FIRE PROPERTIES OF EUCALYPTUS BOSISTOANA:

Investigating the Correlation between Density & Heat Release Rate

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Abstract

The New Zealand forestry industry is heavily reliant on the production of radiata pine, with an estimated 90% of plantation forests being used for this. To be used effectively for construction, radiata pine is needed to undergo chemical treatment for preservation. However, using these treatments has given rise to substantial environmental concern. With growing efforts to mitigate the effects of climate change, alternatives are being considered such as New Zealand-grown hardwood.

Eucalyptus bosistoana is a fast-growing hardwood that grows well in New Zealand conditions. It has been found that *E. bosistoana* has favourable mechanical properties, such as its natural durability, which presents opportunities for products in both domestic and international construction markets for untreated timber. However, no data is evaluating the performance of *E. bosistoana* under fire conditions which is important for both domestic use, and meeting bushfire requirements in Australia for an export product.

Oxygen consumption cone calorimetry can be used to analyse the burning behaviour of a material and can be used to calculate important fire properties for design; most notably the heat release rate (peak and total), the ignition time, and the mass loss rate. This study aims to provide preliminary data on the fire properties of *E. bosistoana* using cone calorimetry – primarily the heat release rate behaviour and the ignition time and identify whether there is a correlation between the peak heat release rate and the density of the timber. The other primary objective of this study was to provide an indicative test to investigate whether *E. bosistoana* met the bushfire attack level (BAL-29) criteria, the highest zone for untreated timber for construction use in Australia.

The results showed that the average peak heat release rate for 10 mm thick samples of *E. bosistoana* tested at an irradiance of 25 kW/m^2 was 257.07 kW/m^2 and that the average total HRR was 106.25 MJ/m^2. The ignition times for these samples ranged between 52 and 64 seconds. When testing a 20 mm sample to an irradiance of 25 kW/m^2, it was found that *E. bosistoana* did not meet the requirements for BAL-29, as although the average heat release rate was less than the required 60 kW/m^2 (30.6 kW/m^2), it exceeded the maximum pHRR of 100 kW/m^2 (132.7 kW/m^2). It was also found that a correlation between measured density and both peak heat release rate and total heat release was found, with an R^2 value of 0.8725 and 0.8653, respectively.

This study was significantly constrained by both time and budget, which resulted in a reduction in sample size, and it is recommended that future research with a greater number of experiments and a wider range of species would be beneficial. The initial results found in this study indicate the potential for *E. bosistoana* to be used as an alternative to chemically

treated softwoods, however future research into international compliance is required for use in export markets.

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List of Symbols

Symbol	Definition	Unit
A_s	Initial exposed area of the specimen	m^2
C	Calibration constant for orifice flow meter	$m^{1/2}/g^{1/2}/K^{1/2}$
d	Thickness of specimen	mm
Δh_c	Net heat of combustion	K J/g
L	Length of specimen	mm
m	Mass of specimen	g
Δp	Pressure differential for orifice flow meter	Pa
$\dot{q}$	Heat release rate	kW
$\dot{q}_A(t)$	Heat release rate per unit area	kW/m^2
$\dot{q}_b$	Heat release rate of methane supplied	kW
q''	Total heat released during combustion	kJ
r_0	Stoichiometric oxygen/fuel mass ratio	1
ρ	Density	kg/m^3
t	Time	s
T_e	Absolute temperature of gas at the orifice meter	K
Δt	Time interval for sampling	s
W	Width of specimen	mm
$X_{O_2}^0$	Initial oxygen analyzer value	1
X_{O_2}	oxygen analyzer value before delay time correction	1

Introduction

Timber has a wide range of applications used across numerous industries in New Zealand, particularly in construction. The selection of wood species is crucial when determining the performance, durability, and safety of timber products. Among these performance properties, fire properties are a key requirement to determine. The natural flammability of timber requires careful planning so that fire spread is both limited and delayed, especially in densely populated areas where fire hazards are both higher, and potentially deadly (Zang et al., 2023).

The Case for *Eucalyptus bosistoana*: Issues with Chemically Treating Timber

The New Zealand forestry industry is heavily reliant on the production of radiata pine (*Pinus radiata*). NZ's commercial plantation forests comprise approximately 90% radiata (Ministry of Primary Industries, n.d.) Similarly, the species comprises approximately 90% of structural timber application in New Zealand (Xu, 2000).

The use of hardwoods in timber products in New Zealand present several opportunities in competition with radiata pine. It has been well established that structural use of Radiata Pine in New Zealand requires that it must undergo preservative treatment as it is a non-durable wood species. The most common preservative treatments used New Zealand is copper-chrome-arsenate (CCA), light organic solvent preservatives (LOSP), and boron compounds (BRANZ Limited, 2023).

Both CCA and LOSP preservative treatments are used for preventing timber decay in outdoor areas exposed to moisture and are commonly used in products such as fencing or decking. Boron preservative is commonly used for H1.2 framing timber in New Zealand. This is a water-based preservative and has reported no long-term adverse effects under normal conditions and using good building practices (BRANZ Limited, 2023).

Using chemical treatment to enhance the timber properties is not without cost. CCA is a toxic chemical mixture but is relatively impotent once fixed in the timber. However, over time small quantities of chemicals can leach out over time (BRANZ Limited, 2023). In 2003, Environmental Protection Agency (EPA) made it so chromated arsenicals manufacturers discontinued the distribution of chromated arsenicals treated timber to homeowner uses (United States Environmental Protection Agency, 2024).

A major issue is the disposal of CCA-treated timber after service life as the treatment severely impacts recyclability. At significant costs, large numbers of CCA-treated posts have been disposed of in secure landfills, or else stockpiled on-site (NZDFI, n.d.). Due to the adverse effects treated timber can have on the environment, some sectors refuse to use treated timbers (NZDFI, n.d.). The substitution of CCA-treated pine with naturally durable hardwood likely reduces the production of hazardous timber waste (Nicholas & Millen, 2012).

The banning of CCA-treated wood for many uses opens new opportunities for naturally durable hardwoods. It has been found that a range of eucalyptus species exhibit high levels of natural durability (Li & Altaner, 2016). Natural durability is defined by the Australian Durability Standard AS5604 as “the inherent resistance of a specific timber to decay and to insect attack” (NZDFI, n.d)

Eucalyptus bosistoana has been shown to exhibit natural durability and is categorized to supply class 1 ground-durable hardwood as per the classification provided by the Australian standard for natural timber durability (Australian Standards, 2005). The natural durability exhibited by *E. bosistoana* species allows for it to be a viable option for domestic-grown hardwoods to compete in markets desiring durable timber without needing chemical treatment. However, the fire performance of *E. bosistoana* is relatively unknown, and needs to be established as this is an important factor when using timber for structural application and design.

Fire Properties Used in Design

Different wood species’ fire properties can vary due to a range of factors like density, dimensions, and moisture content. These factors significantly affect ignition time (t_{ig}), effective heat of combustion ($\Delta h_{c,eff}$), heat release rate (HRR), and char formation (Sanned, 2022). Some of the parameters used in the testing of fire properties are defined as follows:

Ignition Time:

The ignition time reflects the ability of materials to resist from burning with sustainable flame when exposed to high temperature. Ignition time is calculated as the time from the start of high heat exposure to the point when the composite burns (Tran et al., 2018).

Effective Heat of Combustion:

The effective heat of combustion refers to the amount of heat released by the burning material divided by the mass loss for a specified amount of time. This will show how much energy will be released when the material is burnt to see how efficient it is when used as a fuel.

Heat Release Rate:

The rate of heat release is the most important parameter for characterizing an unwanted fire (Redfern, 1989). Knowing the HRR curve will allow for the determination of how quickly and severely a fire will grow, which is important during designing for smoke and fire detection, suppression, and escape models. Figure 1. shows a general example of a HRR curve, and different life stages of the fire.

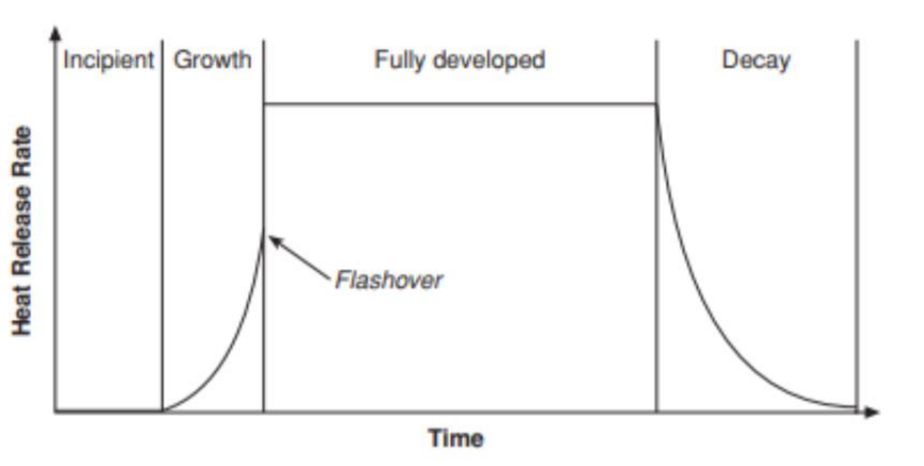

Figure 1 Idealized HRR history showing all stages (Spearpoint, 2008)

In general, fire life can be characterized into 4 different stages in terms of the HRR; the incipient, growth, fully developed, and decay. These are described as follows:

- ***Incipient Stage***: is when it has small flames and low heat, where ignition and early pyrolysis happen. Smoke from an incipient fire does not obstruct visibility (Western Fire Chiefs Association, 2024). Negligible HRR.
- ***Growth Stage***: this can be split into two parts which are pre-flashover, and flashover. As the fire accelerates it fills the area with a hot smoke layer, which thickens until flashover conditions are reached.
- ***Fully Developed Stage:*** occurs when flash-over happens and nearly all exposed combustibles ignite virtually simultaneously. At this stage HRR is sustained and peak temperatures occur.
- ***Decay Stage***: at this stage, HRR declines as combustible mass is spent, or ventilation is reduced by collapse/debris,

  (Spearpoint, 2008)

The total heat release (THR) is another important parameter in assessing fire behavior as it characterizes the total available energy in the material in a possible fire situation. It can be calculated as the area under the HRR curve, measured in the cone calorimeter (Grexa, et al., 1997). THR provides valuable insight into the potential severity of a fire event.

The most important property to consider for fire design is the HRR curve, as this allows for the determination of how quickly and severely an unwanted fire can grow (Redfern, 1989). Higher levels of external irradiance are strongly correlated with increased HRRs and THR, while decreasing the time to ignition. Additionally, both THR and ignition times increase with wood density (Grexa, et al., 1997). Investigating the possible relationship between the density and HRR of eucalyptus wood could be used to help predict fire performance based on wood density.

Fire Safety Requirements: Bushfire Attack Levels (BAL)

As of 2023, Australia is New Zealand's second largest export market for forestry products, with a total value of ~$563 million exported during that year (Forest Owners Association, 2023).

Eucalyptus bosistoana grown in New Zealand could have potential as in export product to Australia due to the natural durability of the timber outlined above.

One of the important factors to consider when exporting New Zealand-grown *E. bosistoana* is the compliance to international standards for fire rating. In Australia, the risk of building exposure to bushfire is classified using the bushfire attack level (BAL) criteria.

Outlined in the standard AS 3959, the BAL identify the severity of impact that factors such as exposure to embers, flame contact and radiant heat have on a building site, as well as site characteristics such as slope and vegetation (Wiesner, 2023).

In terms of construction materials, the highest BAL zone level for untreated timber is BAL-29. To meet the criteria, the timber must be classified as a bushfire resistant timber by being tested using oxygen consumption cone calorimetry outlined in the AS/NZS 3837 standard in which the timber is exposed to a radiant heat flux of 25 kW/m^2. To satisfy the BAL-29 criteria, the timber must meet the following two conditions:

- A measured value of 100 kW/m^2 cannot be exceeded for the peak heat release rate (pHRR) per unit area
- An average value of 60 kW/m^2 cannot be exceeded for the HRR per unit area

Assessment on whether New Zealand grown *E. bosistoana* complies with the requirements outlined in the BAL-29 could provide a potential avenue for an export market for hardwood timber without needing additional chemical treatments.

Rationale for the Study

The purpose of this study is to assess the fire performance of New Zealand grown *E. bosistoana*. This will be achieved by evaluating the current research about the properties of *E. bosistoana* and apply standardised testing methods outlined in both the ISO 5660 and AS/NZS 3837 standards. The resulting data can be used to illustrate how *E. bosistoana* performs and provide initial datapoints for future investigation.

Literature Review

Durability

New Zealand Dryland Forests Innovation provides the classification system used in determining durability class for timber. This is shown in Table 1. *E. bosistoana* has been classified as a class 1 ground-durable hardwood in accordance with the Australian standard for natural timber durability (Australian Standards, 2005).

Table 1 Classification of Natural Durability (probable life expectancy) in accordance with the Australian Standard AS 5604. Data obtained from (NZDFI, n.d).

Class	**Probable in-ground life expectancy (years)**	**Probable above-ground life expectancy (years)**
1	>25	>40
2	15 – 25	15 – 40
3	5 – 15	7 – 15
4	0 - 5	0 – 7

Mechanical Properties

Although there is significant interest in New Zealand for *E. bosistoana* due to growing well in New Zealand conditions and its reputation of being a highly durable wood (Apiolaza, et al., 2011), the only reported testing of mechanical properties is on wood grown in Australia. The reported mechanical properties have shown substantially better mechanical properties compared to radiata pine, shown in Table 2 (Nicholas & Millen, 2012).

Table 2 Mechanical properties of different species at 12% moisture content in Australia and New Zealand (Nicholas & Millen, 2012).

Origin/Species	Modulus of Rupture (MPa)	Modulus of Elasticity (MPa)	Compression Parallel (MPa)	Hardness (kN)	Density (Air-Dry) (kg/m^3)
Australia					
E. bosistoana	163	21	73	13	1100
E. globoidea	133	17	68	8.8	880
New Zealand					
E. bosistoana	N/A	N/A	N/A	N/A	N/A
E. globoidea	132	14.6	66.7	6.9	805
Pinus radiata	89	8.5	38	5.0	500

If the mechanical properties of *E. bosistoana* were tested under New Zealand conditions, the results would likely be lower compared to the known values in Australia, following the trends established in Table 2, with *E. globoidea*, as these are typically determined through standardised testing methods. A study conducted in Uruguay that showcased the characterization of mechanical and durability properties of *E. bosistoana* trees with ages ranging from 7 to 49 years found that the density, hardness, and strength values were 727.39 kg/m^3, 114.12 MPa, and 61.31 MPa respectively. The findings of this study suggest that *E. bosistoana* can perform favourably in construction applications requiring high density and durability such as and flooring. It was also found to be relatively dimensionally stable, as the shrinkage measurements were 6.2% in the radial direction, and 11% in the tangential direction. This indicates that *E. bosistoan*a is classified as “suitable for drying or normal use” and “stable” (Passarella, et al., 2023).

Fire Properties

Although there are currently no documented HRR graphs available for *E. bosistoana*, a 2015 study developed HRR curves for plywood samples constructed from a range of eucalyptus species. Subject to an irradiance of 50 kW/m^2, the HRR graphs were obtained via testing using a cone calorimeter and are showcased in Figure 2. The study highlights the difference in HRR curves for both untreated and veneer-treated eucalyptus plywood.

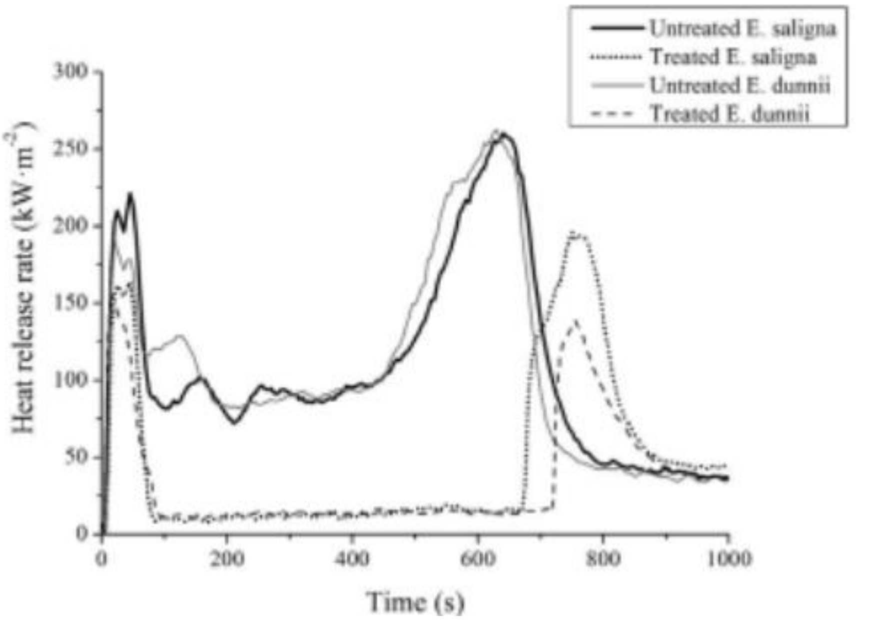

Figure 2 HRR behavior for a variety of species of eucalyptus plywood (Hu et al., 2015)

The research suggests that the presence of multiple peaks is commonplace among timber. The initial peaks tend to occur immediately after ignition of the outer wood, before declining to a relatively steady state. This happens likely due to char formation which acts as an insulation layer, slowing heat transfer throughout the wood. The secondary peak is theorised to form via sample burn through and char cracking (Hu et al., 2015).

A notable result was that fire treated eucalyptus plywood exhibited lower pHRR across species than untreated, with samples of *E. saligna* having pHRR values of 218 kW/m^2 and 162 kW/m^2 respectively, and *E. dunni* showcasing pHRRs of 222 kW/m^2 and 147 kW/m^2 respectively (Hu et al., 2015).

Char formation is an effective method of increasing the fire resistance of materials. The material which forms carbonaceous char has a reduced ability to supply the gaseous fuels required to fuel the fire (Wypych, 2016). This is an important parameter in determining fire resistance and can help explain the behavior of the HRR curves. It is important to note that the fire performance of engineered wood products such as plywood may not necessarily indicate the fire performance of solid wood, as a study by Chanda, Das and Bhattacharyya (2024) showed that solid wood samples of radiata pine with a thickness of 25 mm exhibited a pHRR of 185.3 kW/m^2 as opposed to thin plywood samples (2 mm thick) of radiata pine showcasing pHRRs between 536.3 and 571.6 kW/m^2 depending on adhesive type. These variations are mostly attributed to the ability for char formation to be increased on solid wood (Chanda et al., 2024). The current research does not indicate the HRR behavior of solid wood *E. bosistoana* and thus provides an avenue for this study to investigate.

Density and Correlation with HRR

Bulk density (ρ), defined as the mass of oven-dry wood per unit volume, has been recognized as a key determinant of fire intensity. From a cone calorimetry test, the HRR curve can give a pHRR, an average HRR and the THR. In controlled cone calorimetry tests, the THR due to combustion showed a positive correlation with density. However, the THR might not be the most important value from the HRR curve as the pHRR is considered to be the parameter that best expresses the maximum intensity of a HRR curve (Xu et al., 2015). The average HRR is a linear function of irradiance (Tran, 1996), therefore, it would not be appropriate to use the average HRR to develop a correlation between density and HRR. It was also suggested that other factors besides density such as conditioning, irradiance and orientation of the specimen were influential (Janssens, 1990; Nagaoka, et al., n.d.). Although density may likely be influenced by other physical properties of wood, it is the most reliable indicator of ignitability and combustibility for wood (Nagaoka, et al., n.d.).

Bushfire Attack Levels

The factors that are used to evaluate the risk level of bushfire attack and identify a BAL are radiant heat exposure, ember exposure, direct flame exposure and environmental conditions such as slope, type and proximity to vegetation, and wind. The Australian standard AS 3959 categorises six BAL levels which are outlined in Table 3.

Table 3 Defining bushfire attack level (BAL) zones as outlined in AS 3959, Appendix G

BAL	**Definition**	**Risk Level**	**Maximum Heat Flux Exposure (kW/m²)**
BAL-LOW	Insufficient risk to require construction specifics	Very low	n/a
BAL-12.5	Risk of ember attack	Low	12.5
BAL-19	Risk of ember attack and burning debris exposure	Moderate	19
BAL-29	Increased risk of ember attack and burning debris exposure	High	29
BAL-40	High risk of ember attack and burning debris – some likelihood of fire front exposure	Very high	40
BAL-FZ	Exposure to extreme levels of radiant heat from fire front	extreme	40

The highest BAL zone permissible for untreated timber is BAL-29 (Wiesner et al., 2023). Therefore, testing *E. bosistoana* at the level of irradiance consistent with this level becomes important in determining its viability for BAL-29 classification. The AS 3959 has currently determined nine species that meet the requirements for BAL-29 classification which are listed in Table 4.

Table 4 Tested wood species that are compliant to the BAL-29, alongside their corresponding air-dried density (WoodSolutions, n.d.).

Botanical Name	Standard Trade Name	Density (kg/m^3)
Eucalyptus sieberi	Ash, Silvertop	850
Eucalyptus pilularis	Blackbutt	900
Eucalyptus camaldulensis	Gum, River Red	910
Corymbia maculata	Gum, Spotted	990
Corymbia henryi	Gum, Spotted	990
Corymbia citriodora	Gum, Spotted	990
Eucalyptus sideroxylon	Ironbark, Red	1,050
Intsia bijuga	Merbau	860
Syncarpia glomulifera	Turpentine	945

These species exhibit similar density to *E. bosistoana and* are already compliant with BAL-29. An indicative test on the HRR can help determine whether *E. bosistoana* could be classified under the BAL-29 criteria.

Literature Summary

Reviewing Australian research has outlined that *E. bosistoana* exhibits desirable mechanical properties for construction use as well as meeting Australian durability standards. It was determined that *E. bosistoana* outperforms radiata pine in the relevant mechanical properties.

In terms of fire properties such as HRR and ignition, there is no current research that provides data on the performance on E. bosistoana. However, samples of eucalyptus plywood have been tested to identify HRR behavior (Hu et al., 2015). Research by Chandra et al., (2024) found that there can be vast differences in fire performance between solid wood and engineered wood products, regardless of if they are of the same species.

As one of New Zealand's largest export markets for forest products, research into whether New Zealand grown *E. bosistoana* meets Australian bushfire construction standards is of importance. The species that currently classify under the highest zone for untreated timber (BAL-29) exhibit similar densities to *E. bosistoana*. Research into both compliance with the requirements for BAL-29 and evaluating whether wood density can provide insights to fire performance was identified as an important component for this study.

The interest in the uses for New Zealand grown *E. bosistoana* coupled with the lack of relevant data on the fire performance and adherence to Australian bushfire construction standards have helped identify the direction and objectives for this study.

Objectives

The objectives of this project are to apply a standardised test method using oxygen consumption calorimetry (outlined in the standards ISO 5660-1, and AS/NZS 3837:1998) to samples of *E. bosistoana* to determine key parameters used in assessing fire performance and safety to determine whether the species can be classified as a bushfire resistant timber according to the BAL-29 criteria for untreated timber. This will mean assessing the HRR and ignitability.

To provide initial data points for fire design using *E. bosistoana* and give baseline data for future research in this area, the experimental HRR curves for Eucalypts across a range of densities will be determined so that relationships between pHRR and measured density can be identified and assessed.

Ideally, the results of these tests can be used to help provide design data for *E. bosistoana*, resulting in a more complete database for the species, as well as aiding for design metrics for domestic and international application.

Methodology

Overview

The methodology of this study can be comprised of two main components: testing for relevant fire properties using the ISO 5660 standard and testing *E. bosistoana* for classification to the BAL-29 criteria using the standards AS/NZS 3837, and AS 3959. Standard AS/NZS 3837 is directly derived from the ISO 5660 standard, with changes to sample thickness restrictions and end of test criteria. This was done to meet constraints pertaining to time and budget. Testing was provided by BRANZ using oxygen consumption cone calorimetry.

Samples of untreated *E. bosistoana*, *E. globoidea* and *E. nitens* were chosen for testing, as they represented a wide range of densities across the available eucalypts. These samples were prepared and conditioned in accordance with the ISO 5660 standard and testing using the experimental procedure outlined in the next part of this report. The resulting data obtained from the cone calorimeter was used to calculate HRR behavior as well as mass loss rates and ignition data. Both pHRR and total HRRs were used to develop correlations with the measured density.

A sample of New Zealand grown untreated *E. bosistoana* was prepared according to the AS/NZS 3837 for testing using the cone calorimeter with a heat flux of 25 kW/m^2. This was used as an indicative test to measure HRR behavior to determine compliance to the BAL-29 criteria outlined in the Australian standard AS 3959.

Sample Preparation

The samples used for determining the HRR curves were prepared in accordance with the ISO 5660 standard. To obtain data from a range of densities, samples were obtained from a range of species of eucalypts. These were as follows:

- *Eucalyptus bosistoana*
- *Eucalyptus globoidea*
- *Eucalyptus nitens*

Samples from all species were cut to dimensions 100 x 100 mm. The thickness was set at 10 mm, as this allowed for more efficient testing in terms of time while conforming to the standard. Four samples of each species were prepared, as the standard requires three tests for validity, as this accounts for the natural variability of timber. The fourth sample was prepared in the event of failure during testing.

The samples were then placed in a conditioning chamber set to 65% relative humidity and at a temperature of 20°C to reach their equilibrium moisture content (EMC), and the weight was measured daily until constant. Once equilibrium was achieved, the length, width, and thickness were recorded, as well as the mass. These values were used to calculate the density for each sample using Equations 1 and 2.

$$\rho = \frac{m}{V} \tag{1}$$

$$\rho = \frac{m}{L \times W \times d} \tag{2}$$

The densities were recorded, and the average values were used to determine a maximum, minimum and midpoint as candidates for testing in the cone calorimeter. The species that fit this categorization were:

- *Eucalyptus bosistoana - (*Maximum average density)
- *Eucalyptus globoidea* - (Median average density)

- *Eucalyptus nitens* - (Minimum average density)

Three species were chosen due to constraints for both time and cost. The samples used for testing are shown in Figure 3.

Figure 3 Showcase of samples prepared for cone calorimeter testing: Eucalyptus bosistoana (left), Eucalyptus globoidea (center), Eucalyptus nitens (right).

Test Apparatus

The test apparatus was set up in line with the system outlined in the ISO 5660 and AS/NZS 3837-1998 standards. It is comprised of the following components:

Cone-shaped Radiant Electric Heater

This component was used to generate a controlled, uniform radiant heat flux up to 100 kW/m^2 onto the specimen surface to simulate exposure to a fire. Its truncated conical shape is designed to direct heat onto the specimen while allowing combustion gases to escape upwards.

Radiation Shield

This component was used to protect the specimen from irradiance before the test begins. It was quickly withdrawn at the start of the test, ensuring the specimen was exposed to the full radiant heat instantaneously.

Temperature/Irradiance Controller

Used to precisely regulate the heater's power to maintain a steady temperature, resulting in a consistent irradiance level.1

Weighing Device/Load Cell

Used to continuously measure the mass of the specimen during the test. The rate of change in this measurement was used to calculate the mass loss rate of the specimen to show the burning behaviour.

Specimen Holder

A square pan that held the specimen and its insulating backing in place during the test. It is designed to be placed securely on the weighing device and positioned directly under the heater.

Retainer Frame

A steel frame was used to secure the top of the specimen holder to prevent the specimen from expanding or warping during heating.

Exhaust System

The exhaust system used a fan to draw all combustion gases through a hood and ducts. It includes an orifice plate to measure the flow rate and a sampling probe to extract gases for analysis.

Gas Sampling Apparatus

The extracted gas samples went through this element by removing soot particles and moisture. It then delivered a clean, dry gas stream to the oxygen analyser for accurate concentration measurement.

Ignition System

This element included the circuit and timer, which had a high-voltage spark generator to ignite pyrolysis gases and an integrated timer that automatically recorded the precise time to sustained flaming. It provided both the pilot ignition source and the critical time to ignition measurement.

Oxygen Analyser

This is a paramagnetic sensor that measured the depletion of oxygen concentrations in the exhaust system. This depletion is directly proportional to the heat released by the burning specimen.

Heat Flux Meters

This is another sensor that was placed at specimen position to measure the actual irradiance provided by the cone heater. It was used to verify and calibrate the heater's output setting.

Calibration Burner

This element burned a precise flow of high-purity methane gas to generate a known and constant HRR. It was used to calibrate the entire instrument's heat release measurement system.

Data Collection and Analysis System

This was used to record electronic signals from all instruments (oxygen, temperature, pressure, mass) at regular intervals. It processed this raw data to calculate and report all required test results.

Optional Side Screens

These are protective panels that were installed around the test area for operator safety. Their use was permitted only after validation proves they did not alter ignition times or heat release measurements.

Smoke Obscuration Measuring System

This laser-based (helium-neon laser) system projected a beam across the exhaust duct to measure how much light was attenuated by the smoke. The degree of light attenuation was used to calculate the smoke extinction coefficient and production rate.

Smoke System Thermocouple

This is a temperature sensor that measured the temperature of the smoke-filled air inside the exhaust duct. This temperature reading is essential because it tells the instrument how much the hot smoke has expanded, which is needed to accurately calculate the volume and production rate of the smoke.

Experimental Procedure

Preparation & Conditioning

To comply with the testing requirements outlined in standard ISO 5660, three specimens were tested at the same level of exposed irradiance: 50 kW/m^2 in the case of this experiment. Although the ISO 5660 standard allows for a heat flux range up to 75 kW/m^2, the reason why 50 kW/m^2 was chosen was because it allows for a faster test while still modelling a realistic fire scenario. The specimens were conditioned to a constant mass at a temperature of 23 ± 2 °C and relative humidity not exceeding 50 ± 5%. In this case, constant mass is defined by the difference of measured weight within a 24-hour period not exceeding 0.1% of the mass or 0.1grams (whichever value is greater). The environment in which testing was to take place was specified to have conditions of relative humidity ranging between 20% and 80% and an ambient temperature between 15 °C and 30 °C.

Once the required conditioning was achieved, the specimens were wrapped in a single layer of aluminum foil with the shiny side facing the specimen. The foil was cut so that both the bottom and sides of the specimen are completely covered, and the foil extends 3 mm past the upper surface. It is then folded down to form a seal around the top-facing surface of the specimen. It will then be placed in the specimen holder and encased in a retainer frame so that none of the foil is visible.

To prepare for testing, a refractory fiber blanket with nominal thickness of 13 mm and a nominal density of 65 kg/m^3 was placed in layers on top of the retainer frame encasing the specimen so that a minimum of one layer extended above the rim of the frame. This was fitted with the sample holder so that the layers of refractory fiber were pressed down and the frame was secured.

Test Calibration

Prior to test commencement, a series of both preliminary and operational calibrations must be performed to meet the requirements of the ISO 5660 standard. The preliminary calibrations include:

- The cone-heater heat flux and exhaust fan flow rate were calibrated at 50 ± 1 kW/m^2 and 0.024 ± 0.002 m3/s so that equilibrium is reached and the average heater temperature was recorded at this time. A dummy test is performed on a specimen of black PMMA (polymethyl-methacrylate) so that the validity of the test can be checked against the expected average HRR over the first three minutes post ignition.
- Weighing device response time was calibrated by placing an empty specimen holder and a 500 ± 25 g calibration mass onto weighing device and taring the output to zero. A 250 ± 25 g was gently added to the holder, and the output was recorded. After equilibrium was reached, the mass was gently removed, and the output was recorded again. The response time was calculated as the average time for the output signal to shift from 10% to 90% of its full-scale deflection during both the application and removal of the mass. The cone heater remained off throughout this procedure.
- Weighing device output drifts was assessed under operational thermal conditions. With the cone heater and exhaust fan set to an irradiance of 50 ± 1 kW/m^2 and a flow rate of 0.024 ± 0.002 m^3/s, a thermal barrier was used during system warm-up. After thermal equilibrium was reached, the barrier was replaced with the specimen holder and the 500 ± 25 g mass, and the output was tared. A 250 ± 25 g mass was then added, and the stable output was recorded. After 30 minutes, the output was recorded again. The drift was defined as the absolute difference between the mean of 12 initial and 12 final output readings.

- Oxygen analyzer delay and response times were calibrated with the cone heater turned off. The exhaust fan was set to the standard flow rate of 0.024 ± 0.002 m^3/s. A methane flow equivalent to a 5 ± 0.5 kW fire was delivered to a burner, which was lit and stabilized outside the hood before being quickly inserted underneath. The burner remained for 3 minutes before being removed and extinguished. The analyser output was recorded throughout this process. The turn-on and turn-off delay times were defined as the time for the oxygen reading to reach 50% of its ultimate deflection after burner insertion and removal, respectively. The final delay time t_d was the average of these values. The response time was the average time for the output to change from 10% to 90% of its ultimate deflection.
- Oxygen analyzer output noise and drift was evaluated with the exhaust fan turned on and set to the standard flow rate of 0.024 ± 0.002 m^3/s. The analyser was first supplied with oxygen-free nitrogen gas for 60 minutes. The supply was then switched to dried ambient air from the exhaust duct. After the output stabilized at 20.95% O_2, it was recorded at 5-second intervals for 30 minutes. The short-term drift was calculated as the absolute value of the difference between the start and end values of a least-squares-fitted trend line. The noise is computed as the root-mean-square (RMS) deviation of the data points from this linear trend. The cone heater remained off for this procedure.

$$rms = \sqrt{\frac{\sum_{i=1}^{n} {x_i}^2}{n}} \tag{3}$$

  Where x_i is the absolute difference between the data point and the linear trend line.
- Effect of side screens on the test results was evaluated by conducting tests on six PMMA specimens at 50 ± 1 kW/m^2 without the retainer frame. The first three tests were performed with the side screens removed and the next three with them in place. A two-sided t-test at a 5% significance level was used to compare the average values of time to ignition t_{ig}, 180-s average HRR ($\dot{q}_{A,180}$), and pHRR ($\dot{q}_{A,max}$) from the two series. The screens considered to have no significant effect if the differences for all three variables were statistically insignificant.

Operational calibrations are performed at the start of testing each day in the following order:

1. Accuracy of the weighing device will be determined by measuring standard weights within the weight range of the test specimens. Once the scale has been zeroed with the retainer on the scale, the weights added (between 50g and 200g) were recorded once the scale stabilized and the process was repeated 4 times. Once calibration

was completed, the accuracy of the scale was defined as the maximum difference between the mass and the output recorded by the scale which should be ~0.3g.

2. Calibration of the oxygen analyzer will be done by setting the flow rate to 0.0254 ± 0.002 m3/s and feeding it oxygen-free nitrogen gas to zero the analyzer. The analyzer was calibrated by adjusting the response to 20.95 ± 0.01% to dried ambient air. After testing is completed for each specimen, the response level indicated above needs to be ensured using dried ambient air before the next test commences.

3. HRR calibration was performed to determine the calibration constant *C*. This was achieved by collecting baseline data from the exhaust fan set at a flow rate of 0.024 ± 0.002 m^3/s at five second intervals for one minute. Methane was introduced to the calibration burner and allowed to burn for three minutes at a constant rate with data being collected at five second intervals. The orifice constant C was then calculated using Equation 4 (shown below) using 3-minute averages for the values of $\dot{q_m}$, T_e , Δp and X_{O_2}.

$$C = \frac{\dot{q_m}}{(12.54 \times 10^3)(1.10)} \sqrt{\frac{T_e}{\Delta p} \frac{1.105 - 1.5X_{O_2}}{X_{O_2}^0 - X_{O_2}}} \tag{4}$$

4. Heater calibration is performed at the start of the day of testing, or when the heat flux is changed. In this study, a heat flux of 50 kW/m^2 was used on the 10 mm thick samples for obtaining HRR curves for density correlation, and 25 kW/m^2 was used on the 20 mm specimens of *E. bosistoana* in accordance with the BAL-29 criteria.

5. Smoke meter calibration is done before the commencement of each test by setting the zero values of extinction coefficient (performed by software).

Testing & Data Collection

The experimental procedure using the cone calorimeter follows the instructions set out in the ISO 5660 standard. Once the calibrations have been performed, the data collection was started and one minute of baseline data is collected at intervals of 5 seconds. The prepared specimen was then placed onto the weighing device. The spark plug was then inserted, and the radiation shield was removed. Once the shield was removed, the ignitor was activated.

When flashing or transitory flaming occurred, the time of occurrence was recorded. Once the specimen exhibits sustained flaming, the spark was deactivated and spark ignitor removed. The time of sustained flaming was then recorded, and data collected in intervals of 5 seconds. Figure 4 shows a sample of *E. bosistoana* during the test procedure after the point of sustained flaming was reached.

Figure 4 cone calorimetry testing on a sample of E. bosistoana using the method described in the ISO 5660 standard.

Data was collected until one of the following 4 failure criteria was met:

1. An elapsed time of 32 minutes after sustained flaming was achieved. This consists of a 30-minute test period and a 2-minute period after the test finishes to collect further data.
2. An elapsed time of 30 minutes in which the specimen did not ignite.
3. The oxygen analyzer value (X_{O_2}) returns a value that exceeds the value before testing occurs minus 100 μl/l of oxygen concentration for 10 minutes.
4. The total specimen mass is less than 0.1 g for 60 seconds.

Once the test was completed, then specimen was removed from the weighing device. To account for variability in timber and to allow for differences in data, three tests must be recorded and compared for each species. If the 180-second average HRR readings differ from each other by more than 10%, a further three tests must be conducted. For this study, this was not required.

Figure 5 Sample of E. Bosistoana immediately following the end of the cone calorimeter test.


In the case of this study, all tests were terminated at 20 minutes, as this gave both primary and secondary peaks for the HRR curves for each specimen and the HRR were flat and stable before the test ended. Continuation of the test for the full duration outlined in ISO 5660 would have resulted in slightly higher values for the THR for all specimens, but the vast majority were captured, and all tests were performed consistently to allow for fair analysis and comparison.

Fire Property Calculations

After the completion of testing, calculations for the following parameters were determined using oxygen consumption calorimetry using the following Equations:

Heat Release Rate:

This will be calculated as a function of time, as well as by area and during combustion. The 3 equations are showcased below.

$$\dot{q}(t) = \left[\frac{\Delta h_c}{r_0}\right](1.10)C\sqrt{\frac{\Delta p}{T_e}}\frac{\left(X^0{}_{O_2} - X_{O_2}(t)\right)}{1.105 - 1.5X_{O_2}(t)} \quad (5)$$

The heat release rate per unit area (HRRPUA) will then be determined by the following equation.

$$\dot{q}_A(t) = \frac{\dot{q}(t)}{A_S} \tag{6}$$

Total heat released during combustion

$$q'' = \sum_i \dot{q}_A(t)\Delta t \tag{7}$$

For this calculation, the summation begins with the first reading after the final negative rate of heat release measured at the beginning of the test. The final reading for the calculation is the final reading of the test.

BAL-29 Fire Testing Criteria

Determining the bushfire resistance of a timber using the BAL-29 criteria uses oxygen consumption calorimetry outlined in the AS/NZS 3837 standard. The method for testing using the cone calorimeter is largely the same as the method outlined in ISO 5660 described above, as the AS/NZS 3837 is based on this standard. However, the failure criteria are different in the AS/NZS 3837 testing procedure. The data during testing is collected until one of the following 3 conditions are met:

I. 2 minutes have elapsed since all combustion and flames have subsided
II. the average mass loss rate is lower than 150 g/m^2 over a period of 1 minute
III. A period of 60 minutes has elapsed

The test was run with an imposed heat flux of 25 kW/m^2, which agrees with the AS/NZS 3837 as well as the required irradiance for classifying bushfire resistant timber in the AS 3959 standard. This particular level of irradiance is used as it likely simulates non-piloted ignition of timber (Wiesner et al., 2023). The test specimen was a sample of *E. bosistoana* with dimensions 100 x 100 mm, and a thickness of 20 mm as per standard requirements.

After the conclusion of testing with the cone calorimeter, the HRRPUA was determined across the duration of the experiment using Equation 5. to classify as a bushfire-resistant timber in accordance with the BAL-29 criteria using cone calorimetry at the prescribed heat flux, the following two conditions must be met:

- The experimental HRRPUA must be less than 100 kW/m^2
- The average HRRPUA for 10 minutes post ignition is less than 60 kW/m^2

If both conditions are met, the timber meets classification requirements for BAL-29 (Wiesner et al., 2023).

Data Analysis

The initial stage of data analysis involved calculating the density of each wood specimen prior to testing. As detailed in the methodology, the density was determined for each conditioned sample using its measured mass, length, width, and thickness using Equation 2. The calculated density values served as the primary independent variable for the correlation analysis.

The key dependent variable, the HRR, was calculated from the data collected during each cone calorimeter test. This calculation is based on the principle of oxygen consumption calorimetry, where the rate of heat released by the burning specimen is directly proportional to the amount of oxygen consumed. The HRR as a function of time was determined using Equation 5, which incorporates real time measurements of oxygen depletion, exhaust gas temperature, and pressure differential at the orifice meter. The data acquisition system recorded this information at 5 second intervals, allowing for the generation of a continuous HRR curve for each sample. The ignition time was recorded when the test sample ignited and exhibited sustained flaming.

For the indicative BAL-29 test, a specific analysis was conducted on the HRR data from the 20 mm *E. bosistoana* sample tested at an irradiance of 25 kW/m^2. Two key metrics were extracted from this data which were the maximum pHRR observed during the test and the average HRR calculated over the first 10 minutes following sustained ignition. These experimental values were then directly compared against the pass/fail criteria outlined in the AS 3959 standard, where the pHRR must be less than 100 kW/m^2, and an average HRR of less than 60 kW/m^2. This comparison determines whether the timber can be classified as a bushfire rated timber (BRT) with a resistance up to BAL-29.

The final analytical step was to investigate the relationship between the physical and fire properties of three species. A linear regression analysis was performed to correlate the calculated density of each sample with the key fire performance metrics derived from the HRR data which were the pHRR, and the THR. This analysis was conducted to quantify the strength of the correlation between the variables. An analysis of variance test was conducted, to determine whether the results obtained were statistically significant.

Results

Densities

The densities of the three different species and their three samples used in the cone calorimetry were calculated and are shown in Tables 5 to 7, and the average densities for each species tested using cone calorimetry are summarized in Table 8.

Table 5 Calculated densities of 10 mm E. bosistoana samples conditioned to equilibrium at 20°C and 65% relative humidity, tested in accordance with ISO 5660.

E. bosistoana	
Sample #	Density (kg/m^3)
1	1129.82
2	1114.41
3	1129.50
Average Density	**1124.58**

Table 6 Calculated densities of 10 mm E. globoidea samples conditioned to equilibrium at 20°C and 65% relative humidity, tested in accordance with ISO 5660.

E. globoidea	
Sample #	Density (kg/m^3)
1	734.66
2	730.56
3	729.73
Average Density	**731.65**

Table 7 Calculated densities of 10 mm E. nitens samples conditioned to equilibrium at 20°C and 65% relative humidity, tested in accordance with ISO 5660.

E. nitens	
Sample #	Density (kg/m^3)
1	595.25
2	491.75
3	527.46
Average Density	**538.15**

Table 8 summary of average densities between species of eucalypts tested at 10 mm thick in the cone calorimeter.

Species	Average Density (kg/m³)
E. bosistoana	1124.58
E. globoidea	731.65
E. nitens	538.15

Heat Release Rates

The average pHRR measured during testing in accordance with the ISO 5660 standard (see Table 9) was highest in *E. bosistoana* samples with an average peak value of 257.01 kW/m². This species also measured the highest average THR of 106.25 MJ/m². *E. globoidea* had the median values for both averages of pHRR and average THR were 223.90 kW/m² and 94.21 MJ/m², respectively. *E. nitens* exhibited the lowest average pHRR of the test species at 201.16 kW/m² and an average THR of 86.15 MJ/m².

Table 9 Summary heat release data for 10 mm eucalypt samples tested according to ISO 5660.

Species	Sample Number	Density (kg/m3)	pHRR (kW/m²)	THR (MJ/m²)	Average Density (kg/m³)	Average pHRR (kW/m²)	Average THR (MJ/m²)
E. bosistoana	1	1129.82	254.59	106.25	1124.58	257.01	106.25
	2	1114.41	260.98	109.02			
	3	1129.50	255.45	103.49			
E. globoidea	1	734.66	213.99	93.70	731.65	223.90	94.21
	2	730.56	216.14	93.43			
	3	729.73	241.56	95.50			
E. nitens	1	595.25	203.19	95.14	538.15	201.16	86.15
	2	491.75	192.07	79.81			
	3	527.46	208.22	83.49			

The data obtained from the cone calorimeter during testing was taken at 5 second intervals and was used to calculate HRRs at each point in time during burning. These points were graphed to form HRR curves to showcase the burning behavior of the timber during a fire scenario. The HRR curves for each sample of *E. bosistoana* are shown in Figure 6.

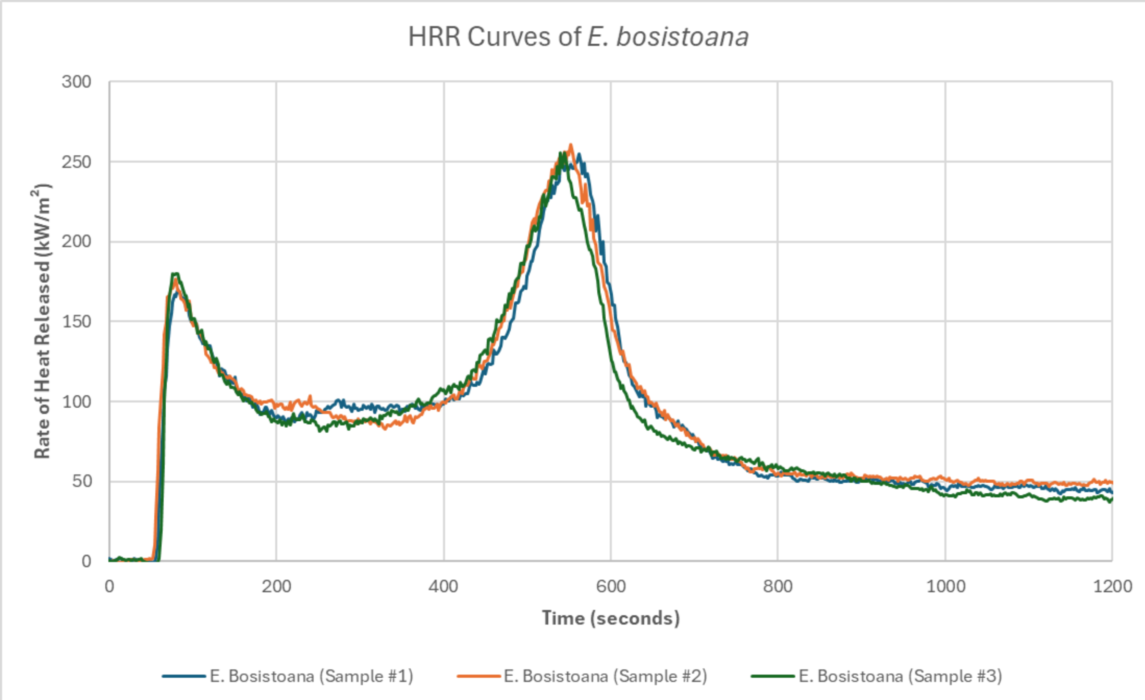

Figure 6 HRR curve for 10 mm thick E. bosistoana samples.

The HRR had two distinct peaks. The first one occurred shortly after ignition, and the second occurred close to the midway point of the test duration. The second peak was the largest observed HRR, with the average value between the three test samples at the second peak being 257.01 kW/m^2. All three samples exhibited similar behavior under fire conditions with very little variance in HRR path. The HRR for all samples was stable by the conclusion of the test at 1200 seconds.

Table 10 shows the comparison between 180-second-mean HRR readings to the actual 180-second HRR for each test sample. This was done to ensure that each data point lies within 10% of the 180-second-mean, as this is a requirement outlined in both the ISO 5660, and AS/NZS 3837 standards. The allowable range for mean HRR at 180 seconds for *E. bosistoana* was 103.92 to 127.02 kW/m^2. The samples were found to be in the acceptable range.

Table 10 Statistical compliance for mean HRR at 180 seconds for E. bosistoana in accordance with ISO 5660 and AS/NZS 3837.

Species	Sample #	Mean HRR (180) (kW/m^2)	Mean HRR (180) (kW/m^2)	Minimum Allowable HRR (180) (kW/m^2)	Maximum Allowable HRR (180) (kW/m^2)
E. bosistoana	1	115.09	115.47	103.92	127.02
	2	117.20			
	3	114.12			

The samples of *E. globoidea* at 10 mm thickness exhibited two distinct peaks in HRR data shown in Figure 7. However, the highest peak occurred at the start of the test immediately after ignition. As in the testing for *E. bosistoana*, the second peak occurred just before the halfway point of the test, but this secondary peak was lower than the initial peak. During the test, the variability in samples was more pronounced, as the HRR curve for each sample showed larger differences, particularly near the second peak. However, all three samples stabilized near the end of the test and showed uniform behavior. A notable observation for the *E. globoidea* was that all samples began audibly crackling at ~20 seconds into testing, followed by constant spalling which occurred throughout the remainder of the test.

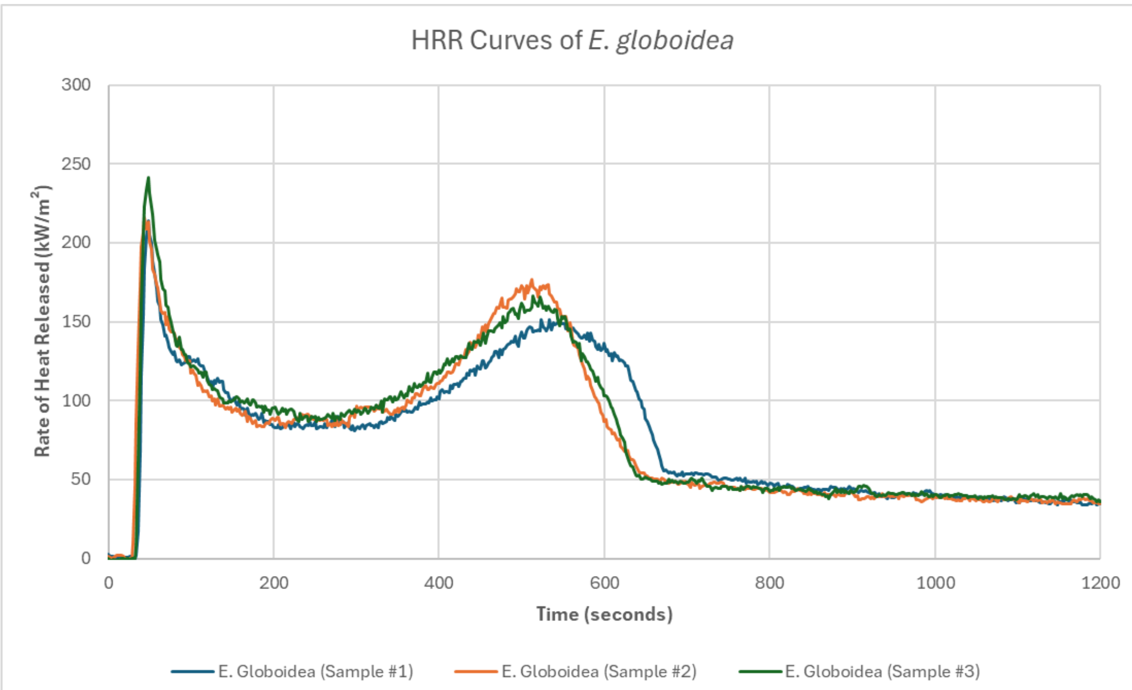

Figure 7 HRR curve for 10 mm thick E. globoidea samples.

Table 11 shows the comparison between 180-second-mean HRR readings to the actual 180-second HRR for each test sample. This was done to ensure that each data point lies within 10% of the 180-second-mean, as this is a requirement outlined in both the ISO 5660, and AS/NZS 3837 standards. The allowable range for mean HRR at 180 seconds for *E. globoidea* was 107 to 127.02 kW/m^2. The samples were found to be in the acceptable range.

Table 11 Statistical compliance for mean HRR at 180 seconds for E. globoidea in accordance with ISO 5660 and AS/NZS 3837.

Species	Sample #	Mean HRR (180) (kW/m^2)	Mean HRR (180) (kW/m^2)	Minimum Allowable HRR (180) (kW/m^2)	Maximum Allowable HRR (180) (kW/m^2)
E. globoidea	1	116.76	119.77	107.80	131.75
	2	117.39			
	3	125.17			

The HRR curves for the samples of *E. nitens* showcased in Figure 8 exhibited similar behavior, as there were 2 distinct peaks. Although the second peak was higher (with an average pHRR of 201.16 kW/m^2), the difference between the first and second peaks was not as pronounced as it was for the other species. Furthermore, it is notable that both the initial and final peaks occurred much sooner into testing than the other species, with the first peak occurring very soon after ignition, and the second peak occurring at ~400 seconds. Also, the curves for each individual sample displayed higher levels of variance than the *E. bosistoana* and *E. globoidea* throughout the duration of the test. The HRR for all samples of *E. nitens* stabilized relatively early in the test at ~600 seconds.

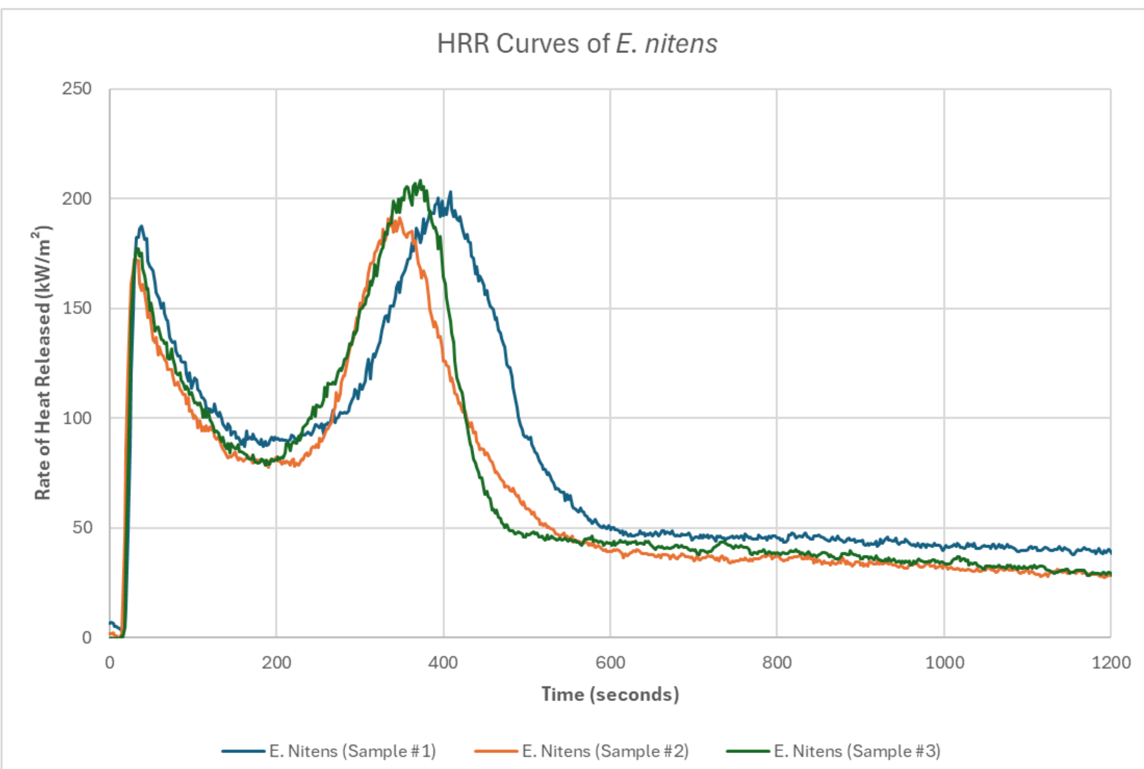

Figure 8 HRR curve for 10 mm thick E. nitens samples.

Table 12 shows the comparison between 180-second-mean HRR readings to the actual 180-second HRR for each test sample. This was done to ensure that each data point lies within 10% of the 180-second-mean, as this is a requirement outlined in both the ISO 5660, and AS/NZS 3837 standards. The allowable range for mean HRR at 180 seconds for *E. nitens* was 99.67 to 121.82 kW/m². The samples were found to be in the acceptable range.

Table 12 Statistical compliance for mean HRR at 180 seconds for E. nitens in accordance with ISO 5660 and AS/NZS 3837.

Species	Sample #	Mean HRR (180) (kW/m²)	Mean HRR (180) (kW/m²)	Minimum Allowable HRR (180) (kW/m²)	Maximum Allowable HRR (180) (kW/m²)
E. nitens	1	117.63	110.74	99.67	121.82
	2	105.36			
	3	109.24			

The heat release behavior for each species was displayed together for direct comparison shown in Figure 9.

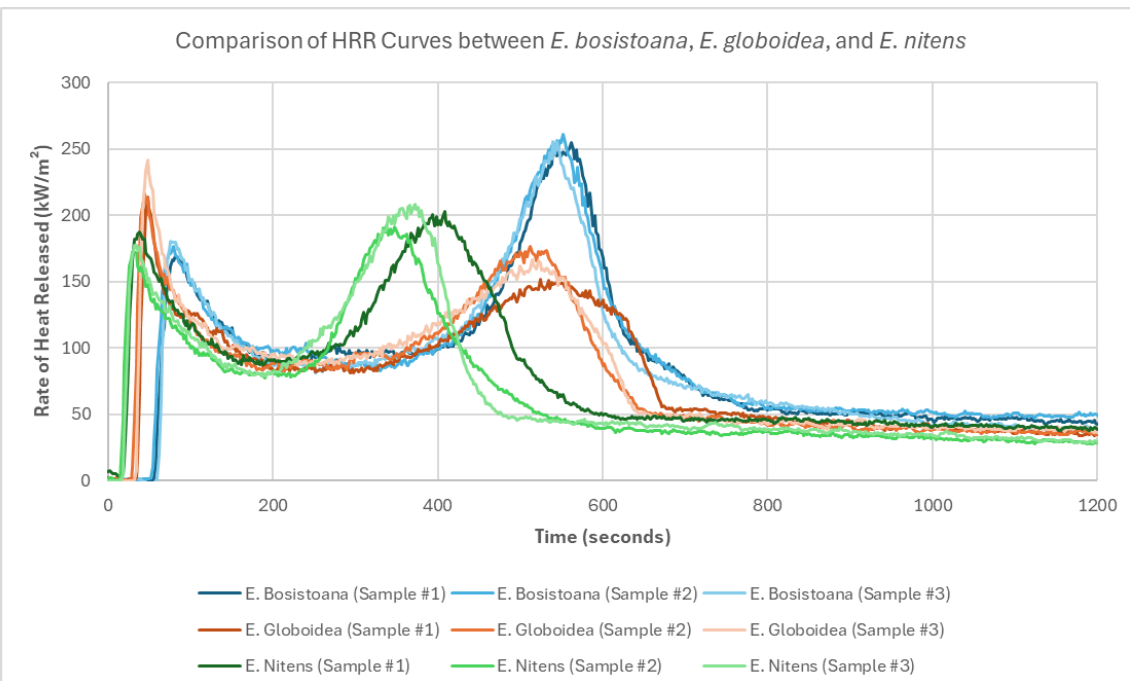

Figure 9 HRR behavior comparison between E. bosistoana, E. globoidea and E. nitens.

The information shown in Figure 9 suggests that the burning behavior differs significantly between the three species of eucalypt tested above. As shown, *E. bosistoana* exhibits the highest pHRR as well as occurring further along the test time interval.

Heat Release Rate & Density Correlation

The pHRR for each sample across the three species was measured and plotted alongside the respective measured density. A linear regression analysis was then performed to determine the correlative properties between density and pHRR. This same analysis was performed for density and the THR. The results are shown in Figures 10 and 11.

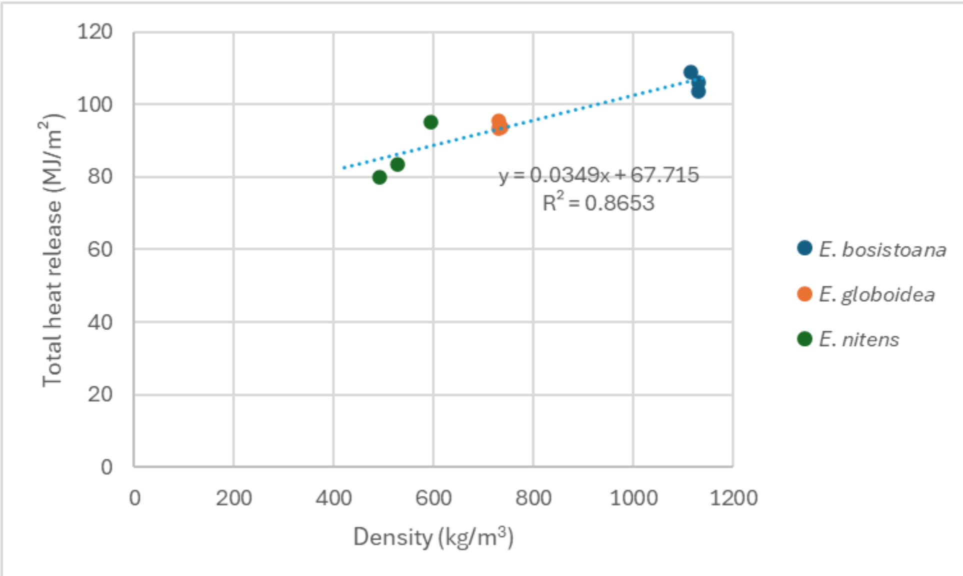

Figure 10 Correlation between THR and density.

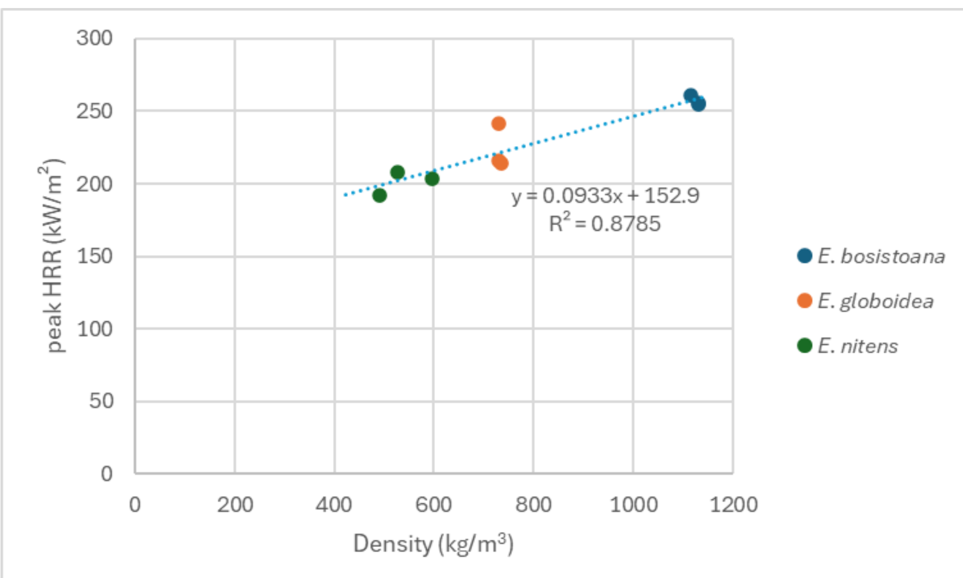

Figure 11 Correlation between peak HRR and density

The correlations identified in this study agree with the research by Grexa, et al., 1997, with a R^2 value of 0.8653 when correlating between density and THR shown in Figure 10. The correlation between density and pHRR's trendline has a R^2 value of 0.8785 shown in Figure

11, it indicates a strong correlation between the two variables. The slopes of the correlation for both pHRR, and THR are 0.0933 and 0.0349, respectively. This indicates that the increase in density would lead to an increase in HRR, however, in this case a large increase in density would only slightly increase both THR and pHRR. Although in this study it is only limited to 3 species, there is significant variability between each species' density. Two one-way ANOVA tests were performed to compare the effect of wood density on the THR, and the effect of wood density on the pHRR. The analysis revealed that there is a statistically significant difference in both tests, where the results are shown in Table 13.

Table 13 One-way ANOVA results show the effect of wood density on THR and pHRR.

Parameter	Between-Group df	F-value	F_{crit}	p-value
THR	2	12.62	5.14	0.0071
pHRR	2	22.51	5.14	0.0016

As both tests' p-value is less than 0.05 it suggests that they are both statistically significant, and both tests' F-value is greater than their F_{crit} value this also suggests it is statistically significant.

Ignition

The ignition time for each species had the sample trend between each sample number. As shown in Figure 12, *E. bosistoana* consistently exhibited the longest ignition times, with values ranging from 52 – 64 seconds, indicating that this species has the highest thermal stability or resistance to ignition. *E. globoidea* showed moderate ignition times showed ignition times between 29 – 37 seconds, while *E. nitens* ignited the fastest, with ignition times between 14 – 19 seconds. Table 14 also shows the mean, and standard deviation of the ignition times between the three species. The difference in ignition performance suggests that there are characteristics that affect fire resistance among the different species, like sample weight (El Gazi et al., 2021). El Gazi (2021) also mentions when comparing dense materials, a more convenient way is to consider the area density or the sample weight when exposed surface is constant. Overall *E. bosistoana* showed the greatest resistance to ignition, while *E. nitens* showed the least. These results highlight species' property variability like density, which is important to consider when choosing materials for their resistance and performance.

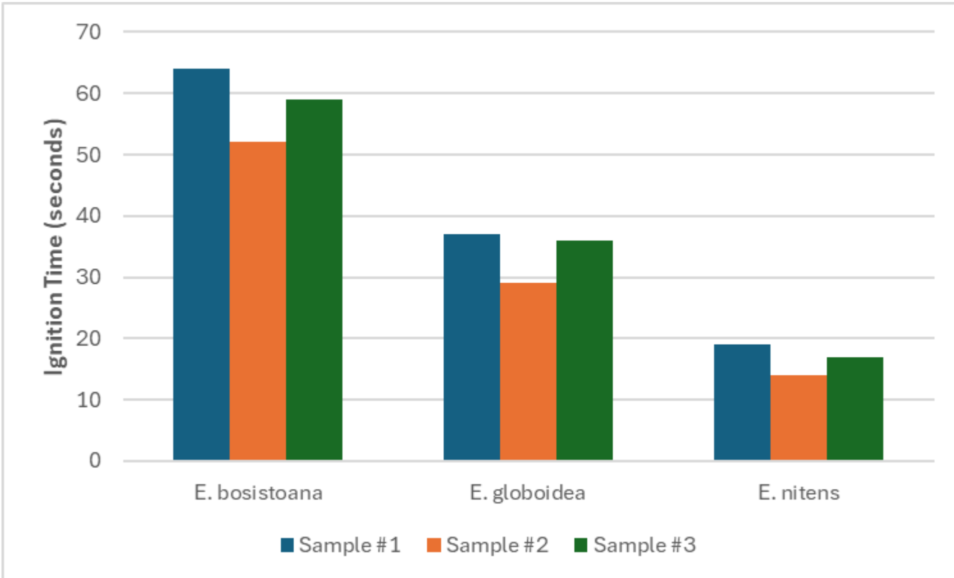

Figure 12 Ignition time for E. bosistoana, E. globoidea, and E. nitens across three different samples.

Table 14 Mean, standard deviation, and range for ignition between the E. bosistoana, E. globoidea, and E. nitens.

Species	**Mean Ignition Time (s)**	**Standard Deviation**	**Range (s)**
E. bosistoana	58	4.92	52 - 59
E. globoidea	34	3.56	29 - 37
E. nitens	17	2.05	14 - 19

BAL-29 Criteria Compliance for *E. bosistoana*

The HRR exhibited for the 20 mm *E. bosistoana* sample shown in Figure 13 had two distinct peaks. The first one occurred shortly after ignition, and the second occurred close to the midway point of the test duration. The second peak had a lower HRR, which had the opposite behavior as the 10 mm samples. The test reached one of the termination criteria of 3600 seconds, however, the sample was still burning after this time, so the entire HRR curve was not fully captured.

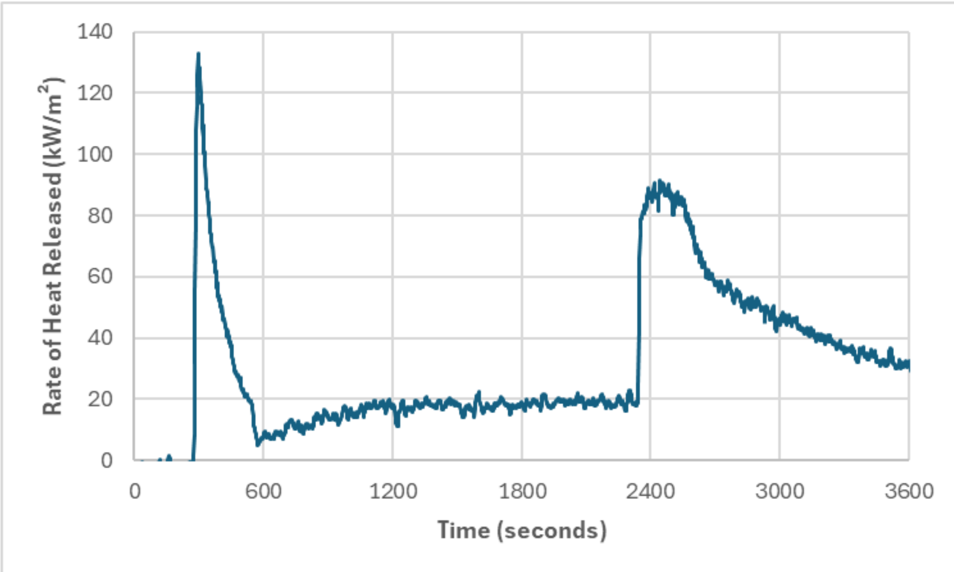

Figure 13 HRR curve for a 20 mm thick E. bosistoana sample tested to AS/NZS 3837

The HRR behavior in this test largely differs from the previous cone calorimeter test using the methodology in the ISO 5660 standard. This can be explained by changes in both the sample thickness and exposure irradiance. As the thickness in this test was doubled from previous tests as well as the irradiant head flux being halved, the resulting HRR behavior showed significant differences.

Discussion

Correlation Between pHRR & Density

From the three species of eucalypts measured for density shown in Table 15, it was found that both *E. bosistoana* and *E. globoidea* shared a relatively uniform spread of densities within samples for the same species with a standard deviation of 8.81 and 2.64 respectively. It was found that the samples of *E. nitens* were less stable in terms of density, with the samples exhibiting the largest changes within species. The standard deviation for the *E. nitens* samples was found to be 52.57; a significantly larger value when compared with the other two species.

Table 15 Summary of density measurements in 10 mm Eucalypts used for cone calorimeter testing

Density Summary for 10 mm Samples		
Species	**Average Density (kg/m3)**	**Standard Deviation**
E. bosistoana	1124.58	8.81
E. globoidea	731.65	2.64
E. nitens	538.15	52.57

HRR Curve comparison between 10 mm and 20 mm *E. bosistoana*

The comparison between the HRR curves for *E. bosistoana* at 10 mm and 20 mm thicknesses, tested at 50 kW/m^2 and 25 kW/m^2, respectively, reveals a difference in combustion behavior due to the thickness of the specimen and the incident heat flux used (El Gazi et al., 2021).

The 10 mm specimens, exposed to a higher heat flux of 50 kW/m^2, exhibited a characteristic HRR curve where the second peak had a greater intensity than the first peak. This is because the material is thermally thin meaning the specimen’s volume always heats up at the same temperature, due to low thermal mass which allows heat to pass through easily, resulting in the initial protective char layer to be cracked at a faster rate. The first peak represents the ignition and initial sustained flaming of the specimen’s surface, during which a char layer is developed. The char layer is used as a shield for the underlying material from the irradiation, limiting further pyrolysis. The second peak is where the main combustion is most likely triggered due to the fracture of the char layer due to thermal stress (Sanned et al., 2023). The cracking exposes the unpyrolyzed material which acts as fuel which is consumed for greater combustion leading to a higher pHRR. The high external heat flux accelerates the process, ensuring that the fuel beneath the char layer pyrolyzes quickly. The HRR curves exhibited by this study show a degree of similarity to the HRR behavior of Eucalyptus plywood determined by Hu et al., (2015).

The 20 mm specimens subjected to a lower heat flux of 25 kW/m^2 had the opposite trend to the 10 mm specimens, with the first peak being greater than the second peak. A reason why this might have occurred is because of the increase of thickness going from 10 mm to 20 mm making the specimen change from thermally thin to thermally thick, where it can resist rapid temperature changes, therefore, it would take longer for heat to penetrate the sample. The first peak likely represents the ignition and combustion of the exposed surface material which is slowly forming a char layer. With a lower heat flux, this could allow for the development of a stable and consistent layer that could act as a thermal shield. The second peak might suggest a fracture of the char layer. However, in this case the char layer is most likely more stable than the one formed in the 10 mm samples, therefore, consistent fuel is released at a slower rate, and it does not reach a higher peak than it did from the first combustion.

BAL-29 Criteria

When compared with the BAL-29 criteria, the sample met one of the two conditions required for classification. The pilot test data shown in Table 16 indicates that *E. bosistoana* does not meet the requirements to be classified under the BAL-29 criteria when tested under the method outlined by the AS 3959 standard. The pHRR exceeded the maximum allowable HRR by 32.7 kW/m^2, however the average HRR was well below the threshold for failure with approximately half of the maximum. It is notable that only one indicative test was performed due to significant constraints to both time and budget, and it is recommended that this experiment should be repeated so that a conclusive result for BAL-29 compliance can be drawn.

Table 16 BAL-29 Criteria requirements compared with experimental results

	pHRR (kW/m^2)	Average HRR kW/m^2)	Pass/Fail
Required	<100	<60	Fail
Measured	132.7	30.6	Pass

Limitations

A limitation of this study was significant constraints to both time, budget, and equipment access; therefore, the sample size was restricted. To improve the findings of this study, it is recommended that a larger sample size should be used, as it shows that there is a significant change in density within *E. nitens*, and this can affect the accuracy of the correlation. It is noteworthy that there was very little variance in density exhibited in the species with higher measured density (*E. bosistoana* and *E. globoidea)*, as this could suggest that denser Eucalypts are more uniform in behavior. From the strong positive correlation between density and pHRR, we can assume that the higher the density is, the higher the pHRR will be. This could be due to a denser material requiring more energy to reach flash over.

Recommendations

Due to lack of sample size in this study, this presents an opportunity for future research to explore. If there could be a larger variety of species used to create this correlation, it could be used to create an equation that could use a species characteristic, in this case density to model and predicted HRR curve or to calculate the THR.

Due to the differences in HRR curves between 10 mm and 20 mm samples of *E. bosistoana,* an interesting potential for future research could be evaluating the behavior of HRR at a range of thicknesses or levels of irradiance. With the results found in this study pertaining to the density and fire properties of *E. bosistoana,* an interesting avenue for future research could be investigating its performance as a biofuel.

Conclusion

This study investigated the fire properties of New Zealand grown *E. bosistoana,* providing data for its potential use as a construction material. The primary finding was a strong positive correlation between wood density against pHRR, and THR with a R^2 value of 0.8785 and 0.8653 respectively. *E. bosistoana* also has the highest average density of 1124.58 kg/m^3, showing the highest average pHRR of 257.01 kW/m^2 and an average THR of 106.25 MJ/m^2. Whereas *E. nitens*, the less dense species in the test, showed the lowest pHRR. This confirms that density is a reliable, key indicator of fire intensity for these eucalypt species.

Furthermore, *E. bosistoana* showed the greatest resistance to ignition, with ignition times ranging from 52 – 64 seconds, significantly longer than *E. globoidea* and *E. nitens*. This indicates that higher wood density is more difficult to ignite which is a critical factor for fire safety in building design.

An indicative test for compliance with the Australian BAL-29 criteria for bushfire resistant timber was conducted on a 20 mm thick *E. bosistoana* sample. While the full HRR curve was not captured due to the test termination criteria from AS/NZS 3837, the data showed that it met one of the two criteria to be able to be classified for BAL-29. However, a definitive classification requires further testing to conclusively meet both the peak and average HRR criteria stated in AS 3959.

A key limitation of this study was the constrained sample size, which particularly affected the results for *E. nitens* due to the high-density variability. Future research should incorporate a wider range of species and a larger sample size to strengthen the correlation between wood density and HRR.

In summary, this research establishes that *E. bosistoana's* high density is strongly linked to higher pHRR but also higher ignition resistance. The initial BAL-29 test results showed some positive results for its potential as a naturally durable, bushfire-resistant timber. This study provides baseline data to support further development of *E. bosistoana* as a sustainable alternative to chemically treated softwoods, both in New Zealand and export markets.

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Appendix

Indicative Summary		*N/A*	CONFIDENTIAL between BRANZ and Client		
E. Bosistoana	FH21123-1-50-1		04/09/25	LMG	
Specimen Thickness		9.8	mm		
Specimen Initial Mass		109.9	g		
Substrate		N/A			
Exposed Sample Area		0.0088	m^2		
Overall Apparent Density		1121.4	kg/m^3		
Nominal Heat Flux		50.0	kW/m^2		
Nominal Duct Flow Rate		0.024	m^3/sec		
C-Factor		0.042840			
Orientation		Horizontal			
Time to Sustained Flaming		52.0	sec		
Mass at Sustained Flaming		108.9	g		
Test Duration		1200	sec		
Specimen Final Mass		21.2	g		
Percentage of Total Mass Pyrolyzed		80.7%			
OVER THE ENTIRE TEST DURATION					
Peak Heat Release Rate		261.0	kW/m^2		
Total Heat Release		109.0	MJ/m^2		
Effective Heat of Combustion		10.9	MJ/kg		
SMOKE					
Pre-Ignition Total Smoke Production		6.93	m^2/m^2		
Flaming Total Smoke Production		246.94	m^2/m^2		
Total Smoke Production		253.87	m^2/m^2		
Average Smoke Extinction Area		24.8	m^2/kg		
FROM IGNITION TO TEST END					
Average Mass Loss Rate		8.6	$g/m^2.s$		
Sample Mass Loss		9.9	kg/m^2		
Average Heat Release Rate		95.0	kW/m^2		
Ignition plus	60.0	180	300	600	sec
Average Heat Release Rate	137.4	117.2	106.3	129.9	kW/m^2
FROM 10% TO 90% OF TOTAL MASS LOSS					
Average Specific Mass Loss Rate		13.6	$g/m^2.s$		
Wire Grid		No			
Retainer Frame		Yes			
MARHE		120.4	kW/m^2