Literature Review on the Contribution of Fire Resistant Timber Construction to Heat Release Rate

Prepared for

Timber Development Association
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* For and on behalf of Warrington Fire Research Group.

EXECUTIVE SUMMARY

This report is a literature review on information that relates to or may assist in the determination of the amount of wood from fire rated timber elements that contributes to the heat release rate of a fire occurring in a building constructed of typical wood framed fire resistant construction.

Timber-based fire load that could be present in non-fire resistant timber construction and non-timber construction is not considered. This includes timber floor covering, timber wall panelling, timber ceiling panels and internal non-fire rated timber-stud wall partitions.

Based on the literature reviewed, the following findings are summarised:

(a) Fire rated timber construction can be categorised into heavy timber members and light timber assemblies. Heavy timber members include large sawn timber and glue laminated timber (glulam) where fire resistance is based on established charring rates on the exposed surfaces. They are used predominantly in floor/ceiling systems and are protectively lined except in a few cases where exposed beam construction is used. Light timber assemblies are a system of stud and joist elements protected with fire grade gypsum board or equivalent non-combustible lining materials used in wall and floor systems. For Class 2 and 3 buildings, fire rated timber construction are predominantly light timber assemblies.

(b) Timber protected by lining materials will delay the consumption of wood until the wood surface temperature reaches approximately 300°C. Linings of timber assemblies that are designed to meet the deemed-to-satisfy provisions for fire resistance are likely to offer substantial protection to the timber studs or joists against the effects of fire and significantly delay or prevent the onset of wood pyrolysis.

(c) A conservative estimate of the potential contribution of fire rated timber construction exposed to the development of fire in an enclosure can be calculated based on reasonably well established charring rates of the exposed surfaces of the timber sections for the estimated duration that the wood temperature exceeds 300°C. Preliminary analysis based on data from Australian manufacturers estimates the percentage contribution of timber charring from walls, ceiling and floor for a 5m×4m×3m high enclosure exposed to an equivalent 60 minute standard fire to be in the order of 8% to 22% of the total fire load, for fire load densities ranging from 15 to 40 kg/m^2.

(d) Information from a detailed investigation of the full-scale six-storey timber frame building (TF2000) following the fire experiment (for a total fire exposure time of 60 mins) suggests that the contribution of timber from fire rated assemblies is approximately 17% of the total fire load, based on 25kg/m^2 of wood cribs distributed over a floor area of 21.6m^2).

(e) The presence of active suppression systems such as sprinklers (if installed) and intervention from the Fire Brigade is likely to reduce the severity of the fire and therefore the pyrolysis of timber in fire rated assemblies. These effects are not considered in the review.

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1 INTRODUCTION

This report is a literature review on information that relates to or may assist in the determination of the amount of wood from fire rated timber elements that contributes to the heat release rate of a fire occurring in a building constructed of typical wood framed fire resistant construction.

Fire rated timber construction can be categorised into heavy timber members and light timber assemblies. Heavy timber members includes large sawn timber and glue laminated timber (glulam) where fire resistance is based on established charring rates on the exposed surfaces. Light timber assemblies are a system of stud and joist protected with fire grade gypsum board or equivalent non-combustible lining materials.

The types of fire-resistant timber construction elements that may contribute to the fire development of a building includes the following:

(a) Timber stud partitions

(b) Timber joists in floors

(c) Timber beams beneath ceiling/roof

(d) Timber columns

Timber-based fire load that could be present in non-fire resistant timber construction and non-timber construction is not considered. This includes timber floor covering, timber wall panelling, timber ceiling panels and internal non-fire rated timber-stud wall partitions.

The level of fire resistance required of construction elements in a building is specified by the Building Regulations (i.e. Building Code of Australia [11]) to limit the spread of fire within fire compartments of the building and to adjacent buildings. The fire resistance levels of timber members and assemblies are determined by testing them in a furnace in accordance with AS 1530.4 [8]. Alternatively, they may be assessed in accordance with AS 1720.4 [9] based on a concept of sacrificial loss in timber section due to charring from exposure to the effects of fire. Hence the potential contribution of fire resistant timber-based construction to the fire development can be estimated by determining the amount of loss allowed for in the timber sections for the required fire resistance level. However, the actual contribution can be expected to be significantly lower for the following reasons:

(a) The overall effect of the standard fire heating profile for a period of 60 or 90 minutes exposure may be more severe than the effects of an uncontrolled fully-developed fire in a modern building.

(b) The presence of lining materials in many fire resistant timber assemblies will significantly delay the onset of high temperatures that will be sufficient to cause pyrolysis of the timber sections.

(c) Intervention from the Fire Brigade is likely to occur and their suppression activities are likely to reduce the severity of the fire.

(d) Active suppression systems such as sprinklers, if installed, are likely to limit the development of the fire prior to pyrolysis of the timber occurring.

Consequently, in assessing the extent by which materials from fire rated timber construction will add to the development of fire in a building, the heat release potential of the fire rated timber will need to be determined. This report reviews work that has been conducted in assessing the thermal degradation of wood (Section 2), with particular emphasis given to charring rate under various heating conditions (Section 3) where a great deal of research has been carried out. Less information was available for full-scale experiments on timber assemblies and structures where thermal degradation was measured that may assist in the determination of the heat release potential of fire rated timber framed construction.

2 BURNING BEHAVIOUR OF TIMBER

2.1 Introduction

This section provides a brief overview of the burning behaviour of framing timber. The burning behaviour can be described by the following processes:

(a) Pyrolysis.

(b) Ignition

(c) Reradiation/thermal feedback

(d) Char formation/oxidation

The pyrolysis of timber is described briefly in Section 2.2.

Factors that affect the burning behaviour of timber elements include the following:

(a) the development of the fire profile in the enclosure that is bounded by the construction,

(b) the exposure of the effects of fire onto the timber elements (affected by factors such as view factor, orientation and cross-sectional dimensions).

(c) the presence of lining materials shielding the timber elements,

(d) the characteristics of the timber and

(e) the oxygen level available for combustion processes

The factors affecting burning rate are described in Section 2.3.

The review on charring rate (which directly accounts for the consumption of timber) is covered in greater detail in Section 3.

2.2 Pyrolysis of timber

2.2.1 Wood undergoes pyrolysis when exposed to the effects of fire. Pyrolysis changes the wood to char and gases and reduces the density correspondingly. The gases from the pyrolysis may undergo flaming combustion as they leave the surface if there is sufficient oxygen and high enough temperatures. The char will undergo glowing combustion from the released gases. These distinct layers or zones (ie char, pyrolysis and residual) are shown schematically in Figure 1.

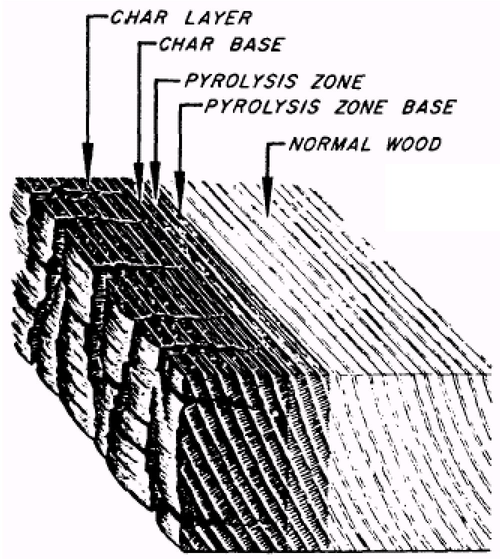


Figure 1. Degradation zones in a wood section [59]

Browne [14] conducted a comprehensive literature review on thermal decomposition of wood in which he divided the pyrolysis and combustion processes into four zones (Table 1), all of which can be present simultaneously in a wood of appreciable thickness.

Table 1. Pyrolysis and combustion processes in wood [14]

Zone	*Temp. range*	*Pyrolysis and combustion processes*
A	~95°C to 200°C	Water vapour is given off and wood eventually become charred
B	200°C to 280°C	Water vapour, formic acid, acetic acids and glyoxal are given off, ignition is possible but difficult.
C	280°C to 500°C	Combustible gases (carbon monoxide, methane, formaldehyde, formic and acetic acids, methanol, hydrogen) diluted with carbon dioxide and water vapour. Residue is black fibrous char. Normally vigorous flaming occurs. If however the temperature is held below 500°C a thick layer of char builds up.
D	above 500°C	Residue consists primarily of charcoal which glows and is consumed.

According to Browne, the minimum rate of heating necessary for ignition by pilot flame is in the order of 0.3 calorie per square centimetre per second (13 kW/m^2) and 0.6 calorie per square centimetre per second (25 kW/m^2) for spontaneous ignition. The separation requirement for buildings laid down by building regulations in the UK were derived from these ignition limits [25].

In a review on the thermal degradation of wood components, three phase points were defined by Kollmann ([12],[40]):

(a) Flame point, 225° to 260° C, at which decomposition gases will burn if an ignition source is present.

(b) Burning point, 260° to 290° C, at which burning occurs with a steady flame. (The decomposition becomes exothermic during the burning point and causes a self-induced flash.)

(c) Flash point, 330° to 470° C, the range of spontaneous ignition.

2.3 Factors affecting the burning behaviour of timber

Factors affecting the burning behaviour of timber will affect the charring rate. These factors include the following:

(a) *level of radiant heat exposure*. The rate at which pyrolysis occurs depends upon the level of imposed radiation on the surface of the exposed timber.

(b) *formation of char*. The charring rate is more rapid initially but stabilises after the formation of a few millimetres (~¼" or 6mm) of char.

(c) *moisture content*. The presence of moisture will delay the formation of char as the temperature will be kept under the charring temperature of 300°C until the moisture has been driven off.

(d) *species of timber*. The properties of timber (eg density, composition and permeability) varies greatly and different species will exhibit different combustion behaviour.

(e) *dimensions of the timber*. The charring rate of timber usually exhibits two peaks - during the initial exposure before the formation of a char and towards the end when the char interface approaches the unexposed surface. Thinner specimens therefore tend to exhibit higher levels of charring rate. In addition, the shape of the timber will influence the rate at which heat is absorbed into the surface as well as the residual section of the unburnt timber.

Some of these factors are described in the following subsections. Values for some of these properties can be found in Appendix B.

2.3.1 Density

Many studies have shown that density has a significant effect on the rate of burning. Early work by Vorreiter [69] showed that the rate of mass loss is proportional to density. Hawley [36] explained that lower density allows more rapid heat penetration and also provided a greater surface area per unit weight. In terms of charring rate, Schaffer [59] and Hall *et al* [34] have shown it to be inversely proportional to density. Hence, although the rate of mass loss increases with density, the rate at which the char develops is lower.

Schaffer [59] also found that lower density specimens tended to have wider cracks or fissures in the char such that the char depths at these locations were slightly greater.

When designing timber based on the sacrificial loss approach, The Multi-Residential Timber Framed Construction (MRTFC) [54] recommends the use of timber with a minimum average density of 450 kg/m³.

2.3.2 *Specimen thickness*

Akita [7] measured the temperature distribution in wood boards and found that the thickness or depth of char does not depend upon the board thickness above a certain limit. In his experiments, he found that specimens over 1/4" (6.4mm) thick have negligible influence on the char rate.

2.3.3 *Moisture content*

Due to the low thermal diffusivity of wood, the temperature gradients in wood within a fire-exposed section are relatively steep. The steep temperature gradient generates movement of moisture within the section. Figure 2 illustrates the temperature and moisture content gradients measured by White and Schaffer [75] within a southern pine specimen exposed on one side to a furnace temperature of 538°C for about 20 minutes. The specific gravity of the specimen was 0.52 with initial moisture content of 10 percent. According to Schaffer [58], the temperature gradient with moisture present is not readily modelled in finite element models. However, the loss of moisture by latent heat of vapourization has been implemented with some success on simpler one-dimensional models [57].

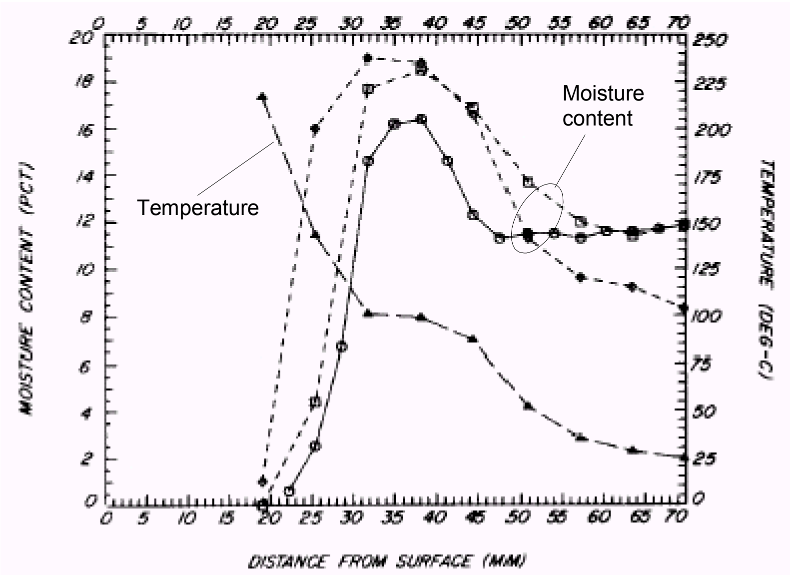


Figure 2. Temperature and moisture content gradients in southern pine section [75]
(0.52 specific gravity and initial moisture content of 10 percent. Exposed on one face to furnace temperature of 538°C for about 20 mins.

Experiments by Schaffer [59] showed that increasing the moisture content increases the dwell in temperature resulting from the energy required to vapourise the moisture (refer Figure 3) and therefore reduces the rate of charring. He developed charring rates for Douglas Fir, Southern Pine and White

Oak exposed to the standard ASTM E 119 test as a function of density and moisture content and is given in Section 3.2.7.

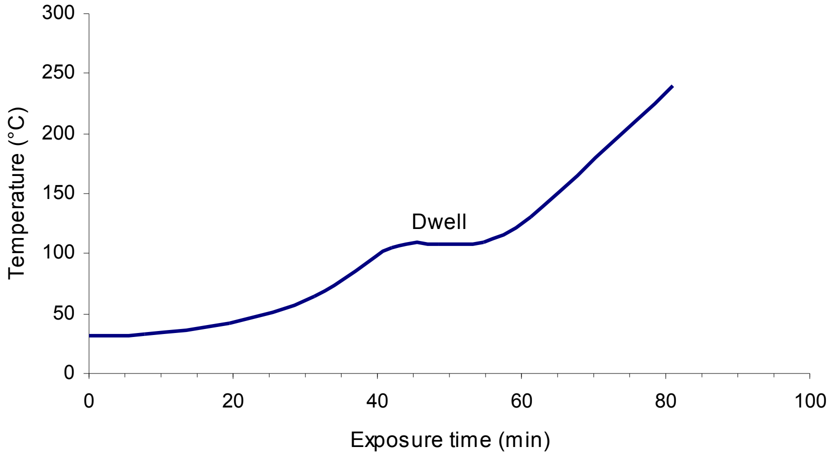


Figure 3. Temperature of thermocouple located in burning wood (Schaffer [59])

Hawley [36] found that moisture contents in the order of 50-100 percent were effective in retarding the rate of combustion. The reduction in the rate of decomposition was also noticeable at low moisture content (10-20 percent).

2.3.4 Permeability

Permeability is a measure of porosity in the wood, ie the flow of fluids through connecting voids under pressure. Research in UK ([30],[31]) on wood with similar densities (*Abura* - highly permeable and *Makore* - highly impermeable) found that increasing permeability was found to increase the rate of charring.

Experiments carried out by Wright and Hayward [86] on 25mm cedar and hemlock specimens exposed to 21 and 42 kW/m² found that decomposition rate for samples cut across the grain was approximately twice that for samples cut along the grain, suggesting that physical characteristics was a greater determinant than chemical composition in the rate of decomposition.

2.3.5 Thermal conductivity

The low thermal conductivity of wood reduces the rate at which heat is transmitted to the interior. Wolgast ([83], [84]) studied the relation between thermal degradation of wood to density and found that thermal conductivity is inversely proportional to the void volume in wood. Hence increasing void volume (ie reducing thermal conductivity) will increase the rate of degradation due to localised overheating at the solid lattice.

2.3.6 Heat capacity

According to Wolgast [83], [84], the heat capacity of wood solids can be assumed constant for any wood. Hence the more mass available to absorb heat energy, the slower will be the degradation.

3 CHARRING RATE OF TIMBER

3.1 Introduction

The effect of charring of wood in timber construction has been a subject of intensive research for many years. Generally, charring behaviour of wood can either be described by the mass loss rate (g/s) or by the rate of advance of the char front from the original surface (mm/s). The latter definition has been more widely used because it enables the determination of an effective residual cross-sectional area commonly employed in timber design calculations.

The interface between charred and uncharred wood has a relatively steep temperature gradient (refer Figure 2). The position of this demarcation plane or char front is usually estimated by an interface temperature of approximately 300°C [63],[44],[33],[20]. The base of the char may be taken as 288°C, a direct conversion from the accepted value of 550°F[1] from earlier work [72],[73],[70].

The rate of charring is a complex process which depends upon the interaction between the pyrolysis of wood and the generation of heat, both of which are a function of a number of factors such as the species, density, moisture content, permeability and thermophysical properties (refer Section 2.3).

Early experimental work have led to the development of empirical models for describing the charring of wood that are in the following form:

$$\frac{\partial x}{\partial t} \approx at^{n} \tag{1}$$

where $\frac{\partial x}{\partial t}$ is the instantaneous charring rate

t is time and

a and n are regression constants.

If the initial non-linear rate was excluded, Truax [66] and Vorreiter [69] showed that the constant n in equation 1, attained a value of 0.

The use of constant charring rates, whilst convenient, does not accurately reflect the actual charring behaviour due to factors such as those described in Section 2.3. Char rates tend to have two peaks - initially when the char has not formed, and later when the centre-point temperature of the member starts to rise.

[1] Truax [66] measured the temperature profiles of a 7½" laminated Douglas fir section and found that the temperature of the base of the char layer to be 550°F after twenty minutes exposure to ASTM E-119 fire conditions. The value of 550°F has since been used by Schaffer [59] and others as a benchmark temperature of the base of the char layer.

Charring rates for the design of heavy timber based on experimental data are relatively well established, based on standard fire exposures such as ASTM E 119, CAN/ULC S1012, ISO 8343, JIS 13014 or DIN 41025. Recommended charring rates [44] are shown in Table 2.

Table 2. Recommended charring rates for timber design

Application	*Charring rate (mm/min)*	*Source*
light, dry wood	0.8	Lie [51]
medium-density softwood	0.6	Lie [51]
softwoods	0.61-0.84	Schaffer [58]
hardwoods	<0.53	Schaffer [58]
heavy, moist wood	0.4	Lie [51]
glue-laminated beams and columns	0.6	App D-2.1, National Building Code of Canada
timber in general	0.6-1.0	Swedish Building Code SBN 1976

Charring rate behaviour has been extensively studied such that models are available that predict the rate of char for timbers exposed to the following conditions:

(a) standard fire (ASTM E 119)

(b) non standard fire (varying heat exposure)

(c) constant temperature

The above list refers largely to empirical models that were derived from experimental data. Considerable efforts have also been given to the development of theoretical models for wood charring that are intended to take into account more complex geometries and variation in heat exposure. Unfortunately, no completely satisfactorily model has yet been developed due to problems associated with the theoretical analysis of burning wood [72].

3.2 Standard fire

3.2.1 AS 1720.4-1990 [9]

The Australian Standard, AS 1720.4, contains design procedures for determining the capability of a timber structural member to sustain a load exposed to the heating regime of AS 1530.4 by determining the residual cross-sectional area due to charring. The notional charring rate is given by

$$\dot{c} = 0.4 + \left(\frac{280}{\rho}\right)^2$$

where $\dot{c}$ = charring rate (mm/min)

ρ = timber density at a moisture content of 12% (kg/m³)

The effective depth of charring is determined as follows:

$$d_c = \dot{c}\,t + 7.5$$

where d_c = effective depth of charring (mm)

t = time of exposure to the heating regime specified in AS 1530.4 (minutes)

The 7.5mm allowance is intended to account for a layer of uncharred timber that has attained a high temperature and has no mechanical properties contributing to the strength of the residual section.

The effective residual cross-section is obtained by subtracting the calculated effective depth of charring from all fire-exposed surfaces of the timber member. The effect of corner charring is ignored.

3.2.2 BS 5268: Part 4 - 1978 [15]

Section 4.1 of BS 5268: Part 4 - 1978 sets out a method of assessing the performance of a structural timber member exposed to the heating regime of BS 476: Part 8. The application of the BS approach was illustrated in the Swedish Finnish Timber Council catalogue [5] for the design of Redwood and Whitewood performance in fire.

The charring rate for Redwood and Whitewood was taken to be 0.67mm/min. For columns exposed on all sides and members in tension, the charring rates were increased by a factor of 1.25.

Unlike AS 1720.4, the rounding at the corners from a cross-sectional view was determined as follows:

$$A = 0.215r^2$$

where A = area of section lost due to rounding at the corner

r = radius of the rounded corner, equal to the calculated depth of charring.

The centre of gravity (from either linear face) was taken as 0.233*r*. The effect of rounding could be ignored for periods of fire exposure not exceeding 30 minutes and where the least dimension of the residual section is not less than 50mm.

3.2.3 Eurocode [27]

Eurocode 5 has a simple constant charring rate relationship as follows:

$$d_{char} = \beta_o t$$

where d_{char} = charring depth (mm)

β_o = charring rate (mm/min)
(usually between 0.5 - 0.8)

Its recommended temperature profile in wood members, based on German experiments on wood slabs and beams exposed to the ISO 834 fire curve, is given as:

$$T = T_o + \left(T_p - T_o\right)\left(1 - \frac{x_c}{a_t}\right)^2$$

where T = temperature (°C)

T_o = ambient temperature (°C)

T_p = char front temperature (°C)

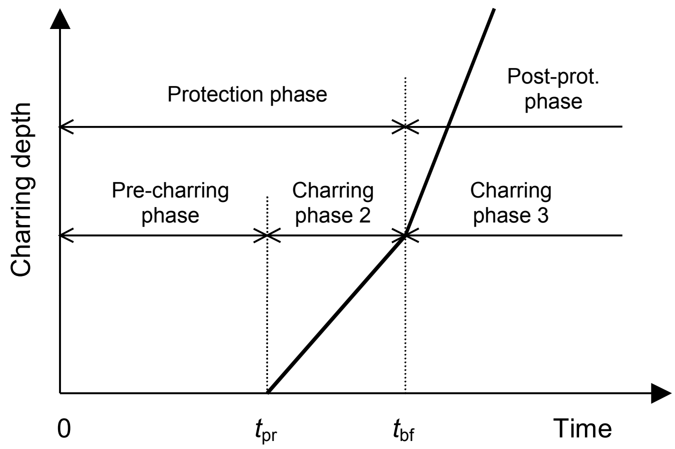
x_c = distance of char base from original surface (mm)

a_t = thermal penetration depth (mm)
(40 for a conservative fir, 35 for a better fit)

The above temperature profile was verified by Janssens and White [38] based on charring rate measurements by White [74].

3.2.4 *König and Walleij [42]*

König and Walleij developed a design model for standard fire exposure for timber framed wall and floor assemblies with linings of gypsum plasterboard and cavities filled with rock or glass fibre insulation. They described the model into two charring phases: protection phase and post-protection phase as shown in Figure 4.



Note: Linear charring rate assumed for simplicity

Figure 4. Charring phases on protected wood [42]

The protection phase is defined as the time period during which the protective lining is attached to the timber frame. This phase consists of the pre-charring phase during which the timber frame does not char (up to time t_{pr}), and charring phase 2 when the timber chars behind the lining. The protection phase ends at time t_{bf} when the lining fails, and enters charring phase 3, during which the timber is directly exposed to the fire.

The charring relationships by König and Walleij are based on the one-dimensional charring rate given by

$$d_{\mathrm{char}} = \beta_0 t$$

where d_{char} = depth of char

β_0 = charring rate for one-dimensional charring of initially unprotected wood exposed to standard fire (= 0.67 mm/min for softwoods)

and t = time of fire exposure

For timber framed members in wall and floor assemblies with cavities filled with insulating material, the charring rate is modified to allow for the rounding at the arisses (corners) given by

$$\beta_1 = \kappa_s \beta_0$$

where κ_s = cross-section factor due to rounding of the narrow exposed timber face

The charring rate for the period where the timber is still protected by the lining is given as

$$\beta_2 = \kappa_s \kappa_2 \beta_0$$

where κ_2 = insulation factor for the protective lining

The corresponding char depth for charring phase 2 is given by

$$d_{\mathrm{char,2}} = \kappa_s \kappa_2 \beta_0 (t - t_{pr})$$

where t_{pr} = time of protection against charring

Similarly, the char depth for the post-protection phase corresponding to an increase in charring rate is given by

$$\begin{aligned} d_{\mathrm{char,3}} &= \kappa_s \kappa_2 \beta_0 (t_{bf} - t_{pr}) + \kappa_s \kappa_3 \beta_0 (t - t_{bf}) \\ &= \kappa_s \beta_0 \left[\kappa_2 \left(t_{bf} - t_{pr}\right) + \kappa_3 \left(t - t_{bf}\right)\right] \end{aligned}$$

where κ_3 = post protection factor under increased exposure

t_{bf} = time of lining (board) failure

The relationships for the above factors were derived as follows.

β_0 = 0.67 mm/min

β_1 = 0.86 mm/min (reasonable up to 40mm for 45mm widths) hence $\kappa_s = 1.29$

For widths between 38 and 90mm, κ_s is represented by the following polynomial:

$$\kappa_s = 0.000167b^2 - 0.029b + 2.27$$

where b = section width (mm)

The calculated times for linings of gypsum plasterboard are as follows:

$$t_{pr} = 2.8\, h_b - 14.2 \quad \text{(no joints in the fire exposed layer)}$$

$$= 2.8\, h_b - 22.8 \quad \text{(joint in the fire exposed layer)}$$

where h_b = the thickness of the board in millimetres

The insulation factor, κ_2, based on a linear relation assumption for β_2 is given as

$$\kappa_2 = \frac{\beta_{2,linear}}{\kappa_s \beta_0}$$

$$= -0.0073\, h_b + 1.05 \quad \text{(no joints in the fire exposed layer)}$$

$$= -0.0037\, h_b + 0.86 \quad \text{(joint in the fire exposed layer)}$$

Similarly, the post protection factor, κ_3, based on a linear relation assumption for β_3 is given as

$$\kappa_3 = \frac{\beta_{3,linear}}{\kappa_s \beta_0}$$

$$= 0.0036\, t_{bf} + 1$$

The failure of standard gypsum plasterboard would normally fall off shortly after the timber member has started to char behind the lining, i.e. $t_{bf} \approx t_{pr}$. Tests reported by König *et al* [41] reported that ceiling linings fall off earlier than wall linings. They suggested the following failure criterion for temperature: 600°C for ceiling linings and 800°C for wall linings, both for temperatures on the unexposed side.

Table 3. Failure times (min) of linings due to mechanical degradation [42][43]

Plasterboard Lining	*Walls*	*Ceilings*
1 layer, 15.4mm fire rated	65	35
1 inner layer 12.5mm standard 1 outer layer 15.4mm fire rated	77	57
2 layers (2×15.4mm) fire rated	>90	>60

Note: Failure times are based on temperatures on the unexposed side of the linings (600°C for ceilings and 800°C for walls) exposed to ISO 834.

It may be possible for the lining to fail due to pull-out of fasteners. These failure times t_{bf} are given as follows [43]:

$$t_{\mathrm{bf}} = t_{pr} + \frac{l_f - l_{a,\min} - h_{b,tot}}{\beta_0 \kappa_s \kappa_2} \qquad \text{(away from joint)}$$

$$t_{\mathrm{bf}} = t_{pr} + \frac{l_f - l_{a,\min} - h_{b,tot}}{1.15\beta_0 \kappa_s \kappa_2} \qquad \text{(near joint)}$$

where l_{f} = total length of fastener

$l_{\mathrm{a,min}}$ = minimum penetration length into unburned wood (≈10mm)

$h_{\mathrm{b,tot}}$ = total thickness of lining

3.2.5 Collier [20]

Collier conducted six fire resistance tests to AS 1530.4-1990 on loadbearing light timber frames as described in Table 4.

Table 4. Properties of tested timber framed walls

Test	*Lining*	*dry density* (kg/m³)	*moisture**** *content* (%)	*Depth* (mm)	*Width* (mm)	*Nominal* (D×H)
1	14.5 fire rated p/board*	344-517	15-16.5	88-90	44-46	100×50
2	"	390-585	13.5-16	88-90	44-46	100×50
3	"	398-518	15-16	88-90	44-46	100×50
4	"	457-497	12-15	138-140	44-46	150×50
5	"	437-526	12-13	138-140	44-46	150×50
6	18 medium density fibre-board**	332-476	14-17	88-90	44-46	100×50

Notes: * Remained intact throughout the test (i.e. > 70 minutes)
** Completely burnt away in 25 minutes, exposing studs within wall cavity.
*** Air-dried for 100×50 mm sections, kiln-dried for 150×50 mm sections.

The walls were tested at various load levels and heights as shown in Table 5. Also shown in Table 5 are the failure times and the equivalent char depths as shown in Figure 5.

Table 5. Wall test configuration and char results

Test	*Load per stud* (kN)	*Wall height* (m)	*Failure time* (min)	*Equivalent char depth* (mm)
1	16	3	46	15.2
2	8	3	70	17.0
3	10	3	60	23.6
4	40	3	40	18.5
5	20	4	71	18.0
6	16	3	30	14.8
			Average	17.8

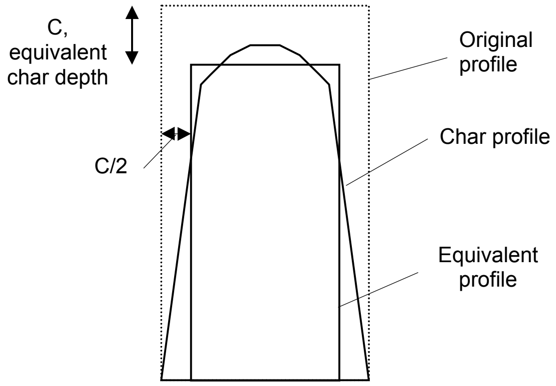


Figure 5. Equivalent char profile

The equivalent char depth was determined on the basis that charring occurred on three sides with the surface against the exposed lining charring at twice the rates at the sides. For larger timber sizes (>80mm in width) Hadvig [33] (see also Section 3.3.6) determined that the charring rate may be considered to be similar for both the width and depth. Widths smaller than 80mm tended to char faster.

The results of Collier tests indicated that the temperature of the inner face of the exposed plasterboard lining took approximately 25 minutes to reach a temperature of 300°C, when charring would be expected to begin. However, the time taken at the stud/lining interface took an additional 5 minutes to reach 300°C due to the conduction of heat into the studs. Hence the presence of the linings in tests 1 to 5 delayed the onset of charring for at least 30 minutes. The rate of char formation thereafter varied between 0.4mm/min away from the lining joint to 0.6mm/min near the lining joint.

3.2.6 *White and Nordheim [70]*

White and Nordheim [70] developed an empirical model for charring rate in the standard ASTM E 119 test based on regression analysis of 40 tests on eight species (both hardwood and softwood) in the following form:

$$t = m x_c^{1.23}$$

where t = time of fire exposure (min)

m = reciprocal char rate (min/mm),

x_c = char depth (mm)

The reciprocal char rate is given as

$$m = -0.147 + 0.000564\rho + 0.0121u + 0.532f_c$$

where ρ = oven-dry density (kg/m³)

u = moisture content (percent), and

f_c = char contraction factor, defined as the thickness of the char layer at the end of the fire exposure divided by the original thickness of the wood layer that has charred.

Using similar regression procedures, an expression for the char contraction factor was obtained as follows:

$$f_c = 0.732\text{-}0.00423d\text{+}0.203c\text{-}0.00164cd\text{-}0.270\rho c$$

where c = classification factor
(1 for softwood and -1 for hardwood)

d = depth of CCA (preservative) penetration (mm)
(3 for low to 36 for highly treatable species)

The char contraction factors for solid wood are 0.59 for southern pine, 0.67 for yellow-poplar and around 0.75 for Douglas fir (based on limited data). An equation for the char contraction factor for hardwood species can be reduced to [78]:

$$f_c = 0.529\text{-}0.0036d\text{+}0.000270\rho$$

3.2.7 *Schaffer [59]*

Schaffer reported charring rates (B, min./inch) in the standard ASTM E 119 test as a function of density and moisture content for the following timbers [72]:

B = 2[(28.726 + 0.578M)ρ + 4.187] for Douglas fir

B = 2[(5.832 + 0.0120M)ρ + 12.862] for Southern pine

B = 2[(20.036 + 0.403M)ρ + 7.519] for White oak

where M = moisture content (%)

ρ = dry specific gravity

The charring rate in SI units can be obtained as follows:

$$c = 25.4/B \text{ mm/min}$$

Schaffer [58] also developed a model for describing the temperature distribution in the uncharred wood below the char-wood interface at a distance x once a quasi-steady-state charring rate v has been reached, as follows:

$$\frac{(T - T_o)}{(T_{cw} - T_o)} = \exp\left[\frac{-vx}{\alpha_q}\right]$$

where T = temperature

T_o = initial wood temperature

T_{cw} = char-wood interface temperature of 288°C

v = charring rate (in./min)

x = depth into wood from char-wood interface

α_q = thermal diffusivity

The quasi-steady-state occurs about 15 to 20 minutes after initiation of fire exposure. The temperature distribution for times between 5 and 15 minutes requires interpolation.

3.2.8 Lawson et al [48]

Lawson *et al* studied the charring rates of spruce timber beams between 38 and 50mm thick at 12% moisture content when exposed to ASTM E 119 heating regime.

$$\frac{\partial x}{\partial t} = 1.041 t^{-0.2}$$

where x = location of char front (mm)

t = time (min)

3.2.9 Gardner and Syme [29]

Gardner and Syme manufactured large sections of glued-laminated (Glulam) beams from eight Australian-grown timber species and exposed them to the standard heating regime of AS1530.4 on three sides. The beams were manufactured to AS1328 and were nominally 4800×270×150mm containing nine 30mm thick laminates glued with resorcinol adhesives. They found that the charring rates were a function of the time to exposure and their densities. They also repeated the tests with specimens protected with 13mm fire-rated gypsum plasterboard on the three exposed sides and found that it delayed the onset of char formation and subsequent rate of char formation.

The properties of the specimens tested are given in Table 6.

Table 6. Properties of test species [29]

Species	*mean density* (kg/m³)	*moisture content* %
Blackbutt	939	12.2
Blue gum	968	14.1
Brush box	819	11.4
Cypress pine	666	10.9
Jarrah	848	12.0
Radiata pine	526	9.2
Spotted gum	901	12.0
Victorian ash	659	10.5

The specimens were subjected to the following furnace exposure conditions:

(a) 1A 1 hour, furnace thermocouples at 300mm below specimen

(b) 1B 1 hour, furnace thermocouples at 150mm from centre of exposed faces

(c) 2B 2 hours, furnace thermocouples at 150mm from centre of exposed faces

(d) 2BP 2 hours, furnace thermocouples at 150mm from centre of exposed faces, specimens protected with fire rated gypsum plasterboard

Furnace exposure 1A was found to be more onerous than 1B because it did not account for the combustion of gases emitted by the pyrolysing timber.

The charring rates were determined as follows:

$$\text{charring rate} = \frac{d}{t} \quad \text{mm/min}$$

where d = depth of char, mm
t = time of furnace exposure, min

Results of the char rate data were based on an interface temperature of 288°C. However, results were given only for specimens which maintained a semi-infinite solid behaviour, ie the temperature in their central zone did not exceed 100°C. These results are given in Table 7.

Table 7. Results of char depths and rates

Species	*Furnace exposure*	*Char depth* (mm)		*Char rate* (mm/min)	
		Side	Base	Side	Base
Blackbutt	1A	32.0	35.0	0.5	0.6
	2BP	28.6	45.0	0.2	0.4
Blue Gum	1A	29.4	29.0	0.5	0.5
	2BP	26.1	41.0	0.2	0.3
Brush box	1A	32.7	32.0	0.6	0.5
	2BP	27.9	31.0	0.2	0.3
Cypress pine	1A	37.3	35.0	0.6	0.6
	2BP	37.2	48.0	0.3	0.4
Jarrah	1A	32.0	39.0	0.5	0.7
	2BP	32.0	39.0	0.3	0.3
Radiata pine	1A	55.5	47.0	0.9	0.8
	1B	47.6	35.0	0.8	0.6
	2BP	52.8	48.0	0.4	0.4
Spotted gum	1A	31.6	29.0	0.5	0.5
	2BP	29.6	32.0	0.3	0.3
Victorian ash	1A	37.2	25.0	0.6	0.4
	2BP	38.5	39.0	0.3	0.3

The charring rates in Table 7 indicate that the difference between the sides and the base were less than 10%, and was predominantly greater for the base.

From their experiments, they determined the following:

(a) The depth of char formation for the range of timbers tested (densities ranging from 545 to 1000 kg/m³) exposed to the standard heating conditions of AS1530.4-1985 is given by:

$$c = \frac{413t}{\rho} + 1.6$$

(b) When the timber is protected with 13mm of fire rated gypsum plasterboard, the depth of char formation is given by:

$$c = \frac{234t}{\rho} - 5.8$$

where c = char depth in mm
t = furnace exposure period in minutes
ρ = air-dried density in kg/m³ of the timber.

The presence of the fire-rated gypsum plasterboard was found to be significant:

(a) The onset of charring was delayed for a mean time of 20.6 minutes (with a range of 14.0-26.5 minutes).

(b) The depth of char can be reduced by approximately 40% for an exposure period of 2 hours (based on the above char formation equations).

3.3 Non-standard fire

3.3.1 Butcher [16]

From a survey by Butcher [16], the char rate of unburnt wood exposed to radiation is given by

$$dh/dt = 0.022Q_r \tag{2}$$

where dh/dt = rate of char (mm/min)
Q_r = radiation (kW/m²)

3.3.2 Leceister [49]

The equation by Butcher (2) did not account for the presence of char which considerably reduces the char rate when it reaches 5mm thick. The insulating characteristic of a char layer is illustrated in Figure 3.

Figure 6 shows the measurements of char depth by Schaffer [59] for Douglas Fir subjected to constant temperature conditions, and to the ISO time-temperature curve. The char rate appears to be constant for the ISO heating curve and was found to be approximately related to density by the following relationship:

$$dh/dt = 360/\rho \tag{3}$$

where dh/dt = rate of char (mm/min)
ρ = density (kg/m³)

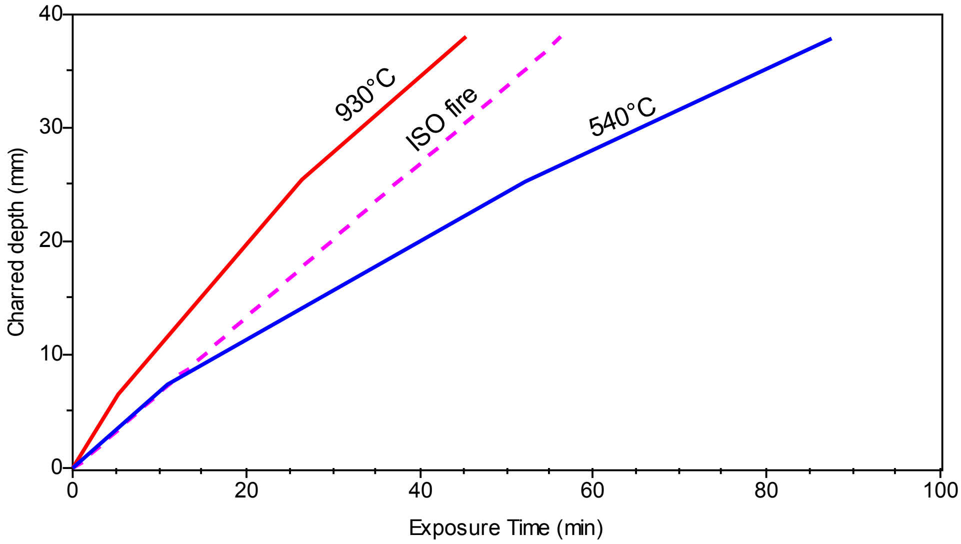


Figure 6. Charred depth for Douglas Fir (Schaffer [59])

Based upon a number of fire test data on timber, Leiceister [49] modified equation (3) to produce an estimate of the final depth of char as follows:

$$h_{eff} = 360 t_{FS} / \rho + 1.5\sqrt{t_{FS}} \qquad \text{such that } 1.5\sqrt{t_{FS}} \ngtr 10 \tag{4}$$

where
h_{eff} = effective final depth of char (mm)
t_{FS} = duration of fire above 300°C (min)
ρ = timber dry density (kg/m³)

3.3.3 *Silcock and Shields [63]*

Tsantaridia and Ostman [68] measured the formation of char in knot-free spruce studs conditioned at 14% moisture content when exposed to both the standard fire in the furnace and the cone calorimeter at 50kW/m². The char depth was defined by a 300°C isotherm within the sample. Results of the char depth variation with respect to time of exposure is shown in Figure 7.

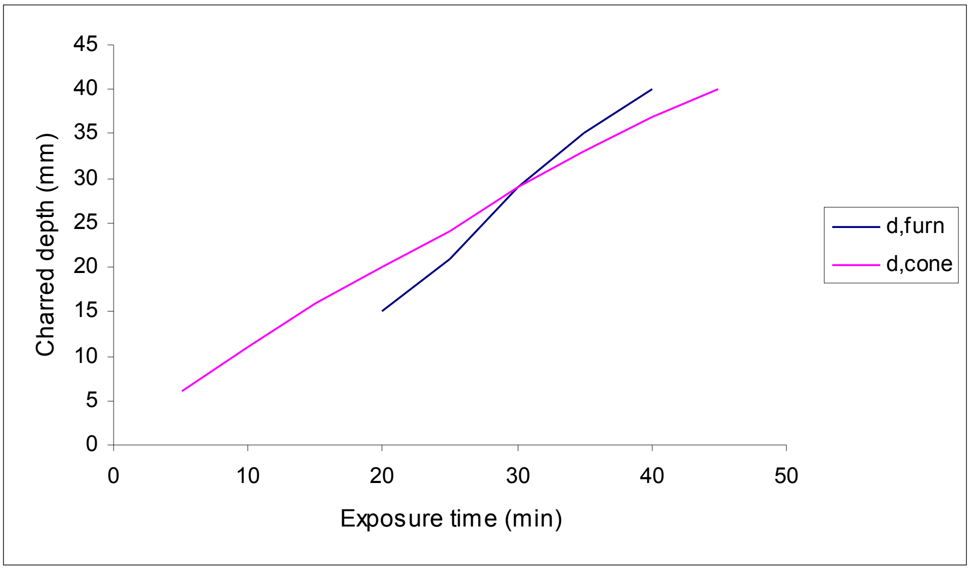


Figure 7. Char depth from furnace (standard fire) and cone (50 kW/m²) tests [68]

Silcock and Shields [63] used the concept of local fire severity (LFS) defined as

$$LFS \;=\; \int_0^t \dot{q}(t)'' dt$$

where $\dot{q}(t)''$ is the incident heat flux which varies with time and duration of exposure, to relate to the induced damage which is measured as the degree of char formation.

Based on the above work by Tsantaridia and Ostman [68], Silcock and Shields developed the following relationship between heat flux and char depth d as follows:

$$LFS \;=\; 0.033d^2 + 1.9d + 4.7 \tag{5}$$

By expressing the heat flux exposure as cumulative heat flux over time, the comparison of equation (5) with the char measurements from Tsantaridia and Ostman are shown in Figure 8.

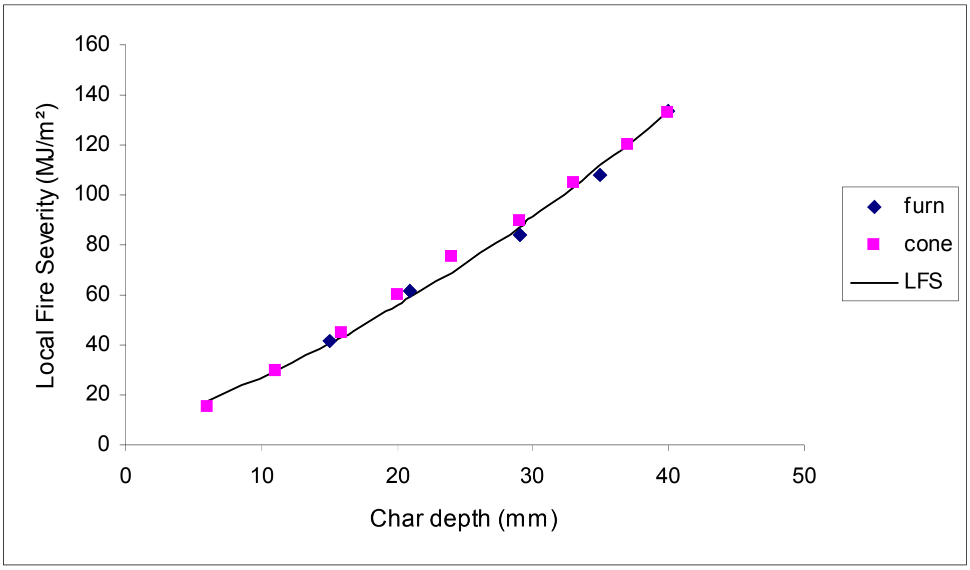


Figure 8. Char depth variation with local fire severity

3.3.4 *Butler [17]*

Butler proposed a linear radiation induced char model based on the incident radiation impinging on the surface:

$$c = 21.96\,\dot{q}$$

where c = char rate (mm/min)

$\dot{q}$ = radiation in MW/m²

$= \varepsilon\phi\sigma T^4$

where ε = emissivity

ϕ = configuration factor

σ = Stephan-Boltzman constant

T = absolute temperature of the radiation source (K)

3.3.5 *Mikkola [53]*

Mikkola extended upon Butler's model by adjusting it for density, moisture content and oxygen concentration as follows:

(a) inversely proportional to the density of timber by

$$\frac{1}{(\rho + 120)}$$

where ρ is the density (kg/m³)

(b) reduced by increases in moisture content according to

$$\frac{1}{(1 + 2.5w)}$$

where w is the moisture content (=mass of water/mass of dry wood)

(c) a reduction in the oxygen concentration from 21% (ambient air) to 8-10% (furnace) can reduce the charring rate by approximately 20%. In a fully developed fire where the oxygen content may approach zero, the charring rate could reduce by 35 to 50%.

3.3.6 *Hadvig [33]*

Hadvig developed equations for real fire exposures that are based upon fire load densities and opening factors as follows:

$$\theta = 0.0175\frac{q}{F}$$

$$\beta_o = 1.25 - \frac{0.035}{F + 0.021} \qquad \text{for } 0.02 \le F \le 0.30$$

$$X = \beta_o \cdot \tau \qquad \text{for } 0 \le \tau \le \theta/3 \tag{6}$$

$$X = \beta_o\left(-\frac{1}{12}\theta + \frac{3}{2}\tau - \frac{3}{4}\frac{\tau^2}{\theta}\right) \qquad \text{for } \theta/3 \le \tau \le \theta$$

where
θ = time at which maximum charring is reached for the values used for F and q (min)
β_o = initial value of rate of charring (mm/min)
X = charring depth (mm)
F = design opening factor ($m^{1/2}$)
q = design fire load (MJ/m²)
τ = time (min)

The design opening factor F is given by:

$$F = F' \cdot k \cdot f$$

where
F' = geometrical opening factor ($m^{1/2}$)
k = transfer coefficient of bounding structure (dimensionless) varies between 0.5 (low insulation) to 3 (high insulation)

f = coefficient to account for horizontal openings (dimensionless) (=1 for only vertical openings, up to about 5 for horizontal openings)

The geometrical opening factor is given by

$$F' = \frac{A\sqrt{h}}{A_t}$$

where A = total area of windows, doors and other openings in walls (ie vertical openings only) (m²)

h = weighted mean value of the height of vertical openings, weighted against the area of the individual openings (m)

A_t = total internal area of the compartment, including floor, walls, ceiling, windows and doors (m²)

The above equations are valid for fire exposures less than 120 min and for enclosures with cellulosic combustibles only. For plastic fuel, the following modifications are required:

(a) char rate β_o is increased by 50%

(b) a shorter time is allowed for maximum charring (θ is cut in half)

(c) equation (6) is applicable for $\tau \leq \theta$

Hadvig's equations are based upon glued timber with a density of 470 kg/m³ with a moisture content of 10 percent and minimum width of 80mm or greater or square members of minimum 50×50 mm. The equations for charring depth X are valid for $0 < X < b/4$ where b is the dimension of the narrow face of a rectangular member. For nonsquare cross sections between 30 and 80 mm, the ratio of the original dimension must be equal to or greater than 1.7, the charring depth perpendicular to the narrow face is determined by multiplying X with the following:

$$1.35 - 0.0044b$$

where b = dimension of narrow face (mm)

3.3.7 *Jones, et al [39]*

Jones *et al* conducted a series of non-loadbearing pilot scale furnace tests (2.22m high × 1.02m wide) on metal stud wall systems using standard and fire rated plasterboards on three heating regimes: high temperature, low temperature and standard (ISO 834). The high temperature heating curve was intended to represent rapid growth fires reaching high temperatures (1200°C) early (~15 minutes) and maintaining it for about 20 minutes before decaying relatively to reach 200° at about 70 minutes. The low temperature curve represented slower burning fires with slow growth to near steady state conditions at moderate temperatures (800°C peak after 60 minutes – no plateau) and slow decay phase. Results of the tests are shown in Table 8.

Table 8. Pilot scale wall tests [39]

Test	*Lining*	*Fire Curve*	*Time of lining failure*
1	Standard	High	16
2	Standard	Low	36
3	Standard	Standard	26
4	Fire rated	High	20
5	Fire rated	Low	Intact up to 122
6	Fire rated	Standard	Intact up to 63

The purpose of the test was to illustrate how both standard and fire rated plasterboard linings behaved when exposed to different heating regimes.

3.4 Constant exposure

3.4.1 Lau, Zeeland, and White [44]

Lau, Zeeland, and White [44] developed an empirical model of charring rates for Spruce-Pine-Fir 2×4 (35mm×88mm) timber subjected to a constant temperature exposure of 500°C. The 55 specimens were 4880mm long and were subjected to a constant force of 15.57 kN (approximately one-third of the tensile capacity) in the furnace.

The charring rate varied from 0.397 mm/min at t=0 to 0.524 mm/min at t =1000s with an average of about 0.451 mm/min. The rate of char at the narrow face of the specimen was observed to be similar to the rate of char at the wide face, and the data could be fitted with a linear regression against the reduction in residual cross-sectional area as follows:

$$A(t) = -1.628t + 3080 \tag{7}$$

where A = residual area (mm²)
t = time (sec)

Based on the above regression, the charring rate β (mm/min) was obtained as

$$\beta(t) = -\frac{\alpha}{8}\left[\frac{\alpha t}{4} + \frac{1}{16}(a_o + b_o)^2\right]^{1/2}$$

where t = time (s)
a_o, b_o = initial cross-sectional dimensions (mm)

$$\alpha = \frac{\partial A(t)}{\partial t}$$

= -1.628 from equation (7)

The observed rate was lower compared to 0.6 mm/min for heavy timber exposed to the ASTM E 119 exposure. This was explained on the basis that the specimens were exposed to a constant temperature of 500°C as opposed to increasing temperatures of the standard fire curve.

In the report, equation (7) was modified to predict char depth as a function of time under variable temperature histories. However, it required calibration against test results to determine the appropriate calibration coefficients.

3.4.2 *Tran and White [65]*

Tran and White [65] investigated the heat release, mass loss and charring rates of thick redwood, southern pine, red oak and basswood specimens for a heat flux range between 15 and 55 kW m² using a modified Ohio State University (OSU) heat release rate calorimeter. Properties of the specimen tested are shown in Table 9.

Table 9. Properties of test materials

Species	*Type*	*Density* (kg/m³)*	*Moisture (%)*	*Char** Contraction*	*Char rate** (mm/min)*
Redwood	Softwood	312	8.3	0.862	0.74
Southern Pine	Softwood	508	9.7	0.589	0.77
Red oak	Hardwood	660	8.5	0.703	0.58
Basswood	Hardwood	420	8.1	0.542	0.87

Notes: * Based on oven-dried wood
** Measured under ASTM E 119 conditions

The specimen samples were prepared by gluing strips of wood to form 150 mm × 150 mm × 64 mm blocks. The specimens were held vertical and subjected to the nominated heat flux perpendicular to the wood grain. A total of 32 tests were conducted comprising of four species, four flux levels and two replicates.

The flux levels are based upon the measured flux, which included heat generated from the combustion, rather than the nominated flux levels. A temperature of 300°C was used as the indicator of char formation. Average charring rate was determined from the time taken for the char front to reach a depth of 36mm.

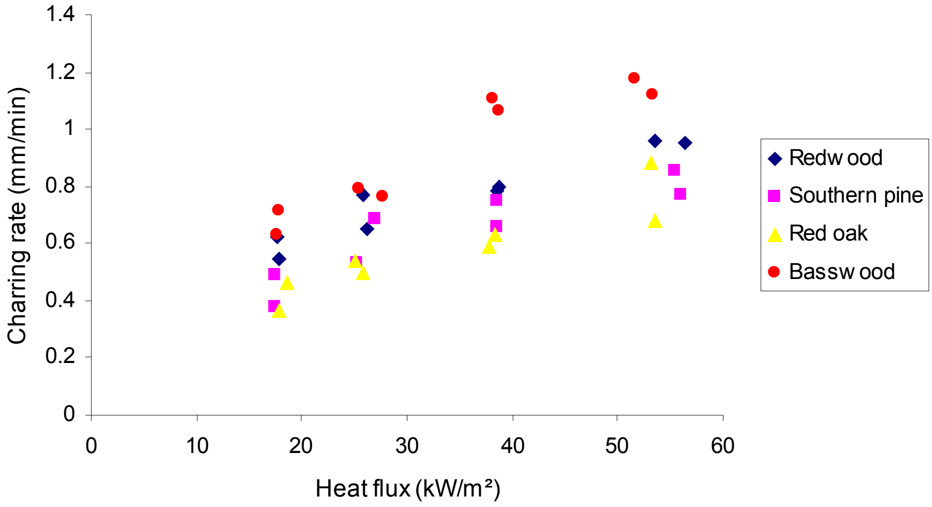


Figure 9. Charring rate of timber specimens

A model for predicting the average charring rate was empirically derived as follows:

$$\dot{c} = \frac{\dot{m}}{\rho_w}$$

where $\dot{m}$ = average mass loss rate (kg/s)

ρ_w = dry density (kg/m³)

The mass loss rate can be determined from the heat release rate determined from the tests as follows:

$$\dot{m} = \frac{Q}{h_c}$$

where Q = heat release rate (W)

h_c = effective heat of combustion (J/kg)

Tran used an empirically derived relationship for h_c as follows (see also Section 6.2.3):

$$h_{c,dry} = 0.057Q + 11.88$$

3.4.3 White and Tran [71]

White and Tran tested two specimens of each of four species (redwood (Sequoia sempervirens), pine (Pinus sp.), red oak (Quercus sp.), and basswood (Tilia sp.)) at each of four nominal heat flux levels (15, 25, 35, and 50 kW/m2) using an OSU calorimeter.

Results of their investigation are shown in Table 10 and Figure 10.

Table 10. Charring rate (mm/min) [71]

Q (kW/m²)	*Pine*	*Redwood*	*Oak*	*Basswood*	*Combined*
15	0.45	0.6	0.39	0.76	0.55
25	0.66	0.74	0.52	0.8	0.68
35	0.8	0.83	0.61	1.22	0.87
50	0.85	1.02	0.73	1.31	0.98

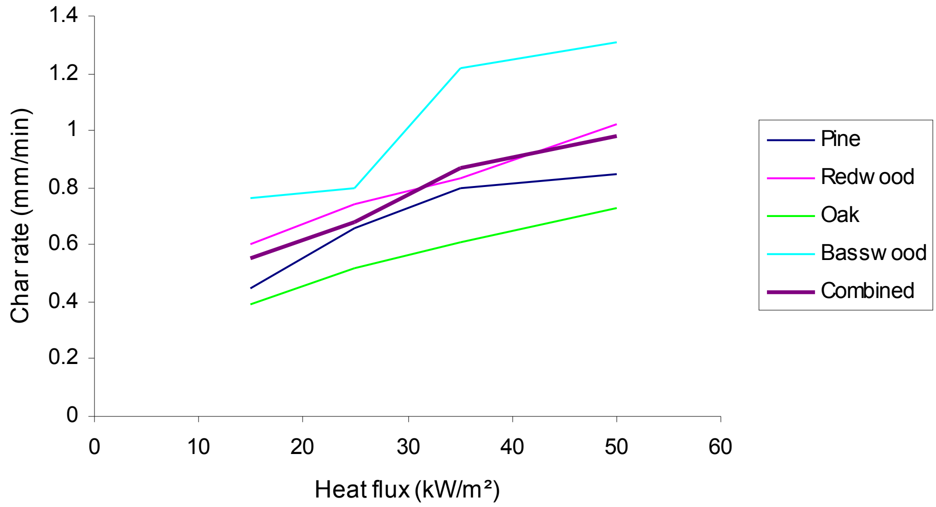


Figure 10. Charring rate [71]

From the results of their investigation, they concluded the following:

(a) Charring of wood exposed to a constant external heat flux can be considered a linear function of time.

(b) At high heat flux levels, the behaviour may become nonlinear with greater times required for a given char depth.

(c) The charring rate is proportional to the ratio of external heat flux level over density.

(d) Temperatures within the uncharred wood can be represented by an exponential function.

(e) For a given char depth, the zone of elevated temperature will be deeper when heated by a lower, constant heat flux level.

3.4.4 *Schaffer [59]*

Schaffer derived equations relating exposure time t (min.) to apparent char depth x (in.) under constant temperature T (K) as follows:

$$\mathrm{v} = \frac{1}{A}(3.0 - x)\exp\left[-\frac{JE}{RT}\right]$$

where v = charring rate (in./min)

J = Joule's constant (4.184 joules per calorie)

R = Gas constant (8.14 joules per gram-mole per K)

T = Temperature (K)

E = Activation energy (calories per gram-mole)
3108 for Douglas fire
3465 for Southern pine
3455 for White oak

3.4.5 *Tsanraridis and Östman [67]*

Tsanraridis and Östman studied the charring of protected wood studs using a cone calorimeter at a constant heat flux of 50 kW/m². They compared the results with full scale furnace wall tests and obtained the following relationships describing the ratio of charring depths:

$$\frac{d_{char,cone}}{d_{char,furnace}} = 1.997e^{-0.019t} \qquad \text{(without boards)}$$

$$= 1.418e^{-0.015t} \qquad \text{(with boards)}$$

where $d_{char,cone}$ = charring depth from the cone calorimeter (mm)

$d_{char,furnace}$ = charring depth from the furnace (mm)

4 ASSEMBLIES

4.1 Wall Assembly

Wall assemblies are typically lightweight framed assemblies in which the charring can occur in two directions due to two-dimensional heat transfer. Studies conducted by Collier simplify the process by assuming that the char rate at the sides of the studs is about half that of the edge that is in contact with the exposed lining (see Section 3.2.5).

4.1.1 Collier and Buchanan [22]

Collier and Buchanan reported three 3m high loadbearing fire resistance tests on timber stud walls of nominal fire resistance levels of 30, 60 and 90 minutes. The walls were lined with fibreglass reinforced fire-rated plasterboards but the cavity was not filled with insulation. Details of the walls and the times to onset of char formation are given in Table 11.

Table 11. Time to onset of char in timber stud walls

Nominal FRL (min)	*30*	*60*	*90*
Studs (mm×mm)	90×45	70×45	90×35
Lining, each side (mm)	9.5	12.7	16.2
Lining density (kg/m³)	721	797	862
Lining moisture content (%)	1	1	1
Load per stud (kN)	8	2	3
Onset of char (min)	15	25	33

They also conducted a room burn test in an ISO standard room of internal dimensions 3.6m×2.4m×2.4m (L×W×H) with an open door at one end of 0.8m×2m (W×H). The room was constructed of light timber frame, walls and ceiling lined with a 12.5mm and 16mm fire rated gypsum plasterboard respectively. The floor and ceiling were of 18mm flooring grade particleboard on nominal 200mm ×50mm joists, with 16mm fire rated gypsum plasterboard on the underside. These linings were intended to provide a nominal 60 minute fire rating.

The fire load comprised nine cribs each weighing 54-56 kg with overall dimensions 550mm × 550mm × 1000mm (L×W×H), made from 25mm × 25mm × 550mm rough sawn pinus radiata giving a total of 500 kg. The fire load was based on Law's equivalent fire resistance time approach [47].

At 21 minutes, small pieces of the room lining was observed to be falling off. The onset of char formation occurred at 29 minutes when the temperature on the cavity side of the exposed lining reached 300°C. The peak temperatures were recorded at about 34 minutes when some of the flooring burned through allowing additional air into the room.

The contribution of the particle board flooring was estimated to be about 80 kg, about 16% of the original fire load.

4.1.2 Young and Clancy [87]

Young and Clancy tested a series of eight timber framed gypsum plasterboard clad walls in a standard fire exposure to AS 1530.4 [8]. The walls measured 3m high × 1.58m wide with 90mm × 45mm timber studs spaced at 380mm centres and were clad with 16mm glass fibre reinforced gypsum plasterboard on each side. Three of the tests were unloaded, four were loaded at 8kN per stud and one was tested by detaching the plasterboard connection from the stud on the non-fire side to remove its composite action. Three of loaded wall tests had pinned[2] end connections (including the non-composite wall) while one was tested with fixed ends.

The three non-load bearing tests failed at 88.5±1 minutes with the timber studs essentially consumed. Unfortunately the rate or extent of consumption was not measured. The loaded composite pinned end walls failed at 34 and 35 minutes respectively while the non-composite wall failed at 28 minutes. The fixed end wall failed at almost 60 minutes. The relatively earlier failure times of the loaded specimens (≤35 minutes) resulted in little reduction in the cross-section due to charring.

An important observation from the tests was that the glass fibre reinforced gypsum plasterboard increased the time of failure of the walls by 40% in ambient conditions and 25% when exposed to the AS1530.4 standard fire.

4.1.3 Collier [21]

Collier conducted four small-scale wall tests (2.2m×1.0m) to provide development data for a cavity-wall model over a range of time-temperature conditions. The test wall was lined with 9.5mm fire-rated paper-faced gypsum plasterboard on each side.

[2] Pinned end means the fixity at the end where it connects to the floor or ceiling/roof is not restrained from rotation. Most end connections of plasterboard walls have some degree of fixity. Walls initially tested as fixed ends eventually behaved more as pinned ends as the fixity of the end connections degraded.

Table 12. Summary of Test [21]

Fire Type	*ISO 834 (fast)*	*ISO 834*	*Fast (hydrocarbon)*	*Slow (wood)*
Stud size (mm×mm)	70×45	90×45	90×45	90×45
Lining density (kg/m³)	696	696	731	731
Load per stud (kN)	5	13	13	13
Onset of char (mins)	11	16	14	35
Structural failure (mins)	39	44	30	69
Insulation failure (mins)	38	44	30	69
Cracking of exposed lining (mins)	10-20	10-20	<21	>41

4.1.4 Hakkarainen [35]

Hakkarainen conducted a series of experiments in rooms of timber construction to study the gas temperature development and charring behaviour of the timber. The internal dimensions of the room were 4.5m×3.5m×2.5m high and it has a single window opening measuring 2.3m wide ×1.2m high at the wall with the narrower side. The room was framed in heavy laminated timber except for one that was built from lighter timber stud construction. The floor was made from 22mm tongue-and-groove particleboard, installed on wooden battens with rockwool insulation beneath the boards. Details of the test configuration are together with the lining used on the walls are shown in Table 13.

Table 13. Test configuration

Test	*Construction*	*Lining*
1	heavy laminated timber	None
2	heavy laminated timber	1×12.5mm standard plasterboard
3	heavy laminated timber	1×12.5mm standard plasterboard + 1×15.4mm fire rated plasterboard
4	timber studs with mineral wool insulation	1×12.5mm standard plasterboard + 1×15.4mm fire rated plasterboard

The fire load comprised of four piles of wooden crib, each of which consisted of two layers of 10 sticks measuring 38mm×38mm×800mm each. The mass of the wooden cribs and the particleboard were 680 and 230 kg respectively, giving a fire load density of 58 kg/m².

From the results of the test, it was found that the gas temperatures of rooms with adequate lining protection resulted in higher room temperatures - up to 1200°C in Test 3 and 4 compared with 700°C-800°C for unprotected (Test 1) and less protected (Test 2) rooms. The single layer of standard plasterboard was found to delay the onset of charring in the timber by 20 minutes. The addition of a fire rated plasterboard doubled the time to initial char to 40 minutes.

4.1.5 Australian Proprietary Systems

In Australia, lining manufacturers (in association with the timber industry) have developed various systems which have been tested and certified by recognised testing authorities. For a single stud wall system, the linings (applied to each side of the wall) required to achieve a range of FRLs are given in Table 14 [55].

Table 14. Linings for single stud wall to achieve various FRLs [55]

FRL	*Lining*
30/30/30 -/60/60	1×13mm Fire Grade Plasterboard
60/60/60 -/60/60	1×16mm Fire Grade Plasterboard
90/90/90 -/90/90	2×13mm Fire Grade Plasterboard, or 1×16mm Fire Grade Plasterboard and 1×6mm Fire Cement Sheet

Notes: -/60/60 and -/90/90 refer to non-loadbearing walls.

CSR Gyprock conducted fire tests [24] on various configurations of their proprietary lining product, Fyrchek, to determine the char depths on timber stud sections. Results of their tests are shown in Table 15.

Table 15. Char depths for various Fyrchek configuration

Fyrchek sheeting configuration	*Time* (minutes)*	*Char depth (mm)*
1×13	30	0
1×16	60	7
2×13	90	5
2×16	120	8

Note: * Duration of standard fire exposure to AS1530.4-1997.

It would therefore appear that for a 60 and 90 min FRL specification, the depth of char for timbers protected by Fyrchek is up to 7mm.

4.2 Floor/Ceiling Assemblies

4.2.1 Cramer and White [23]

Cramer and White developed a model for predicting the fire endurance of gypsum wall board-protected wood floor/ceiling assemblies entitled SAWFT. The degradations of wood members and metalplate-connectors within the model are based upon elevated temperature/mechanical tests with Southern Pine lumber. Comparisons of fire endurance times predicted with the model and measured from ASTM E 119 assembly tests were favourable. However, the application of the model is limited to the use of degradation rules in the integrity of gypsum wallboard that are based on limited test data.

Of particular relevance is the use of an empirical model for the prediction of temperature through a timber cross-section as follows [80]:

$$A_t = \sum_{t=0}^{t} \frac{1}{3}\left(T_s - 3T_0 + 2T_c\right)\Delta t$$

where A_t = cumulative area under the temperature profile from each time step Δt.

t, Δt = time and increment time (min)

T_0, T_c and T_s = initial, centre and surface temperature (°C) of the section

4.2.2 *Schaffer and White [60]*

Schaffer and White reported the results of a series of experiments on 10 2"×10" Douglas Fir joists used in unprotected floor assemblies exposed to ASTM E 119 fire conditions for 6.5 and 17.9 min. The char rate was correlated to density and moisture content using linear regression analysis. For density ρ alone, the expression for char rate was

$$C = 2.3898 - 0.03189\rho \quad \text{(in/min)}$$

For both density and moisture content, the expression was

$$C = 3.674 - 0.0295\rho - 0.1404u \quad \text{(in/min)}$$

where u is moisture content.

They conducted Monte Carlo simulations based upon the experimental results and found that the influence of assumed rate of charring has a lesser influence on time of failure as stress level increases.

4.2.3 *Woeste and Schaffer [81][82]*

Woeste and Schaffer presented an analytical model for assessing the fire endurance of two unprotected light-frame floor assemblies--a conventional joist assembly and a floor-truss assembly. Based upon available test results in the literature, the following moment-residual cross-section modulus model was selected as the best predictor of structural failure time t_f for fire-exposed floor joists:

$$\frac{M\left(d - Ct_f\right)/2}{\left(b - 2Ct_f\right)\left(d - Ct_f\right)^3/12} = \frac{B}{1 + \dfrac{b + 2d}{bd}\gamma t_f}$$

where M = applied moment due to both dead and live loads (in-lb)

d = initial joist depth (in)

C = char rate (in/min)

t_f = time to failure (min)

b = initial joist width (in)

γ = fire-exposed joist performance factor

B = joist modulus of rupture at room temperature (psi)

4.2.4 *Australian Proprietary Systems*

The lining requirements for fire rated floor and ceiling systems (Table 16) are generally higher than the corresponding wall systems (Table 14).

Table 16. Linings for floor/ceiling wall to achieve various FRLs [55]

FRL	*Lining*
30/30/30	1×13mm Fire Grade Plasterboard
60/60/60	2×13mm Fire Grade Plasterboard
90/90/90	2×16mm Fire Grade Plasterboard

Roof/ceiling systems requiring a resistance to the incipient spread of fire to the roof space between the ceiling and the roof will need to meet the BCA [11] requirement of not less than 60 minutes. To meet this requirement the ceiling must be lined with 1×13+1×16mm Fire Grade Plasterboard (or 2×16mm Fire Grade Plasterboard) fixed directly to the ceiling joists or supported on resilient channels or resilient mounted channels.

4.3 Estimated contribution from Australian fire rated wall and ceiling assemblies

Based upon the information from representative Australian manufacturers of fire rated timber wall components, the following provides an estimate of the amount of char that can be expected for exposure to the specified duration of the standard fire in accordance with AS1530.4-1997. The estimates will be based upon a base apartment size of 20m². The corresponding enclosure geometry will be assumed to be 5m×4m×3m high.

Char depth c = 7mm (max char for 60 to 90 min FRL, Table 15)

Stud size $b \times d$ = 90mm × 35mm

Char area A_c = 7×(90+35)

= 875mm²

For a room size of 5m×4m×3m (W×D×H), the amount of char obtained is:

Char per 3m stud = 0.00263m³

Wall perimeter = 18m

Stud spacing s = 600mm

No of studs n = 30

Total char volume = 30×0.00263

= 0.0788m^3

Density of stud = 460kg/m^3 (radiata pine) [3]

Mass of char = 36.2kg

Assuming a fire load density of 15 kg/m^2 (low is conservative since timber mass is proportional to room size), the fire load is:

Fire load FL = 15×20 = 300kg

Percentage of char = 36.2/300 = 12.1%

Hence the maximum char obtained for wall systems that are designed for up to 90 minutes FRL for a 5m×4m×3m (W×D×H) enclosure with 15 kg/m^2 fire load density is 12.1%.

Repeating the same calculations for the floor/ceiling system but conservatively assuming a char depth of 5mm produces a contribution of 3.2%.

The percentage of char from walls, ceiling and floor in a 5m×4m×3m high enclosure for exposure to an equivalent 60mins (and up to 90mins) standard fire for various fire loads ranging from 15-50kg/m^2 (refer Appendix A) varies from approximately 6% up to 22% of the total fire load, depending upon the fire load density. The results are shown in Figure 11.

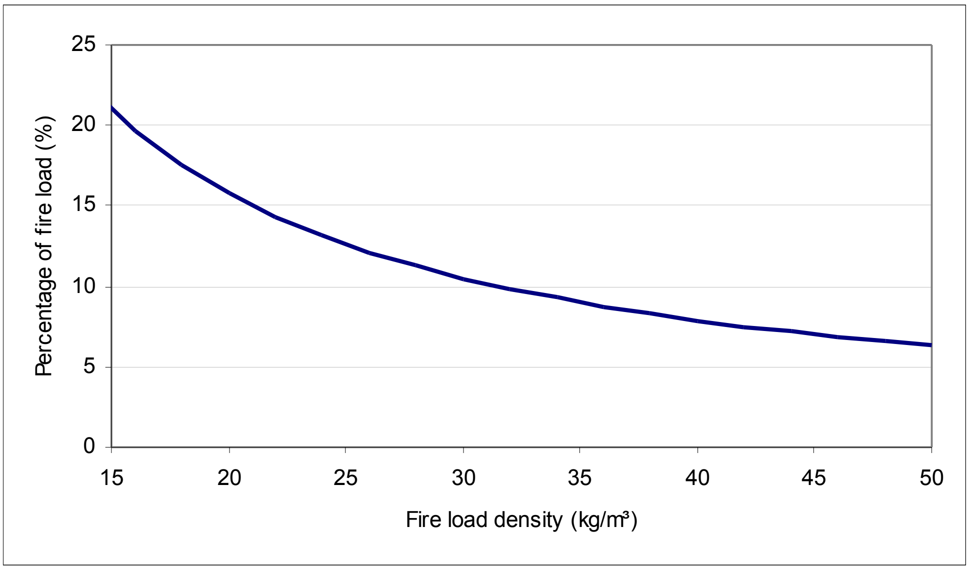


Figure 11. Char consumed from fire rated timber assemblies for up to 90 mins FRL exposure expressed as percentage of fire load in a 5m×4m×3m enclosure

5 OBSERVATIONS FROM FIRE AFFECTED CONSTRUCTION

5.1 Introduction

The following section discusses the observations from investigations that were made to timber constructions that were subjected to fire damage.

5.2 St. Mary's Church, Halewood [56]

St. Mary's Church, located on the Southern outskirts of Liverpool, was built around 1966-67. The church formed part of an integral complex incorporating classrooms, vestries and a church hall. Construction of the church itself was of laminated three pin portals with a pitch of 55° to a ridge height of 10m. All of the arches were fabricated of 125×125 European Whitewood Laminae (12-15% moisture content) and Urea Formaldehyde glue. The adjoining single storey buildings has laminated post and beam frames on the south and west sides.

The fire, which occurred in the early half of 1972, was started in the adjoining classrooms and extended towards the church and entrance area and gutted the single storey roof and upper timber wall panel members

The gable wall and roof members were seriously damaged and the upper sections of the remaining roof were heavily charred for about 5 metres on either side of the ridge. Localised examinations of the portal arch rafters revealed sound timber behind about 3mm to 5mm thickness of charring in most cases. Two of the arches forming the frame nearest to the fire source had surface charring thickness of up to 15mm on each face.

In the restoration works, the upper section of the existing arches were planed down to remove the fire charring

5.3 Redwood Fire Walls [18]

Redwood does not ignite easily and it burns slowly because it contains no volatiles or oils to aid in combustion. A wall section 6" thick, made up of 2×6 redwood sections, were subjected to temperatures ranging from 538°C to 1032°C for over two hours. At the end of the test, the average thickness of the unburned wood was 1½" and a minimum thickness of 1¼". The unexposed surface temperature reached a maximum rise of 13°C (i.e. from 21°C to 34°C) for the two hour exposure.

5.4 TF2000 [45], [46]

5.4.1 Building description

The TF2000 facility was a six-storey timber frame building constructed utilising the platform method. The building was located within the full scale test facility at the BRE Cardington Hangar in the UK. The building had an effective 60 minute rating to its construction. However, it exceeded the height limit allowable under the guidance in Approved Document B (Fire Safety) of the England and Wales Building Regulations and the requirements and recommendations of the Scottish Technical Standards in force at the time.

Figure 12. 6 storey TF2000 timber frame test building in BRE hangar at Cardington [45]

At the time of its construction, the Timber Frame 2000 (TF2000) building was the largest building of its type in the world. It was a timber frame residential building comprising four flats in each of six storeys. The floor plan measured 24.1m×12.386m. The height to the eaves of the building from the ground was approximately 14.4m. The platform method of construction was employed for the erection of the TF2000 building.

The ground floor was notionally a concrete slab-on-ground. Walls consisted of two layers of plasterboard with a vapour control layer and 89 x 38 mm C16 timber studs with mineral wool insulation in between. The sheathing was 9 mm OSB, Type F2 (OSB3). The cavity was 60 mm with single leaf brick cladding tied with stainless steel ties to timber frame.

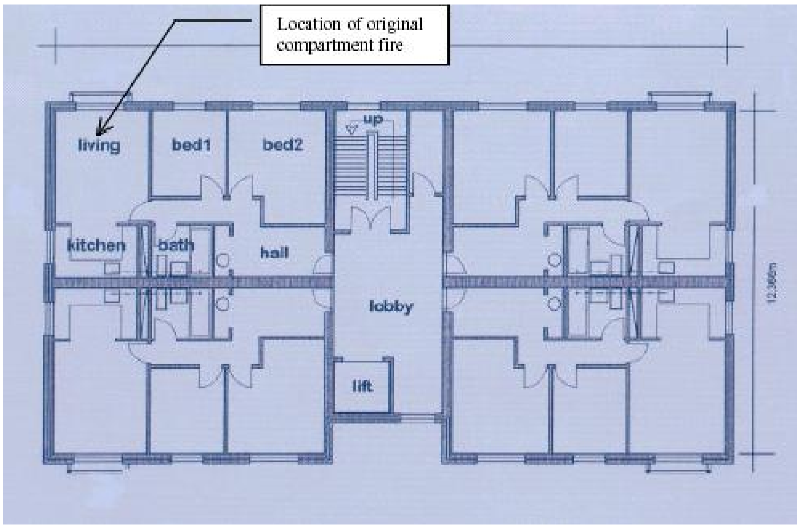


Figure 13. Fire initiated in the living room (level 3) [45]

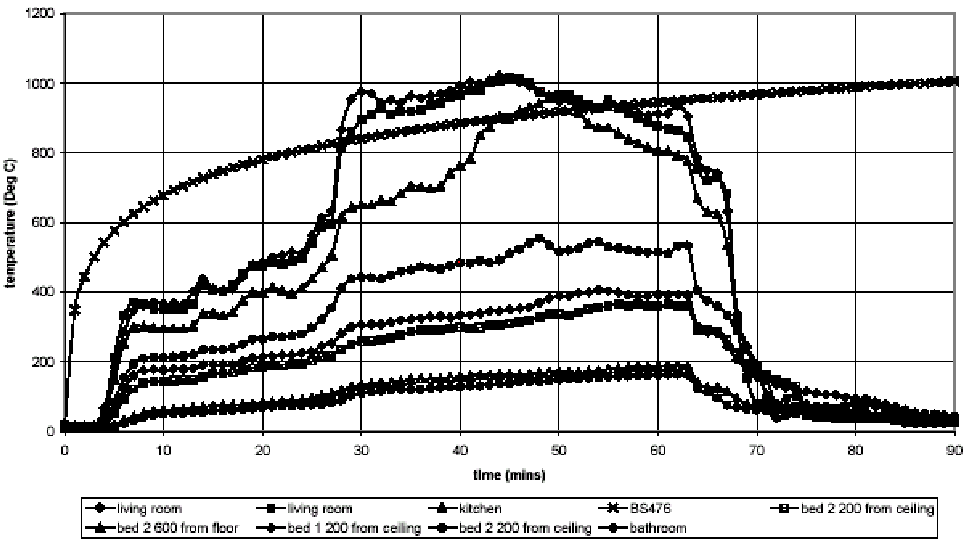


Figure 14. TF2000 atmosphere temperatures in fire flat

Internal load bearing walls consisted of C16 timber studs with two layers of plasterboard and 9 mm OSB, Type F2 sheathing to one side, where needed for wind bracing. The internal non-load bearing walls consisted of C16 timber studs with one layer of plasterboard to each side. The compartment walls were twin leaf with C16 timber studs and mineral wool insulation in between. OSB Type F2 (OSB3) sheathing was used where wind resistance was required.

Compartment floors consisted of two layers of plasterboard ceiling lining (19mm and 12.5mm) and C16 joists with glass wool in between. 15mm thick tongue and grooved OSB Type F2 (OSB3) was used as a floor deck. Floating floors contain proprietary resilient battens with plasterboard and Type C4(M) chipboard.

5.4.2 Building fire test

The fire test compartment was a single flat on the second floor (level 3) in the southwest corner of the building. The fire load consisted of timber cribs spread over the floor area of the flat. Despite average atmosphere temperatures in excess of 900°C for over 30 minutes and a total fire exposure of approximately 60 minutes there was no evidence of fire spread outside of the compartment of origin during the test.

At no time prior to the intervention of the fire brigade (~ 64 minutes into the test when water was applied) did the temperatures in the lobby, the adjacent flat, the flat above or the flat below exceeded 100°C and generally remained below 50°C. The exception to this was the localised breakdown of the plasterboard linings between the kitchen area and the adjacent flat and the loss of plasterboard to the ceiling within the living room. The cavity barriers remained effective for the duration of the test.

The extent of char damage was measured by removing the char layer and measuring the residual timber sections. The findings were as follows:

(a) Vertical Studs – Two sections of studding had the char removed. Both sections of studwork were along the external wall of the living room. One section was in the top half of the wall and one section was in the lower half of the wall. Once the char was removed it was clear that the residual timber section had been reduced in size by 10-12 mm in depth, with the char depth being greater at the nailing positions, to a maximum of 15mm.

(b) Horizontal Joists – Again two sections of joists had the char removed. Both joists were above the seat of the fire in the living room. The timbers in both locations had charred to an average depth of 10mm. This char increased in depth up to 30mm in the areas around the plasterboard fixing locations.

(c) OSB Decking – A section of the floor OSB sub-deck from the underside of the above flat was removed in one of the worst charred areas of the ceiling. Examination showed char depths ranging from 12mm in the worst places to 3mm in the best. The average depth of char was approximately 6mm.

5.4.3 Standard fire tests

During the testing program undertaken on the TF2000 building a full scale compartment fire test was conducted. Following on from the fire test thought was given to the true state and condition of the structural elements and the amount of work required to reinstate the fire damaged flat back to its original condition. The first stage of the project was to remove all the loose debris and damaged material from the flat to enable identification of the true state of the fire damage sustained by the structure.

Two full scale standard fire tests were conducted on a 3m × 4m floor structure to test the reinstatement procedures based employed for the TF2000 test.

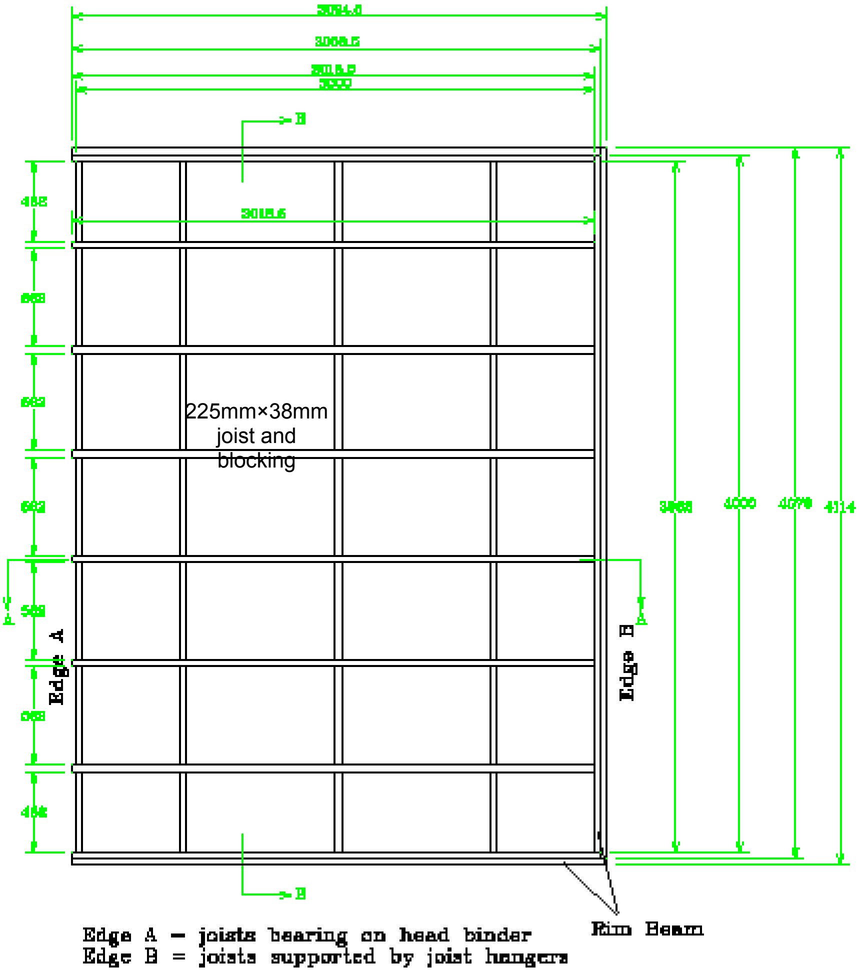
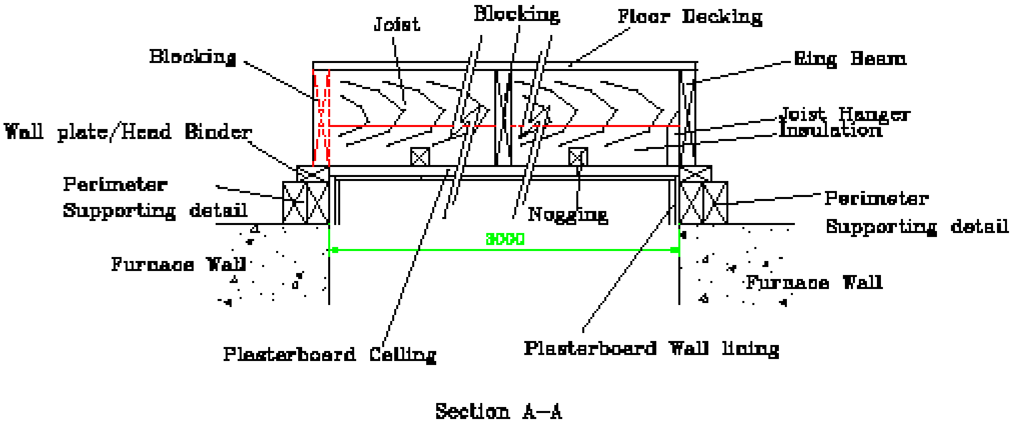


Figure 15. Generic plan view of floor construction [45]



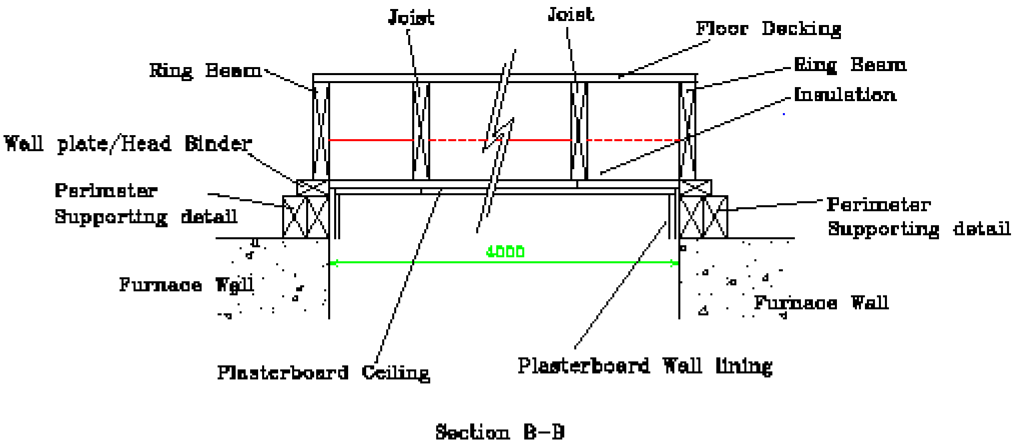


Figure 16. Side elevations of generic floor construction [45]

The test was terminated when the damaged sustained by the floor structure was similar to that which was sustained by the ceiling structure of the TF2000 flat during the compartment fire test.

Once the test furnace was safe, an assessment of the damage sustained to the floor was made. The following observations were made: -

- All plasterboard was lost from the ceiling membrane of the structure
- All six of the joists were charred although not to the same degree
  - 2 of the joists were deeply charred along the entire length
  - 2 of the joists were charred on all sides but to a lesser degree
  - 2 of the joists had localised char damage to the underside of the joist
- All internal blockings and noggings were damaged beyond repair and had to be replaced
- 50% of the OSB floor decking was charred to an average depth of approximately 5mm and therefore removed
- No significant damage was sustained by the ring beam or the headbinder

The depths of char on the joists and the floor decking were comparable to that sustained in the TF2000 compartment fire test. The joists (originally 225mm×38mm) were charred to an approximate residual section size of 205mm high x 28 mm thick (33% reduction in cross-sectional area) with the worst damaged joists being charred to 190mm high x 15mm wide (67% reduction in cross-sectional area). This increased area of charring was associated with two distinct areas of the floor. The first being associated with an area where the first sections of plasterboard fell from the specimen and the second was associated locally around the fixings. The OSB decking (originally 15mm thick) had a varying degree of damage from 0mm of char to 8mm of char, the average char depth was 5mm.

A number of softwood and hardwood cubes were positioned in the fire flat for the test and replicas of these cubes were subsequently exposed to a standard furnace exposure for exactly 60 minutes to provide a comparison of the extent of charring. The results of the charring analysis are summarised in Table 17 below:

Table 17. Charring of cube specimens

		measured depth of charring (mm)		
cube type	*cube location*	*TF2000*	*furnace*	*relative severity*
Hardwood	living room	33	24	1.375
Hardwood	kitchen	20	23	0.87
Hardwood	corridor	15	23	0.652
Softwood	living room	45	41	1.098
Softwood	kitchen	36	39	0.923
Softwood	corridor	26	39	0.667

5.4.4 Contribution of fire rated timber assemblies to fire load

The extent to which the constructional timbers within the living room of the TF2000 fire flat contributed to the overall fire load of the compartment fire test was reported in reference [46]. Because the damage sustained by the timbers within the living room of the fire flat varied depending upon the location of the timbers in relation to the seat of the fire, the assessment had to rely upon photographic evidence together with detailed notes made by the project engineers during the examination of the flat.

The extent of charring was calculated with the following considerations:

(a) average char damage on studs (23.8%) and joists (22.8%)

(b) average percentage of damage of structural timber (80%)

(c) increased charring at plasterboard fixings where observed (50mm each side of fixing)

(d) number of studs (40) and joist (3.5+1) damaged in the fire

(e) Oriented Strand Board (OSB) used for shear resistance (9mm of 3×2.4m)

The total mass of structural timber consumed was calculated to be 92.6 kg. The actual imposed fire loading for the compartment fire test comprised timber cribs distributed within the flat at a density of 25 kg/m² over an area of 21.6 m² giving a total mass consumed by the fire to be 540 kg. Hence the percentage of structural fire timber consumed represented approximately 92.6/540×100 = 17.1% of the fire load on the floor.

5.5 BRI wooden 3-storey apartment building test [2]

The Building Research Institute (BRI) of Japan conducted a full-scale fire experiment of a 12.7m high three-storey timber framed apartment building in 1996 to study the fire development within the building and its effects on neighbouring buildings. The building frame was constructed mainly of 2"×4" timber and each floor had 2 dwelling units (56m²) making a total of 6 units (335m²). Elevation and sectional views are shown in Figure 17 to Figure 20.

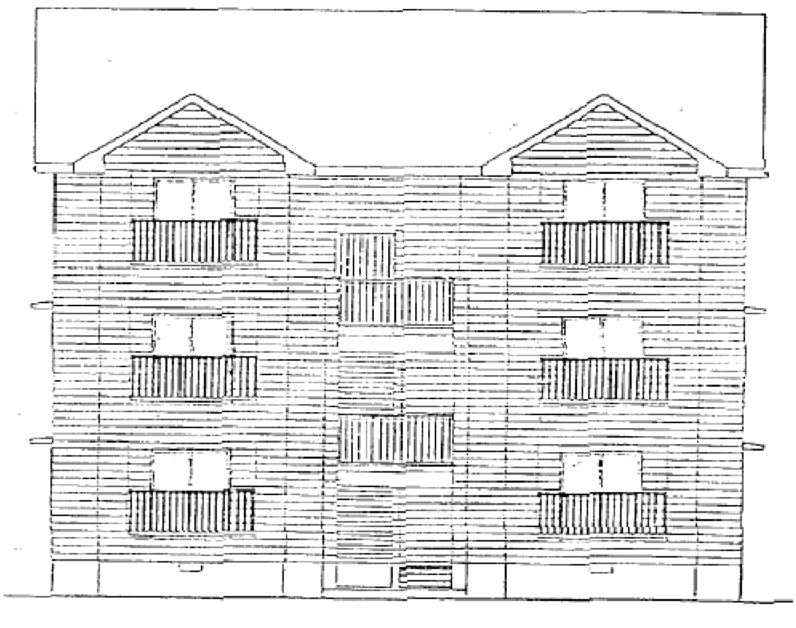


Figure 17. BRI 3 storey timber apartment test - North elevation [2]

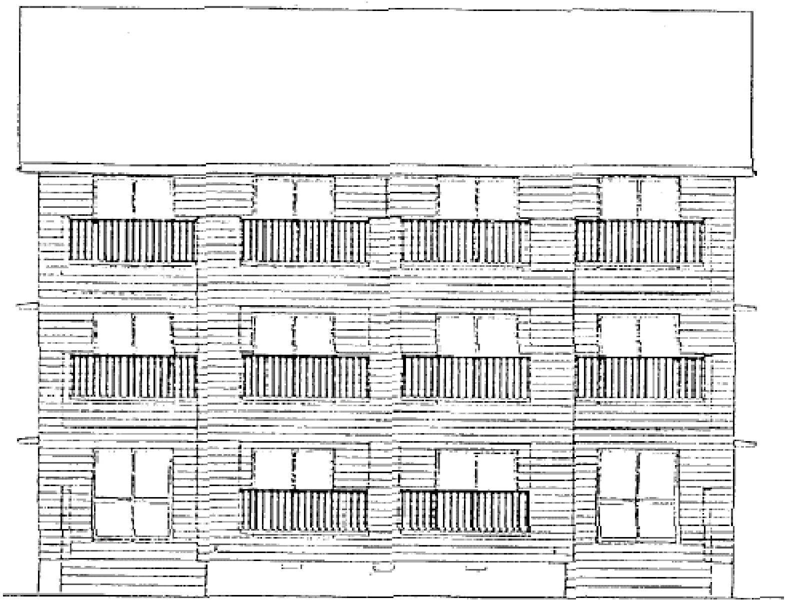


Figure 18. BRI 3 storey timber apartment test - South elevation [2]

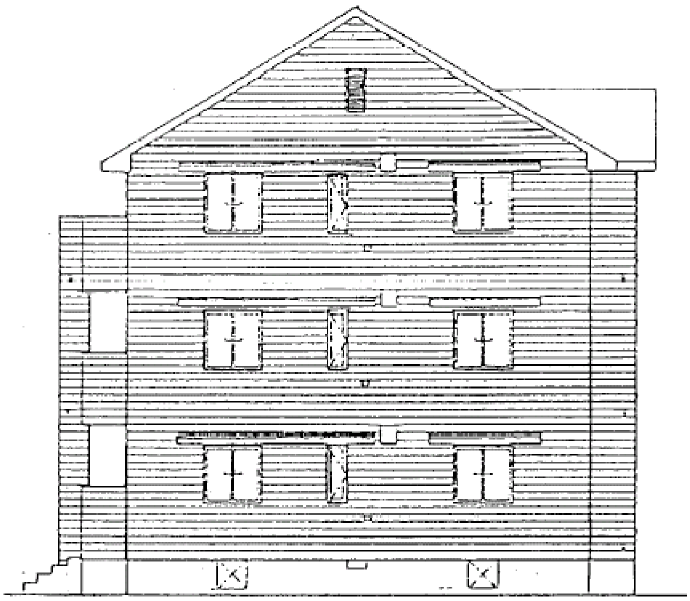


Figure 19. BRI 3 storey timber apartment test - East elevation [2]

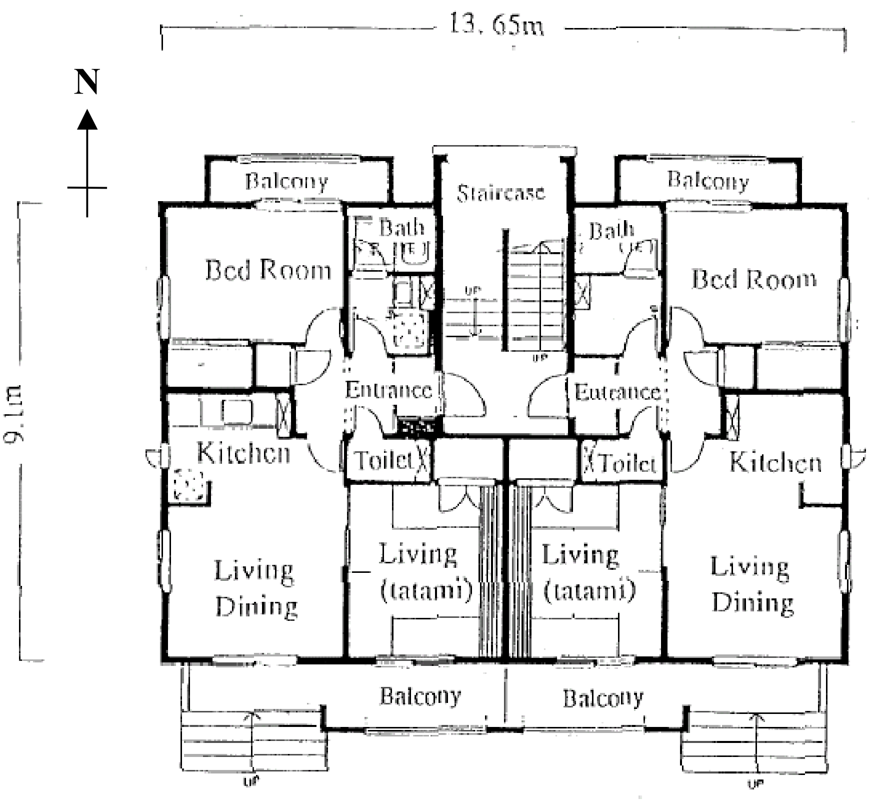


Figure 20. BRI 3 storey timber apartment test - floor plan [2]

The building was designed in accordance with the current Japanese Building Standard Law for wooden three-story collective housing but with a few minor variations introduced for the purpose of the study. For example, the ceiling of one unit at the third floor had approximately 45 minutes resistance performance whilst the other unit on the third floor had 30 minutes. These requirements were for three-storey wooden *independent* housing and *collective* housing respectively in accordance with the Japanese Building Standard Law.

The internal and external walls of five of the six units were artificially damaged to replicate post-earthquake conditions. Various window opening combinations were employed to study their effects on the fire. The fire load was 30 kg/m² for each unit. Real furniture was used in the west unit of the first floor and timber cribs were used in the other units.

Results of the test were not available. However, video footage of the tests were available and the following observations are made. These are given in Table 18.

Table 18. BRI 3-storey wooden apartment building fire test - video observations

Time (min:sec)	*Observation*
0	**fire started in the ground floor west unit with the real furniture.**
0:50	**smoke detector activated**
1	flame height about 1m high
1:36	whitish smoke from windows initiated and developed quickly
2	flame height about 2m high
3:00	smoke emanated from all three windows (can hear glass breaking)
5	**flames emanated from window of room of fire origin (RFO)**
5:50	flames reached window of level above
6	full room involvement visible within RFO
7	smoke from other windows reduced
8	flames appear from window of enclosure east of RFO
9	voluminous flames from both windows
11	both rooms still fully involved
11:20	fire from east window (kitchen and living/dining areas) appeared burnt out
13	RFO still fully involved
14	vigorous flames developed from east window
15:11	very vigorous flames from west windows - reached upper level
16	all four windows had vigorous flames
17	flames from west windows died down - just licking outside of windows
18	east window had visible flames inside
23	investigators appeared in living/dining room of east apartment
24	**fire in living/dining room regressing, other rooms no more significant flames**
33	small fires in living/dining room
41	**fires continued from exposed structural timbers (ceiling joists and studs)**
46	fires in RFO and east unit appear to rejuvenate from structural timbers burning
47	flames becoming vigorous in RFO and adjoining east tatami room
48	flames from structural timbers continue
49	small flames issued from external siding
50	**flames along ceiling of all rooms starting to develop**
50:30	**water from hoses applied**

Note: Times were based on video observations and may not be accurate.

The significant stages of fire development are shown in bold in Table 18. Note that after 24 minutes into the fire the fuel from the furniture appeared to have been depleted. At about 41 minutes, the burning of the structural members appeared to sustain itself and at 46 minutes the fire started to rejuvenate from burning of the structural timbers. There was therefore about 40 minutes following flashover before burning from structural members appeared to become significant. The deemed-to-satisfy BCA requirements specify higher FRLs for bounding construction

Another significant observation was that the fire did not spread to the level above. This may be partly due to the presence of balconies and window canopies preventing direct flame contact to the windows above. All windows on the north and south sides had curtains.

5.6 Heat release rate from wall assemblies [13]

A study by the Forest Product Laboratories (US Department of Agriculture) [13] was performed on fire-retarded wood-based structural wall assemblies to measure the heat release rates (HRR) of these assemblies when exposed to fire. The wall assemblies were non-loadbearing interior wall containing fire-retardant treated timber and lined with 5/8-inch (9.5mm) thick gypsum plasterboard. The assembly measured 8-feet (2.4m) high by 10-feet (3.0m) wide.

The wall assemblies were exposed to a vertical wall furnace programmed to follow the ASTM E 119 temperature-time curve for about an hour (63-67 minutes). The heat release rate from the assembly were determined using three methods:

(a) Substitution method;

(b) Oxygen consumption method; and

(c) Weight of material/heat of combustion method

Results from the tests indicated that at least 23 minutes (24-34min) elapsed from the start of the test to the time when the wall assemblies containing treated wood began to contribute heat. The factors that contributed to the delay were the gypsum plasterboard and the fire-retardant treatment of the timber.

Heat contributions were in the range of up to 80 to 100 Btu per square foot per minute (15-19 kW/m²) near the end of the test. Average HRR for the assemblies containing treated wood were 20 to 70 Btu per square foot per minute (3.8-13 kW/m²) over the active period of heat release. Based on the maximum observed HRR of 100 Btu/ft²/min (~20kW/m²), the contribution of timber based fire-rated walls to the heat release rate for a range of enclosure sizes (5m²-35m²) with an aspect ratio of 2:3 and a wall height of 2.7m ranges between 0.5MW to 1.2MW as shown in Figure 21.

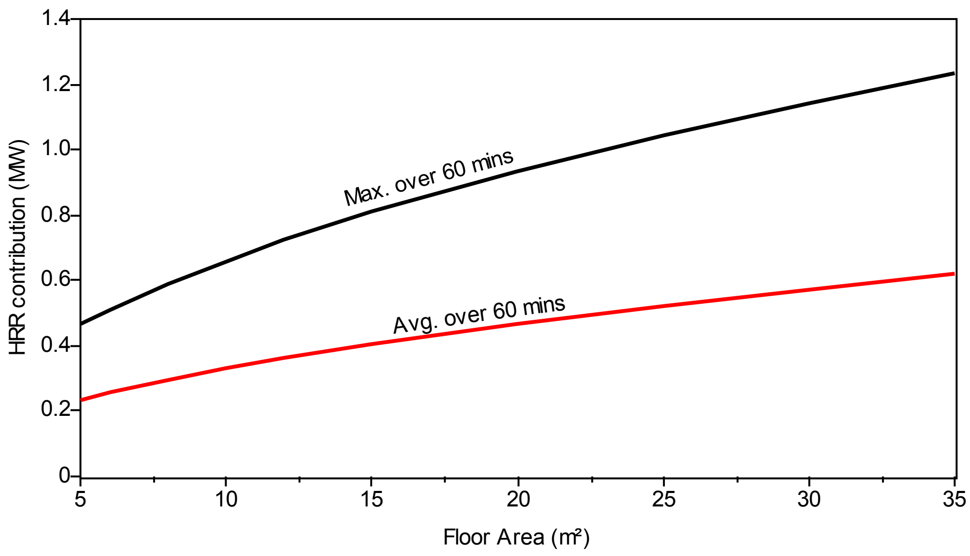


Figure 21. Heat release rate from FR wall assemblies for range of floor areas

Observations from the TF2000 fire test [50] indicated that despite average atmosphere temperatures in excess of 900°C for 30 minutes, there was no evidence of fire spread outside the compartment of origin during the test. At no time prior to the intervention of the Fire Brigade did air temperatures exceed 50°C in the lobby, the adjacent flat, the flat above or the flat below, suggesting that the timber walls and floor/ceiling frames were largely intact and therefore did not contribute significantly to the heat release. With the exception of localised breakdown of the plasterboard linings between the kitchen area and the adjacent flat and the loss of plasterboards to the ceiling, temperatures in the cavities both internally and externally did not exceed 100°C and generally remained below 50°C. The cavity barriers were observed to remain effective for the duration of the test.

6 HEAT RELEASE RATE

6.1 Introduction

Much of the discussion so far has focused on the degradation of wood from exposure to heat. The scope of the investigation requires the determination of how much the fire rated timber assembly contributes to the fire development of a building. Whilst all combustibles, including fire rated timber construction, can be regarded as potentially being part of the building fire load, the contribution is only realised when they are consumed and contribute to the release of heat in the fire.

The means of contribution can be differentiated on the basis of the exposure of the timber assembly considered. These can be generally classified into exposed and shielded construction. The former generally refers to heavy timber construction which are designed for fire protection based upon the sacrificial loss method of the exposed surfaces to the effects of fire. The latter generally refers to wall and ceiling/floor assemblies which have protective linings (usually fire rated) as part of the fire-resistant component of the fire rated assembly.

The contribution of fuel from exposed heavy timber construction will be suppressed by the development of a char layer. Hence the heat release rate from the timber that is additional to the fire will tend to be relatively low. The contribution from shielded timber will depend upon the duration by which the lining material will remain effective in preventing hot gases from penetrating the cavity of the assembly. If designed correctly, the contribution from shielded timber to the fire in the enclosure should be significantly less. Manufacturers of fire rated lining materials for light timber assemblies allow for losses due to charring of the timber studs in order that the strength criteria dominate the design [24].

This section briefly outlines the means of determining the heat release rate and the factors that would affect its determination.

6.2 Calculation of heat release rate

6.2.1 General

When volatiles from thermal degradation from wood are ignited, flaming combustion occurs and heat is released. Heat release rate is related to the mass loss rate by the following:

$$Q = h_c \cdot m$$

where Q = heat release rate (kW)

h_c = effective heat of combustion (kJ/kg)

m = mass loss rate (kg/s)

If the mass of char is considered negligible, the mass loss rate can be determined from the charring rate as follows:

$$m = c' \cdot \rho$$

where c' = volumetric charring rate (m^3/s)

ρ = density of wood (kg/m^3)

The accuracy of the above method is affected by the diversity in the properties of wood, such as moisture content and geometry. Interestingly, the heat release rate does not appear to be affected by density, regarded as the most important physical property of wood [65].

If the mass loss rate and density are known, the effective heat of combustion needs to be obtained before the heat release rate can be determined. The typical gross heat of combustion (h_g) averaged around 20 MJ/kg for ovendried wood, depending on the lignin and extractive content of the wood (Section 6.2.2). The averaged *effective* heat of combustion (h_e) is about 65% of gross value, with a small proportionate increase with imposed heat flux (Section 6.2.3). The heat release rate (HRR), however, has a larger increase with imposed heat flux due to the higher mass loss rate. These characteristics for selected species of timber tested with the OSU apparatus are illustrated in Table 19..

Table 19. Heat release data of selected wood species [76]

Species	*Density* (kg/m^3)	h_g (MJ/kg)	h_e (MJ/kg) 18kW/m²	55kW/m²	*HRR* (kW/m²) 18kW/m²	55kW/m²
Softwoods:						
Pine (southern)	508	20.5	9.1	13.9	40.4	120
Redwood	312	21.1	10.7	14.2	39.0	85.9
Hardwoods:						
Basswood	312	20.0	10.9	12.2	52.8	113
Oak (red)	660	19.8	9.0	11.7	48.7	113

The following subsections describe various work relevant to the determination of the heat of combustion.

6.2.2 *White [77]*

As part of a study into the charring rate of wood, White determined the *gross* heat of combustion h_g of four hardwoods (hard maple, yellow-poplar, red oak, and basswood) and four softwoods (Engelmann spruce, western redcedar, southern pine, and redwood). He found that there was a highly significant correlation between h_g with lignin and extractive (extraneous) contents:

$$h_g = 7696 + 32.0X_l + 28.4X_e \text{ (Btu/lb)}^3 \quad (8)$$

where X_l = Klason lignin content (% oven-dry, extractive free wood)

X_e = extractive content (% oven-dry wood)

The Klason lignin content averaged 30% for softwoods and 20% for hardwoods. The extractive content averaged 6% for both softwoods and hardwoods. For 25% lignin content, the h_g works out to be about 20MJ/kg.

6.2.3 Tran [64]

The mass loss rate can be determined from the heat release rate determined from the tests as follows:

$$\dot{m} = \frac{Q}{h_c}$$

where Q = heat release rate (W)

h_c = effective heat of combustion (J/kg)

Tran used an empirically derived relationship for h_c as follows:

$$h_{c,dry} = 0.057Q + 11.88 \quad (9)$$

6.3 Measuring heat release rate

Calorimeters are used to measure the heat release rate of a timber sample exposed to a predefined heat flux. However, the heat release rate depends not only on the externaI radiant heat flux, but also on the flame flux, sample size and orientation, and mounting conditions.

Two common apparatus for measuring heat release rates are the Cone Calorimeter and the OSU (Ohio State University) apparatus. They are largely similar apparatus and may be modified to achieve similarity. Some of the differences between these two apparatus are shown in Table 20.

[3] 1 BTU/lb equals to 2.324 kJ/kg

Table 20. Comparison between the cone calorimeter and the OSU apparatus

Item	*Cone calorimeter*	*OSU apparatus*
Sample size	100mm×100mm	150mm×150mm
Unexposed side	wrapped in foil and backed by ceramic fiber blanket	wrapped in foil and backed by ceramic fiber blanket
Mass loss	monitored continuously	weighed before and after test (but can be monitored continuously)
Ignition	spark or pilot flame	spark or pilot flame
heat release rate	oxygen consumption method	oxygen consumption method
orientation	vertical or horizontal	vertical only

The oxygen consumption method used in both apparatus is based on the rate of 13.1 kJ/g of oxygen consumed for organic solids, accurate to within 5%. The heat release rate is therefore obtained by measuring the mass flow rate of oxygen consumed in the combustion process.

6.4 Factors affecting heat release rate

6.4.1 Introduction

In addition to the formation of a char layer, there are other factors that affect the combustion of timber elements of construction. This section discusses the various situations in which the extent of contribution of heat release by timber elements of construction can be significantly affected and should therefore be considered.

6.4.2 Lining Material

6.4.2.1 US/Canada additive concept for fire rated timber frame design

Observations from tests [29],[45] have indicated that the lining of the fire rated timber assembly plays an important role in delaying the exposure of the hot gases from the fire to the timber. In many proprietary systems, particularly for fire rated construction, the lining itself is fire rated depending upon the level of fire resistance required. For this reason, the extent of the contribution of the timber to heat release in these assemblies depends significantly upon the type of lining material used. The influence on the use of lining materials such as gypsum plasterboard has been recognised as increasing the overall fire endurance of the assembly as shown in Table 21 [10], [72]. Note that the North American data, particularly the lining properties, will differ from Australian materials.

Table 21. Fire endurance of lining membrane [10], [72]

Lining		*endurance (min)*
Fibreboard, ½ inch (13mm)		5
Douglas-fir plywood, phenolic bonded:		
	⅜ inch	5
	½ inch	10
	⅝ inch	15
Gypsum wallboard,	⅜ inch	10
	½ inch	15
	⅝ inch	30
Gypsum wallboard, type X:		
	½ inch	25
	⅝ inch	40
Gypsum wallboard,	⅜ inch + ⅜ inch	25
	½ inch + ⅜ inch	35
	½ inch + ½ inch	40

Notes: ⅜ inch ≈ 10mm, ½ inch ≈ 12mm, ⅝ inch ≈ 16mm.
Type X gypsum contains fibre glass (ie fire grade).

Table 22. FRL contribution from timber frame*

Description of Frame	*Time Assigned to Frame (min)*
Wood studs, 16 in on centre	20
Wood floor and roof joists, 16 in. on centre	10
Wood roof and floor truss assemblies, 24 in on centre	5

* Minimum size for studs is nominal 2 in × 4 in. Wood joists and members of trusses also must not be less than the nominal 2 in × 4 in. The listing for truss assemblies does not apply to trusses with metal-tube or bar-webs. The spacing between studs or joists should not exceed 16 in. centre. The spacing between trusses should not exceed 24 in. centre.

Table 23. Additional endurance times for insulation

Additional protection	*Time assigned (min)*
Adds to the fire endurance rating of wood stud walls if the spaces between the studs are filled with rock wool or slag mineral wool batts weighing not less than ¼ lb/sq.ft of wall surface.	15
Adds to the fire endurance rating of non-loadbearing wood stud walls if the spaces between the studs are filled with glass fibre batts weighing not less than ¼ lb/sq.ft of wall surface.	5

The equivalent overall fire resistance level of the assembly (for each direction) is obtained by adding the times assigned to the linings, frame and the type of insulation provided in the cavity spaces. The application of the method is generally limited to 90 minutes which is the upper range of the test data.

6.4.2.2 Application of additive concept to steel frame

The additive concept of combining components is usually associated with assemblies containing timber frame. To extend the application of the approach with the use of protective lining to metal framing, Zicherman and Eliahu [88] conducted small scale (4ft×5ft) wall tests using standard (non-fire rated) ½" gypsum plasterboard installed over timber (2"×4") and steel studs. The criteria adopted for the fire rated performance of the lining as, as defined in the UL Fire Resistance Directory [6]:

"A finish rating is established for assemblies containing combustible (wood) supports. The finish rating is defined as the time at which a wood or joist reaches an average temperature rise of 250°F (121°C), or an individual temperature rise of 325°F (163°C) as measured on the plane of the wood nearest the fire".

Gypsum plasterboard from five different manufacturers were used on both timber and steel studs. The results from the tests are summarised in Table 24.

Table 24. Lining endurance results (min) for timber and metal studs

Manufacturer	*Wood studs*		*Metal studs*	
	Single	Average	Single	Average
A	17	16	17	16
B	16	15	15	15
C	17	16	15	16
D	17	16	16	15
E	20	18	16	15

All of the tests exceeded the 15 minute rating for the ½" standard grade gypsum plasterboard given in Table 21. Linings mounted on timber studs showing slightly better performance.

6.4.2.3 Miscellaneous

Discussions on Australian proprietary systems for fire rated wall and ceiling systems are given in section 4.1.5 and 4.2.4 respectively.

The transfer of heat through wall and ceiling systems, due to their large planar areas relative to their thickness, can be readily predicted using one-dimensional models with allowance given to the presence of studs. Various models for predicting the heat transfer across the wall systems have been developed ([19],[52],[57]).

6.4.3 Fire-retardant treatment

Fire-retardant treatments, applied through pressure impregnation or fire-retardant coatings, alter the surface burning characteristics of a timber substrate by lowering the substrate's early fire hazard indices as measured by AS 1530.3 [8]. According to AS 1720.4 [9], the use of fire-retardant treatment to improve the fire-resistance of timber material can only be assessed through testing in accordance with AS 1530.4, and are not likely to materially improve the fire-resistance of timber. They are largely designed for use to reduce the spread of flames over a surface [72].

The effect of fire-retardant treatment on plywood on the heat release rate, determined using a cone calorimeter under 50 kW/m² radiation, can be seen in Figure 22. The initial peak exhibited by the untreated specimen prior to charring is reduced or eliminated when treated.

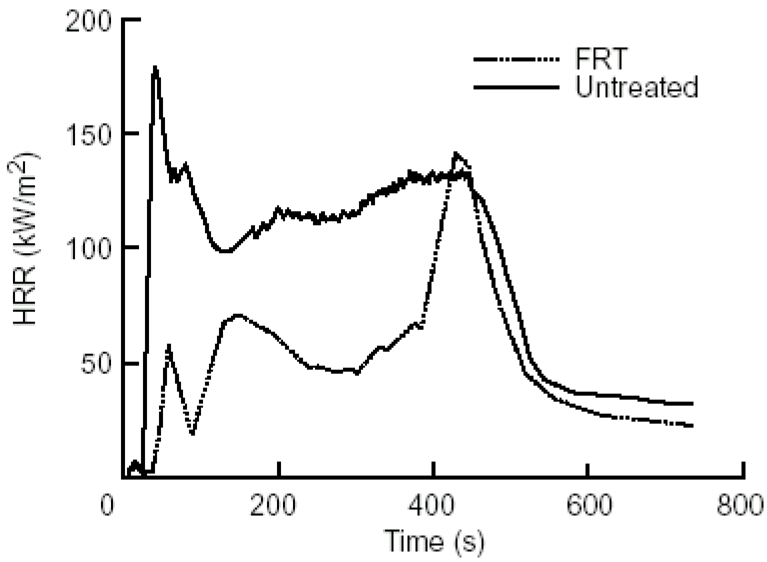


Figure 22. HRR curves for untreated and treated plywood exposed to 50 kW/m² [76]

7 SUMMARY

This report is a literature review on information that relates to or may assist in the determination of the amount of wood from fire rated timber elements that contributes to the heat release rate of a fire occurring in a building constructed of typical wood framed fire resistant construction.

Timber-based fire load that could be present in non-fire resistant timber construction and non-timber construction is not considered. This includes timber floor covering, timber wall panelling, timber ceiling panels and internal non-fire rated timber-stud wall partitions.

Based on the literature reviewed, the following findings are summarised:

(a) Fire rated timber construction can be categorised into heavy timber members and light timber assemblies. Heavy timber members include large sawn timber and glue laminated timber (glulam) where fire resistance is based on established charring rates on the exposed surfaces. They are used predominantly in floor/ceiling systems and are protectively lined except in a few cases where exposed beam construction is used. Light timber assemblies are a system of stud and joist elements protected with fire grade gypsum board or equivalent non-combustible lining materials used in wall and floor systems. For Class 2 and 3 buildings, fire rated timber construction are predominantly light timber assemblies.

(b) Timber protected by lining materials will delay the consumption of wood until the wood surface temperature reaches approximately 300°C. Linings of timber assemblies that are designed to meet the deemed-to-satisfy provisions for fire resistance are likely to offer substantial protection to the timber studs or joists against the effects of fire and significantly delay or prevent the onset of wood pyrolysis.

(c) A conservative estimate of the potential contribution of fire rated timber construction exposed to the development of fire in an enclosure can be calculated based on reasonably well established charring rates of the exposed surfaces of the timber sections for the estimated duration that the wood temperature exceeds 300°C. Preliminary analysis based on data from Australian manufacturers estimates the percentage contribution of timber charring from walls, ceiling and floor for a 5m×4m×3m high enclosure exposed to an equivalent 60 minute standard fire to be in the order of 8% to 22% of the total fire load, for fire load densities ranging from 15 to 40 kg/m².

(d) Information from a detailed investigation of the full-scale six-storey timber frame building (TF2000) following the fire experiment (for a total fire exposure time of 60 mins) suggests that the contribution of timber from fire rated assemblies is approximately 17% of the total fire load, based on 25kg/m² of wood cribs distributed over a floor area of 21.6m²).

(e) The presence of active suppression systems such as sprinklers (if installed) and intervention from the Fire Brigade is likely to reduce the severity of the fire and therefore the pyrolysis of timber in fire rated assemblies. These effects are not considered in the review.

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APPENDIX A: FIRE LOADS

Gross [32] conducted a limited survey of fire loads in Swedish buildings and reported that the 50 and 80 percentile fire loads for Swedish hotels are 18 and 22 kg/m² respectively and Swedish residences are much higher at 40 and 45 kg/m² respectively.

Table 7.2 of the Fire Engineering Guidelines [28] recommends an average fire load density of 780 MJ/m² for dwelling occupancies, with a 80% fractile of 870 MJ/m². In terms of equivalent cellulosic fuel based on the heat of combustion of wood of 18 MJ/kg, the corresponding fire load for average and 80% fractile are 43 and 48 kg/m² respectively. For hotel bedrooms, Table 7.2 recommends a mean of 310 MJ/m² and an 80% fractile of 400 MJ/m² which corresponds to 17 kg/m² and 22 kg/m² respectively.

In the Appendix 7A of the Fire Engineering Guidelines, the average fire load densities for homes and hotels are 500 and 300 MJ/m² respectively. Assuming a coefficient of variation of 50%, the corresponding 80% fractiles are 750 MJ/m² for homes and 450 MJ/m² for hotels. These correspond to mean and 80 percentile wood equivalent loadings of 28 and 42 kg/m² for homes and 17 and 25 kg/m² for hotels. The results are summarised in Table A-1

Table A-1. Fire load densities (kg/m²)

Building Type	*Source*	*average*	*80 percentile*
Swedish Hotels	Gross	18	22
Hotel bedroom	Table 7.2, FEG	17	22
Hotels	App 7A, FEG	17	25
Swedish Residences	Gross	40	45
Dwelling	Table 7.2, FEG	43	48
Homes	App 7A, FEG	28	42

APPENDIX B: PROPERTIES OF WOOD

B.1 Introduction

The following are based on references [72][85].

Most wood properties are functions of density, moisture content, grain orientation and temperature [85].

B.2 Properties

B.2.1 Density

Oven-dry density of wood can range from 160 kg/m³ to over 1040 kg/m³ but most species are between 320 to 720 kg/m³. Generally, materials with higher density will char slower.

B.2.2 Moisture content

Moisture content in wood can vary significantly. Green wood can exceed 100% (ie more water than fibre), air-dry wood comes to equilibrium at less than 30%, and under the conditions for ASTM E 119 (23°C, 50% relative humidity), the equilibrium moisture content is 12%. Moisture can reduce the strength of wood but it also reduces the rate of charring.

B.2.3 Thermal conductivity

The average thermal conductivity perpendicular to the grain for moisture content below 40% is given as:

$$k = S(0.00020 + 0.000004M) + 0.024$$

where k = thermal conductivity (W/m °C)

S = density based on volume at current moisture content and over-dry weight (kg/m³), and

M = moisture content (percent)

The longitudinal thermal conductivity is about 2.0-2.8 times the transverse property.

B.2.4 Specific heat capacity

The specific heat capacity of dry wood is related to the temperature by the following:

$$C = 1.125 + 0.00452\,T$$

where C = specific heat capacity (kJ/kg °C)

T = temperature (°C)

B.2.5 Heat transfer coefficient

The value suggested by Janssen for vertical orientation in the Cone calorimeter was h_c = 13.5 W/m²K. A value of 0.88 for the emissivity, ε, was recommended by Janssens for wood products [37].

B.2.6 Wood components

The major components of wood are cellulose, lignin, hemicellulose, extactives and inorganic materials (ash). Cellulose content is generally about 50% by weight. Softwoods have lignin contents of 23 to 33 percent, while hardwoods have about 16 to 25 percent. The higher the lignin content the greater the char yield. Ignoring the minerals and small amounts of nitrogen and sulfur (0.1-0.2%), the elementary composition of dry wood averages 50% carbon, 6% hydrogen, and 44% oxygen [26].

APPENDIX C: CHILTERN REPORT