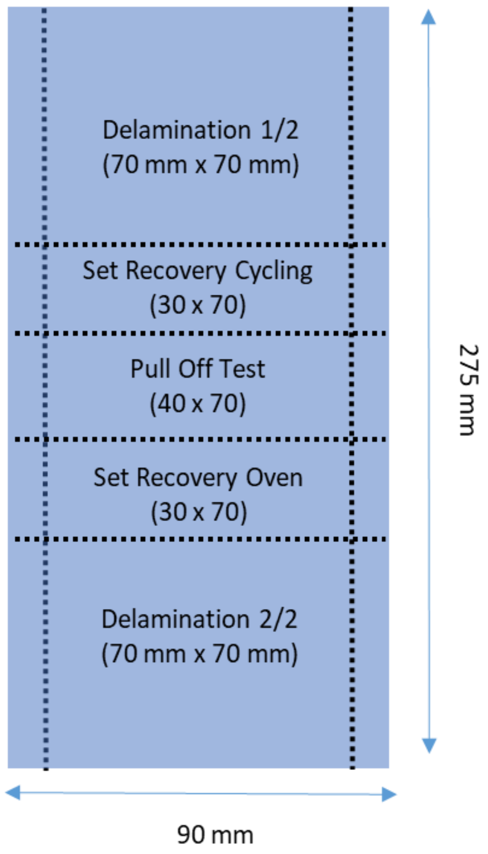


Figure 41. Sample cut pattern following densification.

To evaluate spring back, thickness measurements were taken at three different points on each lamella before densification and after opening the press to determine spring back or immediate recovery. In the preliminary iterations of this Trial, a ten-minute cooling period was trialled, where the temperature in the plattens was reduced to < 60 °C without releasing pressure on the lamellas.

Figure 42. BYK-Gardner digital colour apparatus Photo: Benoit Belleville.

Colour measurements were taken at four different points (C1, C2, C3 and C4) on the surface of each lamella (4 x 4 mm^2) before and after the densification process, for a total of 640 measurements. To ensure that all the colour readings were taken in the same spots before and after the treatment, a colour measurement template was used. The colour measurement was undertaken using a BYK-Gardner digital colour apparatus (Figure 42). The CIELab colour system (ΔEL*a*b*, ΔL*, Δa* and Δb*) and the following specifications were used:

- Light source type D65
- Observation angle of 10 °
- Calibration with standards
- Sample averaging n= 4

Following densification and the evaluation of spring back and colour change, lamellas were reconditioned for two weeks at 23 °C and 65 % RH, and then machined to prepare samples for the remaining tests (Figure 41).

The set recovery evaluation consisted of two tests to assess the suitability of densified wood for specific use in defined environmental conditions:

- dry-use or capable of producing sufficient dimensional stability to make the densified wood serviceable under conditions in which the equilibrium moisture content (EMC) does not exceed 17 %; and
- wet-use or capable of producing sufficient dimensional stability to make the densified wood serviceable under conditions in which the EMC may be 16 % or higher.

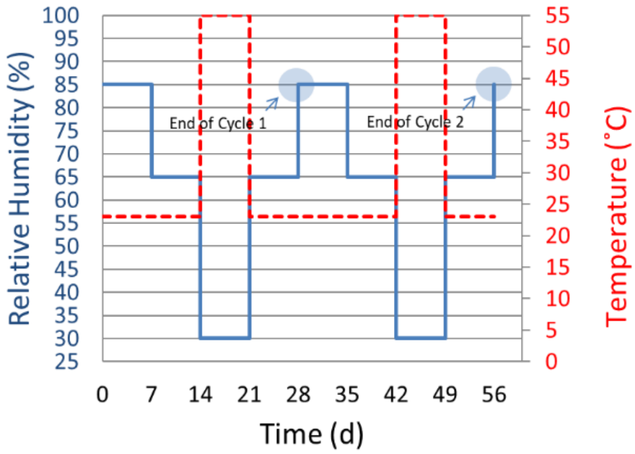


Figure 43. Set recovery desorption/adsorption cycles.

The set recovery was first measured by soaking one hundred and twenty 30 mm x 70 mm densified samples in water for two hours or twenty-four hours and measuring the oven-dried samples' (40 °C, twenty-four hours) thickness and weight before and after soaking following the procedure described in Laine *et al.* (2016). Thickness was measured from each specimen using callipers.

Set recovery was next measured by exposing eighty densified 30 mm x 70 mm samples to different ambient conditions via two desorption/absorption cycles (Figure 43). The test simulated conditions which densified material may encounter in service e.g., humid climate (85 % RH, 23 ˚C), moderate climate (65 % RH, 23 ˚C), and dry climate (30 % RH, 55 ˚C). Thickness measurements were obtained every seven days for a total fifty-six days.

The effect of the densification process on the adhesion property of densified material was evaluated using a pull-off strength test. An oil-based polyurethane coating system was applied (three coats) with a brush on the surface of one hundred and twenty densified 40 mm x 70 mm samples and eighteen controls. The bare densified surface was lightly sanded using 180 grit sandpaper prior to applying the first coat. The surface was again lightly sanded prior to application of the second and third coats using 240 grit sandpaper. One week after the application of

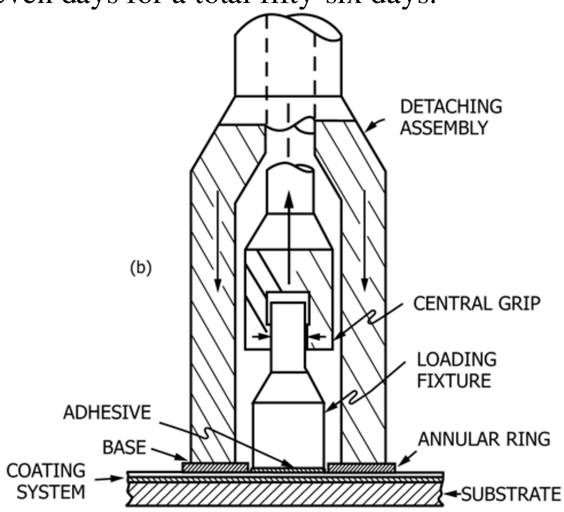


Figure 44. Pull-off test set up.

the third coat, a metallic dolly (20 mm in diameter) was glued to the surface of each sample with an epoxy adhesive and tested using a pull-off test (Figure 44).

Finally, the effect of densification on the performance of glued joints was assessed in various environmental conditions as part of a delamination test where a gradient was introduced in the moisture content of the wood to build up internal stresses, resulting in tensile stresses perpendicular to the glue line. Eighty individual 70 mm x 70 mm densified samples and eighteen controls were face laminated using a liquid one-component polyurethane adhesive for structural wood bonding. The specimens were then trimmed down to 65 mm x 65 mm to remove the glue excess. The specimens were first placed in a pressure vessel and completely submerged in water. A vacuum of 70 kPa (20 in. Hg) was first drawn and held for five minutes. Then, samples were pressurised at 500 kPa (72.5 psi) for one hour. This vacuum-pressure cycle was repeated once more. The samples were finally dried for a period twenty-two hours in air at 60 °C and < 15 % RH. After the cycle, the specimens were evaluated for glue line delamination.

Results: Both shining gum and Tasmanian oak were densified successfully, showing no sign of spring back (*i.e.*, 0 % recovery/swelling immediately after opening the press) using both 25 % and 37 % compression ratios. Steaming instead of preheating prior to pressing was found to have a negative effect on spring back and swelling, so this approach was abandoned after the preliminary trial. In rare circumstances, irreversible damage following the densification process was observed in Tasmanian oak (Figure 47).

Figure 45. Example of spring back from preliminary trial. Photo: Benoit Belleville.

Results (spring back): Results from this research indicate that spring back (see Figures 45 and 46 for example from preliminary trial), was entirely controllable by introducing a ten-minute cooling period directly after densification while the lamellas are still in the press for 25 %, 37 % and 50 % compression ratios. If a cooling period was not introduced, there was evidence of significant spring back observed in all densified samples (Figure 48).

Figure 46. Example of spring back from preliminary trial. Photo: Benoit Belleville.

Results (colour change): There was low colour change (ΔEL*a*b*) or stable colour for shining gum across all the pressing conditions (Table 22). Colour change increased slightly as a function of pressing time and temperature although not enough to be perceived by the naked eye (i.e., ΔEL*a*b* < 5). Tasmanian oak samples showed low colour change or stable colour at a pressing temperature of

Figure 47. Irreversible damage following densification of Tasmanian oak. Photo: Benoit Belleville.

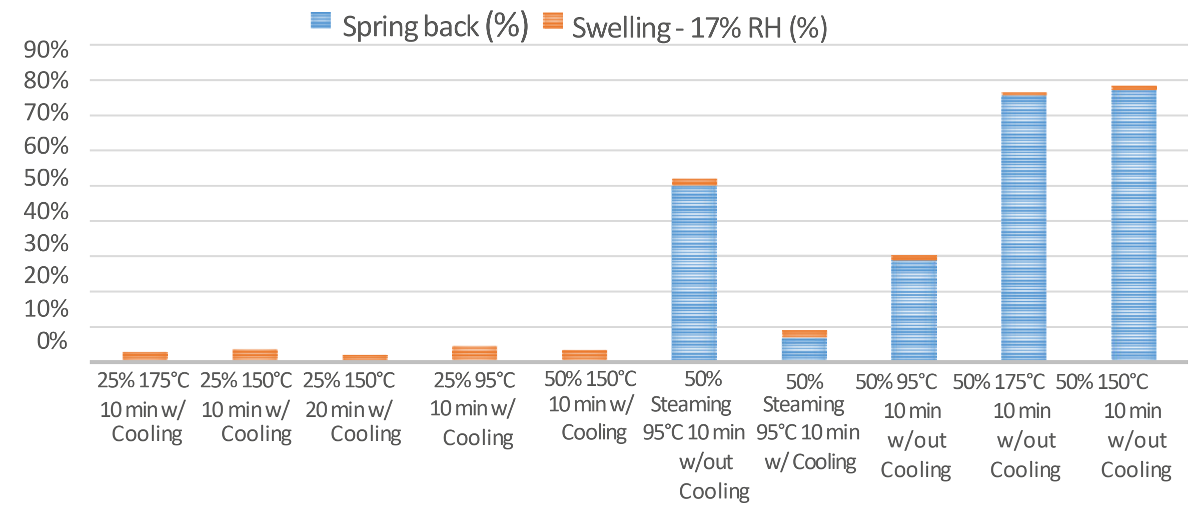


Figure 48. Graph from preliminary trial showing percentages of spring back with and without a cooling period in the press, and percentages of set recovery after exposing densified samples to 17% relative humidity. This led to decisions to reduce the compression ratio from 50% to 30%, and eliminate pre-steaming samples.

150 °C and a pressing time of ten or twenty minutes. Colour change increased as a function of pressing time and temperature. More significant colour change was perceived at 175 °C (ΔEL*a*b* of 6.17 and 6.92 after ten minutes and twenty minutes, respectively). It is generally considered that a colour change above 5 can be perceived by the naked eye and depending on the application the change could be more or less significant. Colour change variability also tended to increase as the pressing temperature increased. The overall trend observed with both species was a shift in ΔL in the negative direction. This means that the samples became slightly darker after the densification process. The second component of the overall colour change was a positive Δb* which means that the samples became slightly yellower after the densification process. The final component contributing to the overall ΔE colour change was a negative Δa* which means that the samples became marginally greener following the densification process. There was a slight but insignificant increase in gloss when going from a pressing temperature of 150 °C to 175 °C.

Table 22. Average colour change as a function of pressing time and temperature
Standard deviation is presented in parentheses

Pressing temp. (°C)	**150**		**175**	
Pressing time (min)	**10**	**20**	**10**	**20**
Shining gum				
Δ $E_{L^*a^*b^*}$	**1.84** (0.73)	**1.82** (0.41)	**3.21** (0.87)	**4.10** (0.89)
Δ *L**	**-1.18** (0.76)	**-1.26** (0.37)	**-2.49** (0.68)	**-3.24** (0.74)
Δ *a**	**-0.06** (0.19)	**-0.12** (0.15)	**0.05** (0.33)	**0.19** (0.35)
Δ *b**	**1.15** (0.52)	**1.24** (0.38)	**1.98** (0.54)	**2.33** (0.85)
Gloss	**0.4** (0.3)	**0.4** (0.1)	**0.5** (0.2)	**0.5** (0.2)
Tasmanian oak				
Δ $E_{L^*a^*b^*}$	**1.71** (0.30)	**2.11** (0.54)	**6.17** (1.94)	**6.92** (1.75)
Δ *L**	**-1.18** (0.26)	**-1.52** (0.49)	**-5.73** (2.11)	**-6.53** (1.88)
Δ *a**	**-0.64** (0.43)	**-0.74** (0.22)	**-1.09** (0.35)	**-1.22** (0.17)
Δ *b**	**0.76** (0.49)	**1.05** (0.57)	**1.49** (0.79)	**1.44** (0.90)
Gloss	**0.4** (0.1)	**0.3** (0.1)	**0.4** (0.2)	**0.2** (0.2)

Table 23. Average set recovery results following oven dry and water soak test – 25% compression ratio Standard deviation is presented in parentheses					
	After 2 hours in water		After 24 hours in water		Set Recovery
Species	Water Absorption	Thickness Swelling	Water Absorption	Thickness Swelling	
Shining gum	7.9 (2.4)	1.9 (1.1)	26.8 (7.1)	10.2 (4.9)	8.2 (13.6)
Tasmanian oak	4.6 (0.9)	1.2 (0.3)	20.4 (7.2)	9.3 (6.0)	7.6 (15.3)
E. delegatensis	5.6 (0.4)	1.5 (0.2)	28.4 (7.0)	14.2 (8.4)	19.7 (22.6)
E. obliqua	4.2 (0.8)	1.0 (0.2)	17.5 (4.2)	8.4 (3.2)	5.1 (5.3)
E. regnans	4.2 (0.5)	1.1 (0.2)	16.4 (2.9)	6.0 (1.0)	-0.4 (1.5)

Table 24. Average set recovery results following oven dry and water soak test – 37% compression ratio Standard deviation is presented in parentheses					
	After 2 hours in water		After 24 hours in water		Set Recovery
Species	Water Absorption	Thickness Swelling	Water Absorption	Thickness Swelling	
Shining gum	5.5 (1.1)	1.8 (0.8)	21.3 (6.0)	11.1 (5.1)	5.3 (7.2)
Tasmanian oak	3.6 (0.6)	1.7 (0.7)	15.7 (3.3)	10.9 (4.5)	6.2 (5.5)
E. delegatensis	3.7 (0.5)	1.8 (0.6)	17.5 (2.5)	12.8 (5.6)	7.6 (7.8)
E. obliqua	3.8 (1.1)	1.9 (0.7)	15.0 (2.9)	12.6 (3.0)	7.5 (3.6)
E. regnans	3.5 (0.4)	1.6 (0.8)	14.2 (3.2)	8.2 (1.1)	4.2 (1.8)

Table 25. Average set recovery as a function of pressing time and temp. – 25% compression ratio Standard deviation is presented in parentheses				
Pressing temp. (°C)	150		175	
Pressing time (min)	**10**	**20**	**10**	**20**
Shining gum	**9.4** (8.8)	**8.4** (13.7)	**8.5** (13.9)	**8.7** (14.0)
Tasmanian oak	**8.4** (15.9)	**5.3** (14.4)	**11.0** (17.7)	**5.5** (11.6)
Highlighted cells indicate best parameters for reducing set recovery at 25% CR				

Table 26. Average set recovery as a function of pressing time and temp. – 37% compression ratio Standard deviation is presented in parentheses				
Pressing temp. (°C)	150		175	
Pressing time (min)	**10**	**20**	**10**	**20**
Shining gum	**10.5** (6.1)	**8.5** (8.9)	**2.0** (3.0)	**0.0** (1.9)
Tasmanian oak	**10.3** (4.2)	**9.2** (4.7)	**2.6** (3.7)	**2.7** (4.3)
Highlighted cells indicate best parameters for reducing set recovery at 37% CR				

Results (set recovery: oven dry and water soak tests): In samples with a compression ratio of 25 % the overall thickness swelling was more pronounced in shining gum after two hours than Tasmanian oak (1.9 % versus 1.2 %) because of faster water absorption (7.9 % versus 4.6 %) (Table 23). Thickness swelling in shining gum remained slightly higher than Tasmanian oak after twenty-four hours (10.2 % versus 9.3 %) again due to higher water absorption (26.8 % versus 20.4 %). Set recovery of densified Tasmanian oak (7.6 %) was slightly lower than shining gum (8.2 %) across all tested densification parameters (Table 22).

There was significant set recovery variability between the species forming the Tasmanian oak group. More specifically, *E. obliqua* and *E. regnans* appeared to be significantly more stable than *E. delegatensis* when exposed to water (Table 22, Figure 49). However, further analysis is needed to better understand these results (e.g., between board variability, anatomical features, heartwood and sapwood proportion, etc.). *E. regnans* was the most stable species

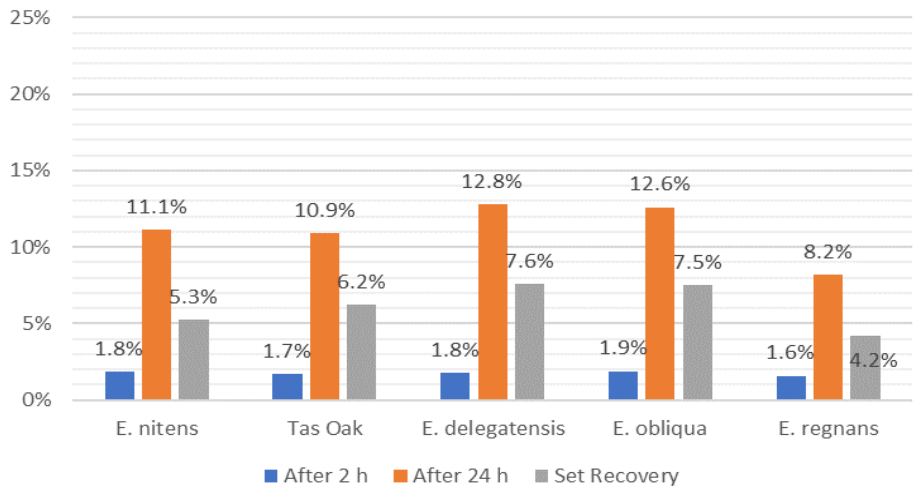


Figure 49. Overall thickness swelling in shining gum and Tasmanian oak at a compression ratio of 25 %.

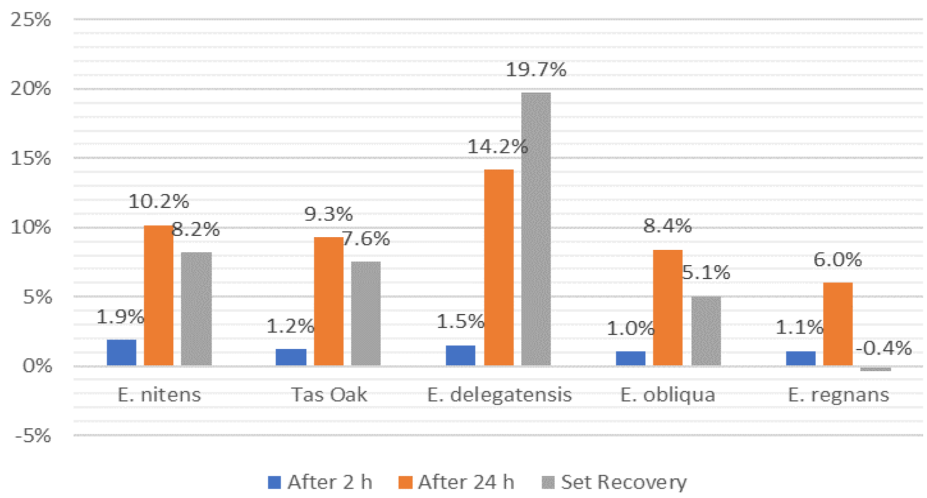


Figure 50. Overall thickness swelling in shining gum and Tasmanian oak at a compression ratio of 37 %.

following the soaking in water and oven-drying test, while *E. delegatensis* was the least stable species following the set recovery test.

For the 25 % compression ratio, overall, water was picked up faster in densified shining gum than in densified Tasmanian oak but water absorption levelled out after twenty-four hours of soaking in water. Thickness swelling was slightly higher in shining gum than Tasmanian oak after two hours and twenty-four hours in water.

In samples with a compression ratio of 37 %, thickness swelling was slightly more significant in shining gum after two hours than Tasmanian oak (1.8 % versus 1.7 %) due to faster water absorption (5.5 % versus 3.6 %) (Table 24). Thickness swelling in shining gum remained slightly higher than Tasmanian oak after twenty-four hours (11.1 % versus 10.9 %) again as a result of higher water absorption (21.3 % versus 15.7 %). Set recovery of densified Tasmanian oak (6.2 %) was slightly higher than shining gum (5.3 %) across all tested densification parameters (Table 24).

Looking specifically at the Tasmanian oak species, *E. obliqua* was significantly more stable when exposed to water when compared to the results for the compression ratio of 25 %. *E. regnans* was the most stable species following the soaking in water and oven-drying test across both compression ratios (Figure 50).

For the 37 % compression ratio, overall, water was picked up faster in densified shining gum than in densified Tasmanian oak. Thickness swelling was slightly higher in shining gum than Tasmanian oak after two hours and twenty-four hours in water. The observed set recovery variability between the species forming the Tasmanian oak group at a compression ratio of 37 % was clearly less pronounced.

In terms of how the other densification parameters (i.e. pressing times and temperatures) affected set recovery, a longer pressing time at 150 °C improved set recovery results (i.e. reduced swelling) for both shining gum and Tasmanian oak, whereas a longer pressing time at 175 °C significantly improved set recovery for Tasmanian oak but not shining gum (Tables 25 and 26). A pressing time of twenty minutes at a pressing temperature of 150°C was the most efficient densification setting in terms of reducing swelling for both shining gum and Tasmanian oak with a 25 % compression ratio. For 37 % compression ratio, a pressing time of ten minutes at a pressing temperature of 175 °C was the most efficient densification setting across both shining gum and Tasmanian oak, although shining gum on its own appeared to respond better to the higher temperature.

As observed previously, *E. delegatensis* did not seem to respond as well as *E. obliqua* and *E. regnans* across all the densification conditions tested in this trial but further analysis is needed to better understand why.

Results (set recovery: moisture content cycling test): The overall average set recovery following moisture content (MC) cycling was more significant in shining gum than Tasmanian oak across all tested conditions (Figure 51). Densified material reacted to moisture like solid wood i.e., swelling when exposed to ambient high humidity conditions and shrinking when exposed to dry conditions. The sorption hysteresis effect naturally observed in wood was clearly noticeable with the densified material i.e., the MC was higher if equilibrium was reached by desorption than if it was reached by absorption under the same ambient climate conditions.

A comparison of the average set recovery results following cycle #1 and cycle #2 suggested that all studied species were stable following the densification process (e.g., set recovery of *E. regnans* after cycle #1 and cycle #2 was 0.3 % and 0.3 %, respectively, Figure 51).

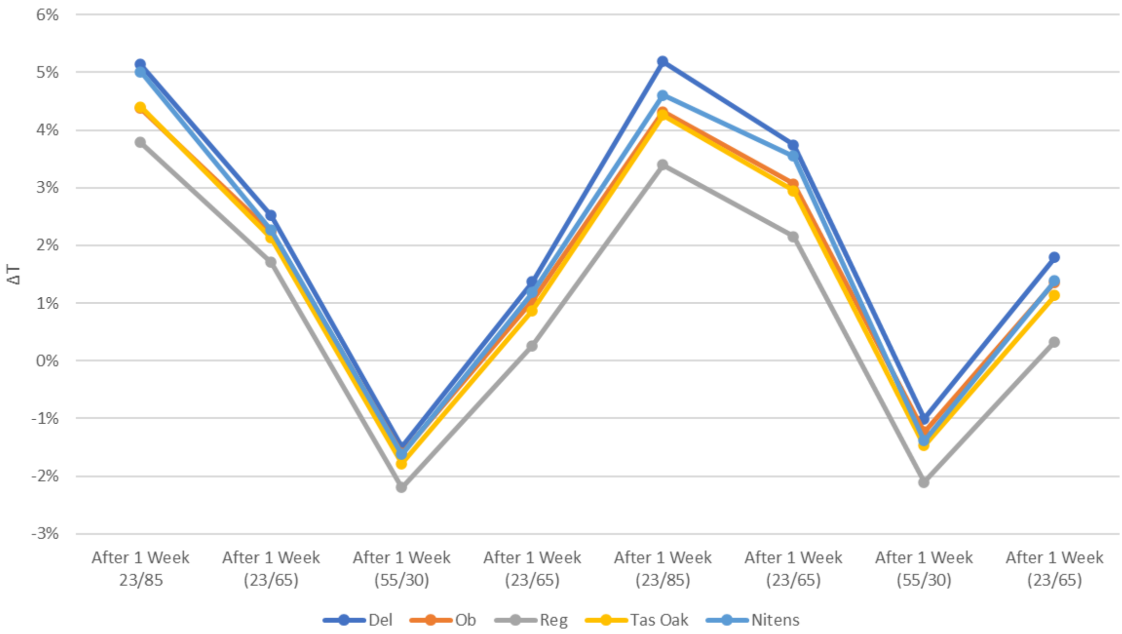


Figure 51. Average set recovery (%) of densified shining gum and Tasmanian oak during moisture content cycling at a compression ratio of 25%.

Therefore, it is possible to assume that densified Tasmanian oak and shining gum wood would be suitable for dry-use environmental conditions i.e., capable of producing sufficient dimensional stability to make the densified wood serviceable under conditions in which the equilibrium moisture content (EMC) does not exceed 17 %. This test would be strengthened by the inclusion of non-densified control samples of the same species to compare swelling.

Results (adhesion of a coating): Extending the densification pressing time from ten to twenty minutes and increasing the pressing temperature from 150 °C to 175 °C had a negative effect on the pull-off strength of densified samples across all tested combinations of parameters except for shining gum with a compression ratio of 37 % (Table 28). A compression ratio of 25 % reduced the pull-off strength for both shining gum and Tasmanian oak when compared to the controls. A compression ratio of 37 % didn't affect the pull-off strength of Tasmanian oak when compared with the control (Table 27), but negatively impacted the pull-off strength of shining gum when compared with the control (Table 28).

Table 27. Tasmanian oak pull-of strength test (MPa)

	Compression ratio 25%					Compression ratio 37%			
	150/10	**150/20**	**175/10**	**175/20**	**Control**	**150/10**	**150/20**	**175/10**	**175/20**
Avg	3.82	3.57	3.76	3.27	4.32	4.65	4.05	4.31	4.25
Std	0.48	0.22	0.33	0.47	0.30	0.43	0.49	0.32	0.65
Min	3.13	3.15	3.33	2.50	3.95	4.21	3.40	3.84	3.29
Max	4.61	3.77	4.46	4.43	4.90	5.41	4.74	4.75	5.22

Highlighted cells indicate top two scores for Tasmanian oak

Table 28. Shining gum pull-of strength test (MPa)

	Compression ratio 25%					Compression ratio 37%			
	150/10	**150/20**	**175/10**	**175/20**	**Control**	**150/10**	**150/20**	**175/10**	**175/20**
Avg	3.22	3.05	3.33	3.15	4.07	3.50	3.63	3.40	3.60
Std	0.70	0.56	0.45	0.48	0.37	0.35	0.37	0.40	0.60
Min	1.56	1.72	2.50	2.33	3.46	2.93	2.92	2.80	2.96
Max	4.46	3.85	4.11	3.88	4.57	3.99	3.93	3.81	4.72

Highlighted cells indicate top two scores for shining gum

Results (delamination): The pressing time and compression ratio had a negligible effect on total delamination for shining gum at a pressing temperature of 150 °C compared to the control (Table 29). Increasing the temperature seemed to have a negative effect although all samples pressed at 175 °C for twenty minutes using a compression ratio of 37 % showed no sign of delamination (Table 29). A pressing temperature of 175 °C and a compression ratio of 37 % appear to have a positive effect on total delamination for Tasmanian oak. There was no significant difference between controls and samples densified using a compression ratio of 37 % and a pressing temperature of 175 °C. Where a higher temperature appeared to improve total delamination of Tasmanian oak samples, it is important to mention that splits and cracks occurring outside the glue line were not included in the total delamination results. Such cracks suggest that buckling in Tasmanian oak species could not be prevented based on selected studied conditions (Figures 52 and 54). A similar pattern was observed on some shining gum densified samples although with less frequency and intensity (Figure 53). Most shining gum and alpine ash samples performed surprisingly well considering the robustness of the vacuum-pressure and oven-drying test.

Figure 52. *Eucalyptus delegatensis* sample following the delamination test (Compression ratio: 37%; pressing temperature: 150°C; pressing time: 10 min; total delamination: 13.0%). Photo: Benoit Belleville.

Table 29. Average total delamination of densified samples

Species, compression ratio	Control	150°C		175°C	
		10 min	20 min	10 min	20 min
Shining gum control	0.0% (0.0% - 0.0%)*				
Shining gum, 25%		2.0% (0.0% - 8.1%)	0.3% (0.0% - 0.9%)	3.7% (1.3% - 7.3%)	9.7% (6.2% - 13.3%)
Shining gum, 37%		1.0% (0.0% - 2.9%)	1.5% (0.0% - 4.5%)	4.4% (0.0% - 16.9%)	0.0% (0.0% - 0.0%)
Tas oak, Control	2.7% (0.0% - 10.6%)				
Tas oak, 25%		32.2% (7.0% - 65.0%)	32.1% (1.0% - 48.4%)	14.6% (0.0% - 53.1%)	7.7% (3.0% - 10.3%)
Tas oak, 37%		36.3% (1.7% - 94.1%)	9.8% (1.9% - 14.6%)	1.8% (0.0% - 3.0%)	3.2% (0.0% - 5.8%)

*range presented in parentheses
Highlighted cells indicate top two scores for both species

Benefits for industry?

This process is not a commercial reality yet, and there are still many stages need to get products to a point where they can be reliably reproduced. The research in this trial considered many aspects of the densification process and has shown that generally speaking a higher compression ratio, higher temperature and longer pressing time seemed to improve set-recovery results, but that densified material is not likely to remain dimensionally stable in an outdoor environment. Although this trial was largely focused on better understanding densified hardwood for interior applications, some material from this trial was subsequently tested in a durability and fire-performance test as part of the affiliated NIFPI trial (see final report for NT047/NIF108) and findings from that research corroborated the suggestion that densified material is likely better used in interior applications. Reasons for pursuing densification might be for its appearance quality, or engineered and composite wood products (e.g. wall panels).

What still needs to be done?

If densification is to be a more broadly adopted treatment option for Tasmanian appearance hardwoods, further investigation into feasible industrial-scale equipment, systems and applications would be of interest. Although this trial was looking at non-structural uses for the material, further investigation into the mechanical properties of densified Tasmanian hardwoods is also necessary to better define the optimal processing parameters. In addition, a trial investigating the termite resistance of densified material would also be of interest, given that there is a broadly assumed correlation between timber density and improved termite resistance, but no literature on the subject. Finally, there is a lot of confusion around different definitions of densification in the literature and potential for misinterpretation.

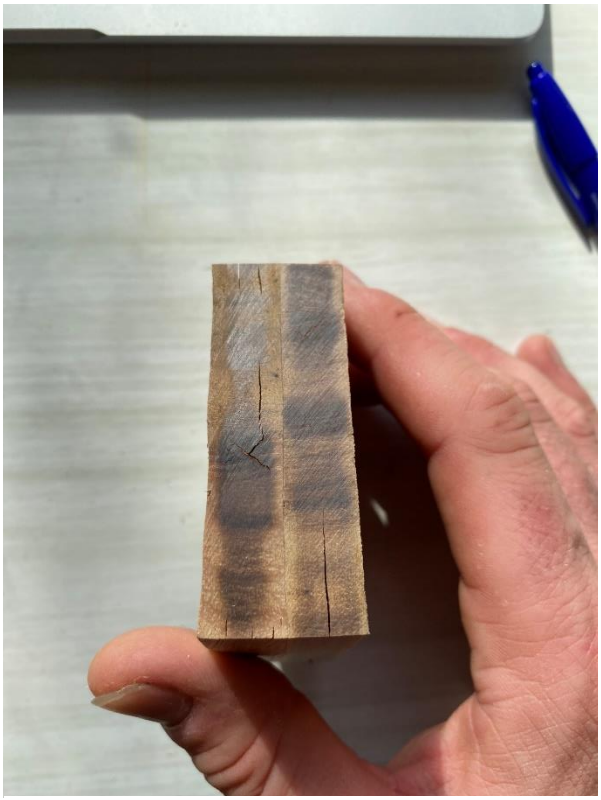


Figure 53. *Eucalyptus nitens* sample following the delamination test (Compression ratio: 37%; pressing temperature: 150°C; pressing time: 20 min; total delamination 0.0%). Photo: Benoit Belleville.

Figure 54. *Eucalyptus regnans* sample following the delamination test (Compression ratio: 37%; pressing temperature: 175°C; pressing time: 20 min; total delamination 5.8%). Photo: Benoit Belleville.

Trial 5 Fire retardants

To qualify as bushfire-resisting, timber must either have inherent properties, or be impregnated with a chemical retardant or coating. Shining gum and Tasmanian oak do not have inherent bushfire resisting properties, however the fire safety of Tasmanian timber cladding in bushfires may be improved by the addition of a fire-retardant treatment.

For the completion of fire testing there are a number of relevant standards that need to be adhered to. Bushfire Attack Level (BAL) is a method of quantifying the severity of a buildings' potential exposure to ember attack, radiant heat and direct flame contact in a bushfire. It is expressed in kilowatts/m^2 and in Australia there are five categories ranging from 12.5kW.m2 (lowest tolerance) to >40kW/m2 (direct exposure parameters). These differing categories are outlined in the National Construction Code (NCC) and detailed in AS 3959:2018. Building materials to be used in these classified zones need to pass certain requirements when exposed to relevant heat fluxes and comply with the building and construction standards.

Exterior building products can be qualified for use in a respective BAL-zone via testing specified in AS 1530.8.1 or 1530.8.2. These tests assess a building product as a finished assembly at full scale. This testing procedure is costly and thus infeasible to characterise a range of different materials or material treatments. For use of timber in BAL-29 a material level test is specified in AS 3959. To achieve a classification as bushfire-resisting timber, samples must fulfil two criteria that are specified in AS 3959:

- The peak heat release rate per unit area (HRRPUA) must be less than 100 kW/m2.
- The mean HRRPUA must be less than 60 kW/m2 for 10 minutes after ignition.

This test is intended to qualify timber as bushfire-resisting through (1) the inherent properties of the tested timber, (2) impregnation with fire-retardant chemicals, and/or (3) application of fire-retardant coatings or substrates.

Interior Group fire ratings refers to fire performance testing for building and construction products to be used in interior settings. The interior requirements for fire performance are stringent and various standards are used for differing products based upon their targeted in-service use. These include (but are not limited to) AS 1530.1:1994 – *Methods for fire tests on building materials, components and structures – Combustibility test for materials*, AS 5637.1:2015 *Determination of fire hazard properties Part 1: Wall and ceiling linings*, AS ISO9705:2003 *Fire tests – Full-scale room test for surface products* and AS/NZS 3837:1998 *Method of test for heat and smoke release rates for materials and products using an oxygen consumption cone calorimeter*. Additionally, there a number of other detailed requirements specified for structural building products to be used in interior settings. Group ratings range from 1-4 with Group 1 being the most difficult to achieve. To achieve a Group 1 fire rating a material must not reach 'flashover' when exposed to 100 kW for 600 seconds followed by exposure to 300 kW for 600 seconds as specified in AS 5637. Alternatively the product must be non-combustible as determined by AS 1530. Timber products are naturally combustible and are usually assigned a Group 3 rating when untreated. Therefore, treatment with fire retardants can increase the potential applications of timber.

Exterior and interior fire-retardant treatments were sourced by researchers at DAF, and the material treatment for this trial was conducted at DAF. The fire-retardant manufacturers expressed their desire to keep treatments anonymous so trial results are reported using de-identified codes (e.g interior A, exterior D). Samples targeted for exterior purposes required an extended weathering cycle and this was completed at the University of Melbourne in a modified QUV weathering system in accordance with ASTM D2898. The fire testing of both interior and exterior products was performed at University of Queensland according to relevant standards focusing primarily on AS/NZS 3837:1998. Testing for heat and smoke release rates of the treated materials and products was done using a non-NATA certified laboratory oxygen consumption cone calorimeter.

The research in Trial 5 was subcontracted to the Queensland Department of Agriculture and Fisheries, and the University of Queensland, and was primarily undertaken by researchers at Salisbury Research Facility using their laboratory-scale treatment cylinder, and researchers in the School of Civil Engineering using their cone calorimeter. Weathering was done by researchers at the University of Melbourne, using their modified QUV.

Trial 5.1 Exterior

Concept: Tasmanian hardwoods under investigation in this project have low bushfire resistance properties and need to be treated with a fire retardant if they are to be used for exterior cladding in certain bushfire zones. Fire-retardant treatments range from treating the wood's surface via spraying, dipping or flow-coating, but some solutions are also suitable for vacuum pressure impregnation, or combine VPI with an overcoat to improve the longevity of the protective system. However, given their refractory characteristics, it was not known whether such systems would be effective with the Tasmanian hardwood species under investigation in this project.

Aims: To treat Tasmanian hardwoods via VPI using commercially available fire retardants to improve their suitability for use as cladding in bushfire exposure zones (targeting BAL-29), and to test their fire performance using cone calorimeter tests, to be able to make recommendations to industry for future certification work.

Materials and methods: Samples included Tasmanian oak, plantation spotted gum and plantation shining gum sawn boards 300 mm x 100 mm x 19 mm, Tasmanian oak and plantation spotted gum veneers that were treated and then laminated into a 5-lamella plywood 300 mm x 300 mm, and Tasmanian oak and plantation spotted gum plywood that was glued and then treated 300 mm x 300 mm. Although not a Tasmanian hardwood, spotted gum was included as a comparator due to its certified bushfire resisting properties (see AS3959). After machining all samples were numbered, labelled, cut to length and end sealed. All individual samples were weighed and measured immediately prior to treatment to assist in calculating the uptake. Plywood was edge trimmed and cut into 150 mm x 300 mm dimensions before treatment to be of comparable size to sawn counterparts. All veneers, plywood and boards were treated with fire retardants using a commercial vacuum pressure cycle following a sequence like that used in charge 1 for the VPI preservative treatment outlined in section 2.1 above. A total of thirty-eight exterior samples were fire performance tested. A number of samples that had been manufactured were not fire tested in the end due to delamination of glue lines or other performance reasons.

Exterior samples, including controls, underwent an intensive weathering cycle in a modified QUV weathering system in accordance with ASTM D2898. Samples were air dried after treatment and weathering (exterior samples only). All samples were tested in a cone calorimeter, which is a standardised fire testing apparatus that imposes a uniform constant heat flux onto a sample surface. It is equipped with a spark igniter to induce ignition, a mass balance, and the means to sample exhaust gases to measure oxygen, carbon dioxide and carbon monoxide. The cone calorimeter was calibrated to impose an irradiance of 25 kW/m2 onto the sample surface, as specified within AS 3959. The samples were tested according to specifications in AS 3837 using piloted ignition. The heat release rate throughout testing was determined from oxygen consumption calorimetry. The moisture content (MC) was measured before testing using a hand-held conductivity-based moisture meter.

Samples were rated with a pass or fail according to the requirements for exterior use for BAL-29. Limited information regarding solution strength and product active ingredients were provided by the suppliers which disallowed theoretical product retention. Additionally, products were not provided with a tracer/penetration indicator which disallowed visual assessment of penetration.

Results: For exterior fire retardants, product D was the highest performing, achieving BAL-29 for all veneer-based products and two out of three sawn shining gum samples (Table 31). Product E achieved BAL-29 on one spotted gum plywood sample however the batch did not pass. Product D contained an additional overcoat, and it is unclear whether this contributed to the fire performance and/or the minimisation of accelerated weathering/product leaching.

Table 30. Average fire-retardant uptakes / exterior treatment			
Average uptakes (L/m3)	Exterior D	Exterior E	Control F
Seasoned shining gum	63.73	161.08	n/a
Seasoned plantation spotted gum	109.41	99.7	n/a
Tas oak veneer	493.17	519.87	n/a
Spotted gum veneer	157.31	194.83	n/a
Tas oak plywood	414.06	437.26	n/a
Spotted gum plywood	248.03	190.43	n/a
Highlighted cells indicate treated samples that achieved BAL-29 performance.			

Following VPI treatment, the average uptakes were highest in Tasmanian oak veneers and plywood (Table 30), with product E showing the highest uptakes at 520 l/m^3 in Tasmanian oak veneers. The presence of the additional coating in addition to the VPI treatment with product D was found to have some correlation with the classification of bushfire-resisting timber however it is not clear whether there was any causation here. Most samples treated with product D and only one sample not treated with it achieved the required thresholds to be classified as bushfire-resisting timber. The bulk density of the samples was found to improve performance, although above average density alone was not sufficient to achieve the required thresholds. The key variables from each test are summarised in Table 31. The values for moisture content (MC) show markedly higher values for product D compared to other samples. This indicates that the measurements could have been influenced by the overcoating, and may not reflect the actual timber moisture content; thus the moisture content values were not considered for further analysis below.

The results (Table 31) show that only one sample not treated with product D passed as bushfire resisting timber, while the majority of the product D samples achieved the necessary criteria for bushfire-resisting timber. Tasmanian oak was the only species for which all product D samples achieved a pass, but it also displayed the worst performance of all species for untreated samples. The best untreated performance was achieved by the plantation spotted gum and it was the only species for which one untreated sample achieved a pass; this was not unexpected, since spotted gum is already classified as a bushfire resisting species in AS 3959. However, the fact that most of the plantation spotted gum samples failed to fulfil the performance conditions calls into question to what extent a species-based classification is applicable across all spotted gum populations. A caveat to this finding is that the testing done herein was not in a NATA accredited laboratory, was performed with a focus on research and the testing outcomes do not constitute legally valid classifications of bushfire-resisting timber.

Shining gum sawn board samples had the worst performance of all the fire-retardant treated samples, with all treated samples igniting.

Laminated specimens were found to delaminate and expand towards the heat source during initial tests. Subsequently a retainer frame with a grid was used to test all laminated samples (Figure 55). Due to the issues with delamination, there are some doubts as to how these samples would perform in a full-scale assembly.

Figure 55. Grid used to prevent sample from delaminating during cone calorimeter test. Photo: Wenxuan Wu.

Some of the product D samples showed a sparking behaviour during the cone test (e.g. sample # D50). This may have been caused by the overcoat treatment. The sparking did not increase the HRR to the point of failure of the test criteria, but the potential implications from this occurrence of sparks should still be considered. BAL-29 conditions are described in AS 3959 as: "There is an increased risk of ember attack and burning debris ignited by windborne embers and a likelihood of exposure to an increased level of radiant heat". Sparks from the overcoated timber once ignited could lead to ignition of nearby debris, however, BAL-29 already explicitly accounts for the possibility of ember caused ignition of nearby debris. It can therefore be reasoned that the occurrence of embers from product D treated material that passed the requirements for 'Bushfire resistant timber' does not introduce additional risk factors beyond those already envisaged in AS 3959 for BAL-29, however, it does increase the risk for potential ember induced ignition and therefore this should be considered in comparison to any equally effective treatments that do not cause sparks, which may be given preference when considering their application on external timber in BAL-29 areas.

The appearance of the various treated samples are indicated in Figures 56 through 58, however these sample sizes are relatively small and full scale samples would provide a better impression of the treatment appearance.

Table 31. Outcomes from exposure to 25kW/m² heat flux in cone calorimeter							
Exterior fire retardants			Time to ignition	Peak HRRPUA*	Mean HRR	Density	Outcome
Product & #	**Species**	**Form**	**[s]**	**[kW/m²]**	**[kW/m²]**	**[kg/m³]**	
D49	Shining gum	Sawn	870	78	36	660	pass
D50	Shining gum	Sawn	508	91	42	644	pass
D51	Shining gum	Sawn	88	247	34	597	fail
D52	Spotted gum	Sawn	621	130	41	1005	technical pass
D53	Spotted gum	Sawn	522	153	47	921	fail
D54	Spotted gum	Sawn	0	2	0	1014	pass
D55	Tas oak	Veneer Treated Ply	0	12	1	882	pass
D56	Tas oak	Veneer Treated Ply	0	5	0	845	pass
D57	Tas oak	Veneer Treated Ply	0	6	2	819	pass
D61	Tas oak	Plywood	0	4	0	960	pass
D62	Tas oak	Plywood	0	3	0	969	pass
D63	Tas oak	Plywood	0	3	1	894	pass
D64	Spotted gum	Plywood	0	4	2	1038	pass
D66	Spotted gum	Plywood	0	5	1	1088	pass
E67	Shining gum	Sawn	168	142	53	677	fail
E70	Spotted gum	Sawn	284	157	76	937	fail
E71	Spotted gum	Sawn	326	149	68	902	fail
E72	Spotted gum	Sawn	201	168	73	835	fail
E73	Tas oak	Veneer Treated Ply	369	186	84	806	fail
E74	Tas oak	Veneer Treated Ply	358	166	80	833	fail
E79	Tas oak	Plywood	365	248	110	900	fail
E80	Tas oak	Plywood	401	248	108	900	fail
E81	Tas oak	Plywood	415	242	98	902	fail
E82	Spotted gum	Plywood	436	98	39	1006	pass
E83	Spotted gum	Plywood	431	132	47	995	fail
E84	Spotted gum	Plywood	379	130	72	979	fail
F85	Shining gum	Sawn	194	180	70	566	fail
F86	Shining gum	Sawn	176	184	62	564	fail
F87	Shining gum	Sawn	170	196	69	519	fail
F88	Spotted gum	Sawn	192	173	77	823	fail
F89	Spotted gum	Sawn	216	180	74	959	fail
F90	Spotted gum	Sawn	157	167	66	873	fail
F91	Tas oak	Plywood	286	272	126	812	fail
F92	Tas oak	Plywood	254	233	119	818	fail
F93	Tas oak	Plywood	290	255	119	797	fail
F94	Spotted gum	Plywood	373	122	62	1006	fail
F95	Spotted gum	Plywood	366	126	53	985	fail
F96	Spotted gum	Plywood	372	103	53	1024	fail

*peak heat release rate per unit area **mean heat release rate; F = untreated controls.

Product	Material	Exterior
D	Sawn shining gum	
D	Sawn spotted gum	
D	Tasmanian oak veneer treated ply	
D	Spotted gum veneer treated ply	
D	Tasmanian oak plywood treated	
D	Spotted gum plywood treated	

Figure 56. Indicative appearance of product D on various sample substrates. Photo: Rhianna Robinson.

Control	Material	Exterior
F	Sawn shining gum	
F	Sawn spotted gum	
F	Tasmanian oa untreated plywood	
F	Spotted gum untreated plywood	

Figure 57. Indicative appearance of untreated control samples. Photo: Rhianna Robinson.

Product	Material	Exterior
E	Sawn shining gum	
E	Sawn spotted gum	
E	Tasmanian oak veneer treated ply	
E	Spotted gum veneer treated ply	
E	Tasmanian oak plywood treated	
E	Spotted gum plywood treated	

Figure 58. Indicative appearance of product E on various sample substrates. Photo: Rhianna Robinson.

Trial 5.2 Interior

Concept: Tasmanian hardwoods under investigation in this project have low fire performance properties and treatment with a fire retardant may extend their utilisation in interior applications. Unlike exterior applications, interior fire-retardant treatments do not have to withstand extreme weather testing, so spray, dip or flow-coat treatments may be suitable, however, vacuum pressure impregnation could still improve longevity.

Aims: To treat Tasmanian hardwoods using VPI and commercially available fire retardants to improve their suitability for use in interior applications, to test their material efficacy using cone calorimeter tests, and to be able to make recommendations to industry regarding treatment options for future certification work.

Materials and methods: Samples were prepared as for the exterior trial (5.1 above) except for a weathering test. A total of forty interior samples were fire performance tested. A number of samples were not fire tested due to delamination of glue lines or other performance reasons. Specimens were placed in a temperature and humidity-controlled environment with temperatures between 23±2 °C and relative humidity of 50±5 %. Before testing the specimens were wrapped with aluminium foil, leaving only the side facing the cone heater exposed, to ensure one-dimensional heat transfer in the cone calorimeter (Figure 59).

Figure 59. Interior fire-retardant treated sample being tested in cone-calorimeter, back wrapped in foil. Photo: Wenxuan Wu.

Fire performance testing was done using cone calorimeter material tests (i.e. not full-scale assembly tests as required for interior product certification). Samples were rated with a pass or fail according to the requirements for interior use (Group ratings), according to calculations in AS 5637.1. The fire-retardant manufacturers have expressed their desire to keep treatments anonymous (as described above) and trial results are reported using de-identified codes (e.g interior A, exterior D). Limited information regarding solution strength and product active ingredients were provided by the suppliers which disallowed theoretical product retention. Additionally, products were not provided with a tracer/penetration indicator which meant visual assessment of penetration wasn't possible.

Results: Only veneer-based samples achieved the required thresholds to be classified as Group 1 material (Table 33). Product A was the highest performing interior product which achieved Group 1 for all veneer-based samples assessed. Interior product B achieved Group 1 for Tasmanian oak plywood only. No sawn samples achieved Group 1.

Following VPI treatment, the average uptakes were again highest in Tasmanian oak veneers and plywood (Table 32), with product B showing the highest uptakes at 454 l/m^3 in Tasmanian oak veneer. Interestingly, Tasmanian oak plywood also recorded relatively high uptake in product A, at 429 l/m^3. As noted above, laminated samples were tested with a grid in accordance with specification in AS 3837. This was implemented after delamination was observed for initial tests of veneer-based samples without the grid. When samples delaminated in the cone calorimeter, their surface moved closer to the cone heater and was therefore exposed to higher heat flux values; thus the grid was used to ensure uniform testing conditions. This is permissible within the context of AS 3837, however, it poses a problem for the interpretation of results within AS 5637.1. Within this standard, cone testing according to AS 3837 is specified to test lining materials as an alternative test method to more costly testing in AS ISO9705, which details a full room test and estimates the time to flashover for lining materials. In this scenario there are no practicable measures to prevent delamination with a grid. Thus, while some treated veneer-based samples satisfied the numerical thresholds for Group Number 1, they could possibly not be suitable due to the practical implications of the delamination of these products. This issue of application of the results is not clearly defined in the code. Technically only materials that do shrink or melt away from the irradiation of the cone heater are classified as unsuitable materials according to AS 5637.1, so materials that delaminate and warp towards the heater are technically speaking, code compliant, however their effectiveness remains to be seen with full-scale testing.

The appearance of the various treated samples are indicated in Figures 60 through 62, however these sample sizes are relatively small and full scale samples would provide a better impression of the treatment appearance.

Table 32. Average fire-retardant uptakes / interior

Average uptakes (L/m3)	Interior A	Interior B	Control C
Seasoned shining gum	103.52	113.95	n/a
Seasoned plantation spotted gum	57.41	113.1	n/a
Tas oak veneer	350.24	453.8	n/a
Spotted gum veneer	143.81	160.41	n/a
Tas oak plywood	429.13	355.56	n/a
Spotted gum plywood	233.35	185.53	n/a
Highlighted cells indicate samples that achieved Group 1 performance.			

Table 33. Summary of Group ratings / interior							
Product & #	**Species**	**Form**	**Density**	**MC**	**Thickness**	**ASEA***	**Group #**
			[*kg/m*^{3}]	[%]	[mm]	[*m*^{2}/*kg*]	
A1	Shining gum	Sawn	561	16.6	19	27	3
A10	Shining gum	Sawn	570	12	20	28	3
A13	Shining gum	Sawn	554	15.3	20	11	3
A14	Spotted gum	Sawn	938	15.1	23	18	3
A15	Spotted gum	Sawn	872	15.2	25	30	3
A16	Spotted gum	Sawn	923	15	26	30	3
A17	Tas oak	Veneer treated ply	681	18.7	10	41	1
A18	Tas oak	Veneer treated ply	691	15.4	10	45	1
A2	Tas oak	Veneer treated ply	671	12.5	10	28	1
A3	Spotted gum	Veneer treated ply	1026	12.1	17	31	3
A4	Tas oak	Plywood treated	835	17.9	10	24	1
A5	Tas oak	Plywood treated	813	17.2	10	27	1
A6	Tas oak	Plywood treated	832	17.5	10	16	1
A7	Spotted gum	Plywood treated	1009	12.6	18	1	1
A8	Spotted gum	Plywood treated	986	12.8	18	2	1
A9	Spotted gum	Plywood treated	1079		17	2	1
B19	Shining gum	Sawn	576	11.6	19	15	3
B20	Shining gum	Sawn	595	11.4	20	11	3
B21	Shining gum	Sawn	565	15	19		3
B22	Spotted gum	Sawn	974	15.1	23	18	3
B23	Spotted gum	Sawn	1012	16.7	25		3
B24	Spotted gum	Sawn	861	11.6	25	15	3
B31	Tas oak	Plywood treated	798	16.1	10		1
B32	Tas oak	Plywood treated	787	17.2	10	5	1
B33	Tas oak	Plywood treated	835	16.3	10		1
B34	Spotted gum	Plywood treated	813	9.7	22		1
B35	Spotted gum	Plywood treated	1018	11.2	17	2	3
B36	Spotted gum	Plywood treated	1015	13.5	18		3
C37	Shining gum	Sawn	521	9	19	26	3
C38	Shining gum	Sawn	548	9.2	19	29	3
C39	Shining gum	Sawn	615	9.3	19	23	3
C40	Spotted gum	Sawn	862	9.1	26	17	3
C41	Spotted gum	Sawn	899	10.5	26	12	3
C42	Spotted gum	Sawn	913	10.4	23	28	3
C43	Tas oak	Blank plywood	736	8	10	13	3
C44	Tas oak	Blank plywood	734	8.7	10	16	3
C45	Tas oak	Blank plywood	698	8.5	10	62	3
C46	Spotted gum	Blank plywood	1009	8.2	17	14	3
C47	Spotted gum	Blank plywood	1018	8.4	17	18	3
C48	Spotted gum	Blank plywood	954	9.1	17	22	3

*Average specific extinction area; C = untreated controls

Product A	Material	Interior
A	Sawn shining gum	
A	Sawn spotted gum	
A	Tasmanian oak veneer treated ply	
A	Spotted gum veneer treated ply	
A	Tasmanian oak plywood treated	
A	Spotted gum plywood treated	

Figure 60. Indicative appearance of product A on various sample substrates. Photo: Rhianna Robinson.

Product C	Material	Interior
Control	Sawn shining gum	
Control	Sawn spotted gum	
Control	Tasmanian oak untreated plywood	
Control	Spotted gum untreated plywood	

Figure 61. Indicative appearance of untreated control samples. Photo: Rhianna Robinson.

Product B	Material	Interior
B	Sawn shining gum	
B	Sawn spotted gum	
B	Tasmanian oak veneer treated ply	
B	Spotted gum veneer treated ply	
B	Tasmanian oak plywood treated	
B	Spotted gum plywood treated	

Figure 62. Indicative appearance of product B on various sample substrates. Photo: Rhianna Robinson.

Benefits for industry?
While further research is still required to determine the effect of product scale and the influence fire-retardant treatment on bond performance, the successful products trialled in this research are commercially available and the suppliers are willing to be contacted for further research and development if it is of interest to our industry partners. Please contact the principal researcher to discuss.

What still needs to be done?
Given that these were material tests and were not carried out in a NATA certified laboratory, a recommended next step would be to undertake some full-scale assembly tests.
It is also recommended that a replicate trial is carried out using shining gum veneer-based products as this could highlight a significant product opportunity using already established products and methodologies. Additionally, schedule length, solution strength and pre-treatments for improved fire-retardant uptake fell outside the scope of this project. Method enhancement in both spaces saw dramatic improvements for treatment and could be applied to increase fire retardant uptake. This is especially important for sawn shining gum having almost achieved BAL29 with 2/3 samples passing. Simple schedule adjustments and/or modifications to solution strength could see sawn shining gum achieve BAL29 and create a new product opportunity.

To combine a fire-retardant treatment option, with a suitable durability treatment remains a key challenge for the global preservative industry, and more specifically, for low durability, non-fire-resisting timber like shining gum or Tasmanian oak to be used safely as material for exterior claddings.

Communication

Industry Engagement Workshop

To communicate the results of the research trials to our industry partners, an industry engagement workshop was developed and run for NIF078 and its affiliated research project, NIF108, at the Centre for Sustainable Architecture with Wood in Launceston, in May 2022. The workshop ran over the course of a day, with research partners travelling from interstate to present and discuss their work with interested timber industry collaborators (Figures 63 and 64). The workshop was held face-to-face, at the T40 workshop in Newnham, with the opportunity for people to handle treated material and directly interact with researchers throughout the day. A small handbook was provided to participants (Figure 63).

Figure 63. Launceston NIFPI durability projects Industry Engagement Workshop at CSAW in Newnham (left) and printed workshop booklets (right). Photos: Donna Jackman (left) and Kyra Wood (right).

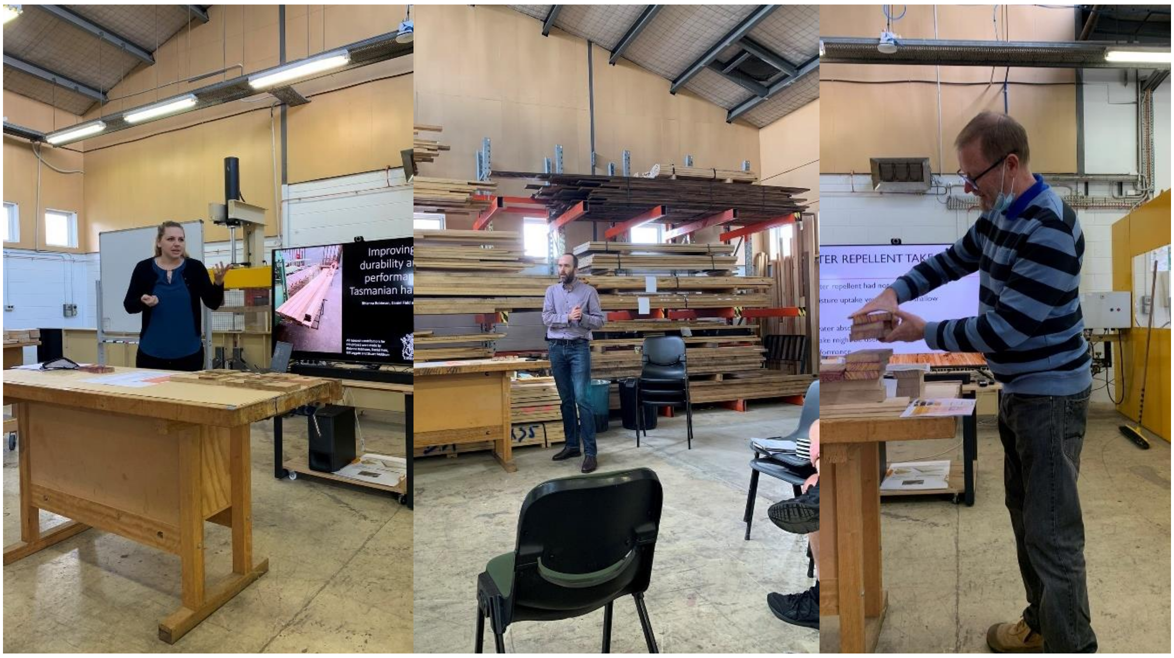


Figure 64. Lead researchers presenting during the Industry Engagement Workshop including: Rhianna Robinson (left), Benoit Belleville (middle) and Stuart Meldrum (right). Photos: Kyra Wood.

Conferences and presentations

Work from this project has already been presented at two conferences in Australia [IFA AFG 2021, Launceston, Australia (Figure 65); and SWST 2022, Kingscliff, Australia], with further presentations planned next year (IRG54, Cairns, Australia).

Figure 65. Forestry Australia (previously IFA AFG) annual conference delegates attending a presentation at CSAW in 2021. Photo: Kyra Wood.

Written Publications

Apart from the initial publication (Wood et al., 2020) this work has not yet been published in scientific journals or other outlets, however several open access peer-reviewed publications are planned or in draft, and a copy will be provided to FWPA, the Launceston NIFPI steering committee, and interested industry partners upon publication.

In addition to journal publications, a series of graphic one-page briefing papers (following a similar format to that used in the industry engagement workshop booklet) are being prepared at the suggestion of the steering committee representative for this project, Ms Suzette Weeding. These will be circulated to interested industry partners and individuals at their request.

Tabulated summaries of research trials

Table 34. Summary of Trial 1 Dual Treatment			
Test	Aims	Results	Recommendations
Trial 1.1 Treatability of Eucalyptus via boron-based dip-diffusion	To test the efficacy of treating GOS Tasmanian hardwoods via dip-diffusion with a boron-based preservative, and establish the appropriate dipping times, solution strengths, and diffusion periods for different thicknesses of timber.	A three-minute dipping time suit the criteria (considering industrial process plus required uptakes), 22mm thick shining gum treats more easily than other thicknesses/Tas oak, 10-15% solution strength is adequate, however stronger concentrations may be needed to account for post-treatment processing, etc.	Test higher concentrations of solution and longer diffusion periods (including exposure to weather, reconditioning and post-treatment interventions like dressing that might affect the treatment).
Trial 1.2 Maximum retention of boron in Tasmanian hardwoods at high concentrations	To establish the highest possible concentration of boron that can be retained in Tasmanian hardwood species.	The highest (theoretical) retention achieved at a solution concentration of 30% was around 0.6% m/m or 3.3kg/m^3. This is significantly greater than the amount required by the Australian Standard for H2 applications, and is also higher than the amount required in the AWPA U1-20 for a dual treatment approach in railway cross-ties (exterior application).	Further research to determine analysed retention of selected boards.
Trial 1.3 Predicting the diffusion rate of boron-based biocides through selected barriers	To collect diffusion-rate data for boron-movement through untreated Tasmanian hardwoods and Tasmanian hardwoods coated with selected preservative barriers and to develop a predictive model for leaching rates over time.	(Data collection is still ongoing)	-
Trial 1.4 Boron-based dip-diffusion with hard preservative overcoat: Upscaled	To test and evaluate the boron-based treatment approach using larger sample sizes and simulating industry standard practices like racking diffusion period (rather than block stacked) air drying (covered and uncovered), reconditioning, final kiln dry and dressing, and waste recovery and disposal.	(Data collection is still ongoing)	Long term durability field trials and short-term laboratory decay tests of the dual treated material.

Table 35. Summary of Trial 2 Vacuum Pressure Impregnation			
Trial	Aims	Results	Recommendations
2.1 + Adjuvants	To establish the most effective combinations of VPI schedule, chemicals, and adjuvants for treating refractory Tasmanian hardwoods to achieve H3	Did not result in consistent successful H3 treatment, but did provide critical data on optimal schedule length, solution strengths, chemical types and adjuvants	Further work with longer schedules could see significant improvements in penetration, uptakes and retention. This work really focussed on trying to match standard treatment schedules, but we saw significant improvements with longer time frames in the treatment cylinder and even slight increases in solution strength. Further work to test the durability of treated material in lab and field trials.
2.2 + Light organic solvent preservatives (LOSPs)	To establish the effectiveness of treating refractory Tasmanian hardwoods with LOSP via VPI to achieve H3	Uptakes were very low, and treated samples would not pass penetration or retention requirements according to AS1604.	Despite the relatively bad result, this approach should not be discounted, as it is a low uptake approach which has advantages for already seasoned timber. Further work to refine solution strength and longer schedules is of interest.
2.3 + Kop-Coat	To establish the effectiveness of treating Tasmanian hardwoods with Kop-Coat proprietary treatment to achieve H3.	Kop-Coat treated samples were difficult to assess using AS1604 benchmarks, as the solution strength was unknown so calculating theoretical retention was impossible. Penetration indicator tests using a boron-reactive indicator spray showed good penetration through the cross section but is worth noting that boron can be unreliable as an indicator if too much time elapses after treatment as the boron may continue to diffuse while other treatments remain relatively fixed. Independent retention analysis showed that some GOS samples passed the required retention target as a % m/m per the requirements in AS1604 for H3.	A Kop-Coat treatment for other refractory hardwoods has received Codemark certification for use in H3 and H4 applications in Australia. This system shows promise, however further research is needed to improve uptakes and retention analysis results, particularly in seasoned material. Further research in laboratory and field trials to assess durability is recommended.
2.4 + Veneer-based	To establish the effect of thinner dimensions (veneers) on treatability of refractory Tasmanian hardwoods	This research successfully developed a veneer-based product from Tasmanian oak that meets the requirement for H3 according to AS1604.	Further research, using different species and full-scale panels is recommended, and NATA certified bond-quality assessment should be undertaken.

Table 36. Summary of Trial 3 Pre-treatments with Vacuum Pressure Impregnation			
Trial	Aims	Results	Recommendations
3.1 Pre-treatments comparison			
3.1.1 Incision	To develop effective incision method for Tasmanian hardwoods, by comparing five novel incision methods.	Most effective was laser followed by nail bed press, using triangulated grid pattern and 10 mm incision depth. Treatment penetrated well through the cross section even though only one surface of each board was incised.	An upscaled trial to refine the use of laser and manual incision should investigate the effects of incising both surfaces, and evaluation the effect of incision on mechanical properties. Short and long-term durability studies on treated material are also recommended.
3.1.2 Microwave	To establish a method to investigate microwave pre-treatment of timber and how it might assist in increasing preservative penetration; and to assess the influence of the board temperature at the time of treatment on preservative uptakes.	Performance improvements were seen in uptake and theoretical retention however a large range was observed between the samples. Moisture gradients within the timber respond unpredictably when microwaved. Preliminary results indicated that the temperature and moisture loss also contributed to preservative uptake.	Exploring mid to low range energy intensity levels for rupturing the wood without causing visible degradation would be of interest.
3.1.3 Compression	To investigate two forms of compression (static and rolling) and establish an appropriate method for Tasmanian hardwoods.	Static and rolling compression recorded the highest uptakes out of all pre-treatments for seasoned shining gum with averages of 287.3 l/m^3 and 289.7 l/m^3 respectively. This was an improvement of approximately 110 l/m^3 in comparison to controls.	Further work to refine the equipment and improve speed in rolling compression is recommended (see also 'best bet' results.
3.2 'Best bet'			
3.2.1 Rolling compression pre-treated samples with VPI charge 3+MCA+adjuvant V	To combine best performing pre-treatment with best performing VPI charge, chemical and adjuvant. Evaluated for penetration, uptakes, and theoretical retention.	Successfully achieved H3 treatment according to requirements of Australian Standard 1604 in 15/15 Tasmanian oak and 14/15 shining gum samples. Analysed retention recorded concentrations below the required levels in the inner $1/9^{th}$.	An upscaled trial to extend the research, and refine the method is highly recommended to enable this approach to reach commercialisation. Slight adjustments to solution strength without a large additional cost, could easily improved analysed retention results.
3.2.2 Thinner dimensioned samples with VPI charge 3+MCA+ adjuvant V	To evaluate the effectiveness of combining the best performing combination of VPI treatment charge, chemical and adjuvant with thinner dimensioned samples.	Did not achieve consistent passes according to the requirements of AS 1604.	Increasing the solution strength could see potential improvements.
3.2.3 Kop-Coat	To see if adjustments to solution strength, etc., could improve retention analysis results.	Impossible for us to assess according to the AS 1604. Recorded two analysed retention passes for the full cross section in Tasmanian oak, but paired and matched inner $1/9^{th}$ did not meet the retention requirements per AS 1604.	An increase in either solution strength or uptake would possibly see increased retention passes. Laboratory and/or field-based durability tests are recommended.

Table 37. Summary of Trial 4 Non-chemical			
Trial	Aims	Results	Recommendations
4.1 Thermo-mechanical densification	to densify shining gum and Tasmanian oak using a THM process and evaluate the effects of varying compression ratios, temperatures and times on set-recovery/swelling (including: immediate recovery after opening the press called 'spring back'; set recovery following a soaking and oven drying cycle; and set recovery following moisture content cycling), colour change, coating adhesion, and delamination	Spring back was entirely controllable Soaking set-recovery test showed that Tas oak was more stable than shining gum in both compression ratios, but both species experienced some swelling. Moisture content cycling tests (using different RHs/temps) showed that densified Tasmanian hardwood would need to be kept at EMCs under 17%. Colour did not change significantly. Coating adhesion was affected by higher pressing temperatures. Compression ratios also had some effect. Most densified samples performed well in the delamination test. Where a higher temperature appears to improve total delamination of Tasmanian oak samples, splits and cracks occurring outside the glue line (and not compiled in the total delamination results) were observed.	Further investigation into feasible industrial systems and application would be of interest. Further investigation into the mechanical properties of densified Tasmanian hardwoods is also necessary. Clarification of different definitions of densification in the literature would help to resolve potential misunderstanding/ misinterpretation. Other non-chemical options, like thermal treatment (i.e. with no compression) may also be of interest for further research.

Table 38. Summary of Trial 5 Fire-retardants			
Trial	Aims	Results	Recommendations
5.1 Exterior	To treat Tasmanian hardwoods via VPI using commercially available fire retardants to improve their suitability for use as cladding in BAL29 bushfire exposure zones, and to test their fire performance using cone calorimeter tests	For exterior fire retardants, product D was the highest performing, achieving BAL29 for all veneer-based products and two out of three sawn shining gum samples. Product D contained a specialised exterior coating, and this could have contributed to the good result.	Full scale assembly tests in a NATA certified laboratory. Replicated trials using shining gum veneers and veneer-based products. Further refinement of the solution strengths and scheduling could see improved results in shining gum sawn boards.
5.2 Interior	To treat Tasmanian hardwoods using VPI and commercially available fire retardants to improve their suitability for use in interior applications, to test their material efficacy using cone calorimeter tests, and to be able to make recommendations to industry regarding treatment options for future certification work	Only laminated samples achieved the required thresholds to be classified as Group 1 material. Product A was the highest performing interior product which achieved Group 1 for all veneer-based samples assessed. Interior product B achieved Group 1 for Tasmanian oak plywood only. No sawn samples achieved Group 1.	(As above.)

Figure 66. Treated and modified samples next to each other for comparison. From top left to bottom right: untreated shining gum; MCA treated shining gum; ACQ treated shining gum; supercritical fluids treated shining gum (see NT047/NIF108 for more detail on SCF treatment); Kop-Coat treated shining gum; LOSP treated shining gum; 37% compression ratio TM densified shining gum; 25% compression ratio TM densified shining gum; rolling compression + charge 3 + MCA + adjuvant V treated Tasmanian oak; and rolling compression + charge 3 + MCA + adjuvant V treated shining gum. Photo: Kyra Wood.

Conclusions

This project experimented with non-pressure dip-diffusion, vacuum pressure impregnation, pre-treatments, non-chemical modification and fire-retardant treatments, with the aim of improving refractory Tasmanian hardwoods' suitability for exterior cladding applications.

This project successfully treated Tasmanian oak and shining gum sawn boards and Tasmanian oak veneer-based products for H3 exposures. Veneer-based products were also successfully treated with commercially available fire-retardants and found to be suitable for BAL29 (exterior exposure) and Group 1 (interior exposure) applications. A summary of the aims, results and recommendations from all research trials has been tabulated (Tables 34 to 38), along with a photo comparing the appearances of the preservative treatments trialled in this project (Figure 65). Indicative images of fire-retardant treatments are included (Figures 55 to 57, and 59 to 61).

The non-pressure boron-based dip-diffusion trial is not complete, as it is affiliated with a PhD investigation, but some interesting findings have already been made, including the optimal dipping times, solution strengths and diffusion times for achieving heartwood penetration in different thicknesses of wood. The PhD candidate has also successfully established the highest concentrations of boron-based preservative treatments that can be retained in Tasmanian hardwood species, and is undertaking an exciting and novel investigation into the diffusion rates through selected barrier treatments, to establish their effectiveness at preventing borates leaching from the timber under high moisture regimes. This research was complemented by an upscaled investigation of the feasibility of the proposed approach in a typical Tasmanian timber industry setting, to better understand the effects of long-term air-drying, reconditioning, and machining/dressing on the proposed treatment.

The vacuum pressure impregnation and pre-treatments trials successfully identified a method to treat sawn shining gum and Tasmanian oak to H3. A rolling compression pre-treatment for shining gum and Tasmanian oak, when used in conjunction with the best performing VPI charge, chemical and adjuvant combination, was highly successful. Slight modifications to the solution strength of the MCA used would see consistent analysed retention passes and would likely meet and/or exceed requirements of AS1604 for both shining gum and Tasmanian oak. It is recommended that further work is completed in this space to confidently establish the concentration parameters for MCA + V to consistently meet and/or exceed the required analysed retentions. In addition to this, further work should be completed to find the upper limit of charge/schedule length. For shining gum, incremental improvements were observed for each increase in schedule length. An ever longer cycle could see increases in uptakes and retentions and potentially negate the need for a pre-treatment. In addition, the impact of rolling compression on wood anatomy and wood properties remains unexplored as it was outside the scope of the research to consider implications of mechanical properties. It is recommended that research and development is completed to improve the rolling compression process and to better understand the rupturing mechanisms, the effects on mechanical properties and wood anatomy. After this work is completed a cost benefit analysis for the potential adoption of compression rolling into large scale industry settings is recommended.

This project also successfully developed a veneer-based H3 product for Tasmanian oak. Whilst this product met the required retentions and penetrations, adhesive performance testing and bond quality assessments to relevant standards were not explored. It is recommended that full size panels are manufactured and NATA accredited bond quality assessments are performed to correctly classify how this product can be used whilst maintaining desired treatment levels. Additionally, exploring differing adhesives fell outside the scope of this project. Work to investigate preservative, adjuvant and adhesive combinations on bond performance is recommended. This work was completed on Tasmanian oak and the performance of shining gum remains unknown. It is recommended that this H3 trial is replicated on veneer-based products made from shining gum and other Tasmanian hardwood species.

Across all trials it was observed that shining gum readily treated in the early wood bands leaving the latewoods bands relatively untreated (except in the rolling compression treatment approach). Boards provided for the trials were predominantly quartersawn emphasizing the treatment disparity between early and latewood zones and creating a striped effect when assessing penetration. This striped effect when assessed against the standard reduces the number of boards that can pass penetration despite showing penetrated heartwood in many instances. Further research is required to better understand this effect as well as potential treatment trials exploring the penetration performance of back sawn timber.
Further treatments in collaboration with Kop-Coat are required to define the appropriate methods to achieve required retentions. Kop-Coat shows promise and some samples have met the required retention however further research is required.

The non-chemical, thermo-mechanical densification trial found that shining gum and Tasmanian oak were both able to be successfully densified using two different compression ratios, and showing no sign of spring back. The colour of shining gum remained stable across all the pressing conditions considered in the present study, while the colour of Tasmanian oak remained stable across all the pressing conditions except for 175°C where significant colour change was perceived.

Water was picked up faster in densified shining gum than in densified Tasmanian oak when soaking in water and this also depended on the compression ratio. Thickness swelling was slightly higher in shining gum than in Tasmanian oak after 2 hours and 24 hours in water. This observation corroborated the set recovery results where densified Tasmanian oak maintained better dimensional stability after exposure to water. Set recovery and set recovery variability between the species forming the Tasmanian oak group reduced significantly going from a compression ratio of 25% to 37%. Set recovery for all studied species could be minimised significantly with the application of an appropriate protective sealant and potentially be used in wet conditions or where the material can produce sufficient dimensional stability to make the densified wood serviceable under conditions in which the equilibrium moisture content (EMC) may be 16% or higher.

A comparison of the average set recovery results following a moisture content cycling suggested that both shining gum and Tasmanian oak species were stable following the densification process and would be suitable for dry-use environmental conditions i.e., capable of producing sufficient dimensional stability to make the densified wood serviceable under conditions in which the EMC does not exceed 17%. Extending the densification pressing time or increasing the pressing temperature appeared to have a negative effect on the adhesion property of densified samples except for shining gum when using a compression ratio of 37%, while a compression ratio of 37% did not affect the pull-off strength of Tasmanian oak when compared with a control. Finally, most *E. nitens* and *E. delegatensis* densified samples performed well in the delamination test. Where a higher temperature appeared to improve total delamination of Tasmanian oak samples, splits and cracks occurring outside the glue line were observed.

The densification work served to show that although material would not likely be suitable for exterior applications, it might be useful for interior linings or composite interior materials where a material that is harder and more resistant to surface abrasion is needed. While densification is not a commercial reality yet, some potential further research would be to investigate different methods of modification, including thermo-hydro-mechanical densification, and developing or building a rig capable of densifying larger scaled boards to more closely represent industrial processing.

Finally, fire-retardant trials proved to be successful in reaching both BAL-29 and Group 1 for veneer-based products. These trials were successfully completed with Tasmanian oak however the performance of shining gum veneer-based products remains unknown. It is recommended that a replicate trial is carried out using shining gum veneer-based products as this could highlight a significant product opportunity using already established products and methodologies from this research. Additionally, schedule length, solution strength and pre-treatments for improved fire-retardant uptake fell outside the scope of this project. Method enhancement in both spaces saw dramatic improvements for preservative treatments and could be applied to increase fire-retardant uptake. This is especially important for sawn shining gum having almost achieved BAL-29 with 2/3 samples passing. Simple schedule adjustments and/or modifications to solution strength could see sawn shining gum achieve BAL29 and create a new product opportunity.

A long-term aim of the preservative industry globally, and one which was outside the scope of this research, is to pursue the effective combination of durability and fire-retardant treatments. While this project successfully treated Tasmanian hardwood timber and veneer-based products for H3 exposure, and veneer-based products for BAL-29 exterior exposure and Group 1 interior exposure, at this stage, there are still limited options available that claim to achieve both durability and fire-retardance satisfactorily according to the relevant Australian Standards. Future research to combine durability and fire-retardance needs to be undertaken from a collaborative approach of industry and research partners.

Recommendations

- Further research into an optimised rolling compression + VPI treatment method is highly recommend, to refine the engineering and design of the pre-treatment system, scale up the sample sizes and scope of the research overall, test mechanical and other properties of treated material, and potentially commercialise this system

- Further preservative and fire-retardant treatment work in veneer and veneer-based products using additional species (e.g. shining gum and blue gum)

- Further work on thinner dimensioned laminated elements (e.g. LVL, plywood) and potential glue line treatments

- Research into the effects and effectiveness of preservative treatment on other laminated elements (e.g. GLT/CLT) using some of the methods and approaches trialled in this project

- Further work to optimise the solution strengths and VPI pressures and schedule lengths for fire-retardant treatments on sawn shining gum boards

- Further refinement to optimise the solution strengths and schedule lengths of the adjuvant VPI treatment approach (this could eventually eliminate the need for a rolling compression pre-treatment to achieve H3 compliance according to AS1604.1:2021)

- Further research into the effect of initial wood moisture and grain orientation on the densification profile in compressed solid wood and the development of a rig capable of densifying larger scaled boards

References

Amburgey, T. L. and 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. and 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. and 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/WP97-40093, 8pp.

Archer, K. and Lebow, S. (2006) 'Wood Preservation'. In: Walker, J.C.F. (ed.) PRIMARY WOOD PROCESSING PRINCIPLES AND PRACTICE, 2nd edition, 297-338.

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

AWPC. (2015) ‘Protocols for assessment of wood preservatives’. *Australian Wood Preservation Committee*, 32pp.

Bao M., Huang X., Jiang M., Yu W. and Yu, Y. (2017) ‘Effect of thermo-hydro-mechanical densification on microstructure and properties of poplar wood (Populus tomentosa)’. *Journal of Wood Sciences,* 63:591-605.

Balasso, M., Kutnar, A., Niemela, E. P., et al., (2020) ‘Wood properties characterisation of thermos-hydro mechanical treated plantation and native Tasmanian timber species’. *Forests,* 11(11), 1189. DOI: https://doi.org/10.3390/f11111189.

Beadle, C., Volker, P., Bird, T., Mohammed, C., et al., (2008) ‘Solid-wood production from temperate eucalypt plantations: a Tasmanian case study’. *Southern Forests 2008*, 70(1): 45-57.

Blomberg, J., Persson, B. and Bexell, U. (2006) ‘Effects of semi-isostatic densification on anatomy and cell-shape recovery on soaking’. *Holzforschung,* 60: 322–331.

Cech, M. Y. and 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. and Morrell, J. J. (1999) ‘Effect of incising on the strength of green Douglas-fir lumber’. *Forest Products Journal*, 49(9): 55-58.

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. and McCarthy, K. (1998) ‘Boron treatment methods for lyctid susceptible hardwoods growing in Tasmania’. *Proceedings IRG Annual Meeting*, IRG/WP98-30168, 12pp.

Deng, X. (1990) ‘Compression rolling of timber: a theoretical model and experimental verification’, Thesis, University of Canterbury, pp. 183.

Esteves, B., Marques, A.V., Domingos, I. and Pereira, H. (2007) 'Influence of steam heating on the properties of pine (*Pinus pinaster*) and eucalypt (*Eucalyptus globulus*) wood'. *Wood Sciences and Technology,* 41:193-207.

Findlay, W. P. K. (1985) 'Preservative methods'. In: Findlay, W.P.K. (ed.) PRESERVATION OF TIMBER IN THE TROPICS, Dordrecht, Springer-Science + Business Media B.V., 43-57.

Francis, L., Semple, K., Hassan, B. and Morrell, J.J. (2022) 'Natural durability of young plantation and native forest regrowth *Eucalyptus cloeziana'*. Presented at: *2022 SWST 65th International Convention*, July 10-15, Kingscliff, NSW.

Gunzerodt, H., Walker J. C. F. and Whybrew, K. (1986) 'Compression rolling and hot-water soaking: effects on the drying and treatability of *Nothofagus fusca* heartwood'. *New Zealand Journal of Forestry Science,* 16(2): 223-236.

Huang, X., Kocaefe, D., Kocaefe, Y., Boluk, Y. and Pichette, A. (2012) 'Study of the degradation behavior of heat-treated jack pine (*Pinus banksiana*) under artificial sunlight irradiation'. *Polymer Degradation and Stability*, 97:1197-1214.

Ingram, J. K. and Morris, P. J. (2015) 'Performance of borate-treated glulam and LVL after eight years in an accelerated above-ground field test'. In: *Field Performance of Durable Wood Products – Progress Report 2015/16*. Canada, FPInnovations, pp. 58.

Kariz, M., Kuzman, M.K., Sernek, M. et al., (2017) 'Influence of temperature of thermal treatment on surface densification of spruce'. *European Journal of Wood and Wood Products*, 75: 113–123.

Kumar, C. (2021) 'Investigation of an innovative preservative treatment of green timber using compression'. *Wood material science and engineering*,
DOI: 10.1080/17480272.2021.1898466

Kutnar, A., Kamke, F.A. and Sernek, M. (2009) 'Density profile and morphology of viscoelastic thermal compressed wood'. *Wood Science and Technology,* 43:57-68.

Laine, K., Segerholm, K., Walinder, M., Rautkari, L., Ormondroyd, G., Hughes, M. and Jones, D. (2014) 'Micromorphological studies of surface densified wood'. *Journal of Materials Science*, 49: 2027-2034.

LeVan, S.L. and Tran, H.C. (1990) 'The role of boron in flame-retardant treatments'. In: *Proceedings, Hamel, M., (ed), 1st International conference on wood protection with diffusible preservatives*, Nov. 28-30, Nashville TN., 47355, 39-41.

Metsa-Kortelainen S., Antikainen T. and Viitaniemi P. (2006) 'The water absorption of sapwood and heartwood of Scots pine and Norway spruce heat-treated at 170 °C, 190 °C, 210 °C and 230 °C'. *Holz als Roh-Werkst: European Journal of Wood and Wood products*, 64: 192-197.

Morrell, J. J. and 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.

Morris, P. J., Wang, J. and Ingram, J. K. (2008) 'Ability of Transparent Coatings to Retard Leaching of Borates in a Weather-Ometer Test'. In: *Proceedings, FSCT Advancement in Coatings Series. Coatings, Wood and Wood Composites: Design for Durability*, July 23-25, Seattle, WA., 44-47.

Navi, P. and Heger, F. (2004) 'Combined densification and thermo-hydro-mechanical processing of wood'. *Materials Research Society Bulletin,* 29: 332–336.

Nicholas, D. D., Siau, J. F. (1973) 'Factors influencing treatability'. In Nicholas, D.D. (ed.) WOOD DETERIORATION AND ITS PREVENTION BY PRESERVATIVE TREATMENTS, Vol II, Syracuse, NY, Syracuse University Press, 299-343.

Ra, J.B., Barnes, H.M. and Conners, T.E. (2001) 'Determination of boron diffusion coefficients in wood', *Wood and Fiber Science*, 33(1): 90–103.

Rautkari L., Laine K., Laflin N. and Hughes, M. (2011) 'Surface modification of Scots pine: The effect of process parameters on the through thickness density profile'. *Journal of Materials Science*, 46: 4780-4786.

Sandberg, D., Kutnar, A. and Mantanis, G. (2017) 'Wood modification technologies - a review'. *iForest - Biogeosciences and Forestry*, 10: 895–908.

Sandberg, D., Haller, P. and Navi, P. (2013) 'Thermo-hydro and thermohydromechanical wood processing: an opportunity for future environmentally friendly wood products'. *Wood Materials Science and Engineering*, 8: 64–88.

Sanders, M. G., Amburgey, T. L. and Barnes, H. M. (2000) 'Innovations in the treatment of Southern pine heartwood'. *Proceedings IRG Annual Meeting,* IRG/WP/0040172, 7pp.

Siau, J. F. (1971) FLOW IN WOOD. Syracuse University Press, Syracuse, NY.

Standards Australia. (2021) Standard AS/NZS 1604, 'Preservative-treated wood-based products'. Melbourne, Australia.

Standards Australia. (2018) Standard AS 3959, 'Construction of buildings in bushfire-prone areas'. Melbourne, Australia.

Standards Australia. (2016) Standard AS ISO9705, 'Fire tests - Full-scale room test for surface products'. Melbourne, Australia.

Standards Australia. (2015) Standard AS 5637, 'Determination of fire hazard properties'. Melbourne, Australia.

Standards Australia. (2012) Standard AS/NZS 1080, 'Timber – Methods of test moisture content'. Melbourne, Australia.

Standards Australia. (2005) Standard AS 5604, 'Timber- Natural Durability Ratings'. Melbourne, Australia.

Standards Australia. (1998) AS/NZS 3837, 'Method of Test for Heat and Smoke Release Rates for Materials and Products Using an Oxygen Consumption Calorimeter'. Melbourne, Australia.

Tamblyn, N. E. (1985) 'Treatment of wood by diffusion'. In: Findlay, W.P.K. (ed.) PRESERVATION OF TIMBER IN THE TROPICS, Dordrecht, Springer-Science + Business Media B.V., 121-140.

Tarmian, A., Zahedi Tajrishi, I., Oladi, R. and Efhamisisi, D. (2020) 'Treatability of wood for pressure treatment processes: a literature review'. *European Journal of Wood and Wood Products*, 78: 635-660. DOI: https://doi.org/10.1007/s00107-020-01541-w

Tenorio C. and Moya, R. (2021) 'Development of a Thermo-Hydro-Mechanical Device for Wood Densification Adaptable to Universal Testing Machines and Its Evaluation in a Tropical Species'. *Journal of Testing and Evaluation*, 49(4): 2597-2608.

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

Torgovnikov, G. and 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, 7pp.

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

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, 5pp.

Wood, K.C., Morrell, J.J. and Leggate, W. (2020) 'Enhancing the durability of low durability Eucalyptus plantation species: a review of strategies'. *Proceedings IRG Annual Meeting*, IRG/WP 20-40910, 21pp.

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

Zabel, R.A., and Morrell, J.J. (2020) WOOD MICROBIOLOGY. 2nd edition, Academic Press, San Diego, CA.

Acknowledgements

The authors would like to thank the National Institute for Forest Products Innovation for the opportunity to undertake this research. We would also like to acknowledge the significant input and sponsorship from associated industry partners, specifically from the project's lead industry partner, Shawn Britton (Managing Director, Britton Timbers), project steering committee chair, Suzette Weeding (General Manager, STT), Launceston steering committee chair, Terry Edwards, and other key industry partners affiliated with the project. The authors would like to acknowledge the support and input of Forest and Wood Products Australia. The authors would like to acknowledge the significant contribution of various named and unnamed research partners who participated in trials or otherwise contributed to the research at the University of Tasmania, the Queensland Department of Agriculture and Fisheries, the University of Melbourne, the University of Queensland and the University of the Sunshine Coast.

Researcher’s Disclaimer (if required)