bushfire CRC

A collaborative project between BlueScope Steel Limited and the Bushfire CRC

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RESEARCH AND INVESTIGATION INTO THE PERFORMANCE OF RESIDENTIAL BOUNDARY FENCING SYSTEMS IN BUSHFIRES

Report to
BlueScope Steel Limited

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Bushfire Research

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1 EXECUTIVE SUMMARY

BlueScope Steel Limited, CSIRO Bushfire Research and the Bushfire CRC set up a project to research and investigate the performance of residential boundary fencing systems through small and full-scale experiments. The objectives of this research were:

- To investigate the performance of the most common commercial fencing systems made from pre-painted and metallic-coated sheet steel and timber. These fencing systems are mostly used as residential boundary fencing in urban and urban–rural interfaces in the built environment in Australia.
- To investigate the potential of using fencing systems as protection for houses and residential-type buildings against attack from radiant heat, burning debris and flame impingement during bushfires.
- To investigate experimentally whether the behaviour of fencing systems contributes to the risk of house loss or risk to life.

This research was conducted in the following three experimental stages:

1. Small-scale flammability experiments – basic flammability properties of typical timber fencing materials were measured using the cone calorimeter, a small-scale fire experiment apparatus. The effects of different aging and weathering conditions were investigated.
2. Toxic contaminant release experiments were also performed by measuring gaseous and ash products from small-scale samples, and also ash product left after the full-scale experiments.
3. Full-scale experiments – a series of 23 full-scale experiments were conducted on common timber and COLORBOND®[1] steel fencing systems of typically 1.8 m height. A range of different bushfire exposures were achieved using a gas burner bushfire flame front simulator. The effects on a simulated residential building and adjacent objects behind the fencing systems were investigated.

1.1 Air toxic key outputs

The cone calorimeter experiments were only indicative of the fire release of the combustion gas species measured. This experimental method alone does not assess the fire hazard of the materials, or products made from them, under actual fire conditions. Consequently, the results of these experiments cannot be quoted in support of claims with respect to the fire hazard of the materials, or products made from these materials, under actual fire conditions. The results, when used alone, should only be used for research and development, quality assurance or similar industrial needs. The cone calorimeter experiments determined that the combustion of both samples resulted in measurable levels of volatile organic compounds (VOCs) and aldehydes, as follows:

- The major air toxics released during the combustion of both materials were benzene and formaldehyde – both human carcinogens.
- COLORBOND steel fencing material released higher levels of benzene, but lower levels of aldehydes than CCA-treated pine.
- The only aldehydes emitted at levels above the detection limit were formaldehyde for both materials, and acetaldehyde for CCA-treated pine.

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[1] COLORBOND® is a registered trademark of BlueScope Steel Limited.

The major issue related to the combustion of CCA-treated pine is the release of significant levels of arsenic, as well as the high arsenic content in the timber ash (2.2% by weight). Arsenic can cause eye, throat and respiratory irritation, and is a confirmed human carcinogen. Note that the National Environmental Protection Measure (NEPM) (http://www.ephc.gov.au/nepms/air/air_toxics.html , refer to NEPC 1999) provides health-impact criteria for arsenic in soils in the range of 0.01–0.05%, and so the dispersion of CCA-treated pine ash could lead to site contamination, especially where large quantities of the material has been burnt.

Two human carcinogens (benzene and formaldehyde) were detected in the air toxicity experiments conducted on COLORBOND steel. Note that, while these gases were detected, the risks they present would depend on the levels of exposure to nearby occupants, which is unknown. In fact, evaluating risks from these gases will depend on the combustion conditions, the quantity of material burnt, the volume of combustion gases generated and its dispersion, and the degree to which site occupants are exposed to the gases. These will vary for each specific situation, and it is not possible to predict levels of these gases in real situations from cone calorimeter measurements.

For real fires in Australia, there are exposure standards that are relevant. The 24-hour average monitoring investigation level for benzene is 0.003 ppm. The monitoring investigation levels represent 'levels of air pollution below which lifetime exposure, or exposure for a given averaging time, does not constitute a significant health risk'.

There are exposure standards to assess atmospheric contaminants in occupational environments (http://www.nohsc.gov.au/OHSInformation/Databases/ExposureStandards/ExposureStandards4AtmosphericContaminants.pdf). The Worksafe occupational exposure standard for benzene is an 8-hour average of 0.5 ppm. These standards apply to workplace situations only and would not be applicable for assessing fire fighters' exposure. However, it is clearly stated that these exposure standards should not be applied in the control of community air pollution.

More extensive experiments could be conducted to simulate fencing exposure to bushfire for a quantitative risk assessment of:

- The toxic gases released during combustion of each fencing material.
- The impact of air emissions of arsenic.
- The exposure of site occupants (whether fire agency or general public) to arsenic from the ash from CCA-treated pine.
- The contamination of building sites from arsenic.

1.2 Small-scale experimental key outputs

This experimental investigation confirmed that COLORBOND steel fencing panels do not ignite and contribute significant heat release during cone calorimeter exposure. Both pine and hardwood materials provide significant heat release under these exposures. The ranking of performance of these materials in descending order are: COLORBOND steel (insignificant heat release), new hardwood, old hardwood, old pine and new pine.

Of particular interest was the effect moisture content had on the time to ignition for all these materials. In particular, the observation that a material exposed for six hours to 40°C and 20% relativity humidity (RH) had similar fire properties to the same material when conditioned at same temperature and relative humidity until moisture equilibrium was achieved. This highlights a significant point that the fire behaviour of these specimens was influenced more by the surface moisture content rather than the average moisture content of the specimens, and hence the weather conditions on the day of fire impact will have a significant effect on the fire performance of timber elements. In all cases, conditioning at 23°C and 50% RH generated longer ignition times.

1.3 Large-scale experimental key outputs

- COLORBOND steel: This had the best performance as it is a non-combustible material, it maintained structural integrity as a heat barrier under all experimental exposure conditions, and it did not spread flame laterally or contribute to the fire intensity during exposure. The fencing reduced radiation levels within the fencing boundary to below 5 kw/m^2 immediately behind the fencing system during all radiation exposures, and reduced the radiant heat exposure on a structure 9 m from the fencing by at least a factor of two.
- Hardwood: Although combustible, closed paling hardwood fencing maintained a radiant heat barrier during radiation-only exposures, resulting in a greater than three times reduction in radiant heat received at the structure. In exposures where flame contact of the fencing occurred, flame emission from the fencing provided additional radiant heat exposure on the structure. Open paling hardwood fencing systems were effective in attenuating incident radiation when flames did not contact the fencing systems, however they provided little barrier during direct flame contact. Neither fencing configuration supported lateral flame spread to the extent that would expose the structure to direct flame contact. Under structural fire exposure conditions, the fencing quickly burnt away leaving no barrier to the impinging flames.
- Treated pine: This had the worst performance, as its integrity under leaf litter attack resulted in potential for loss of the adjacent structure due to lateral flame spread. Its performance as a heat barrier was good until ignition of the fencing occurred, after which point additional heat impact was received by all elements behind the fencing. Significant risk of house loss occurred during all experimental exposures, either through thermal exposure or mechanical impact as the fencing collapsed onto the structure. Under structural fire exposure conditions, the fencing quickly burnt away leaving no barrier to the impinging flames.

2 INTRODUCTION

The objective of this project was to conduct scientific research and investigations into the performance of residential boundary fencing systems in bushfires.

The research aimed to observe, record, measure and compare the performance of commercial fencing systems made from pre-painted and metallic-coated sheet steel and timber (treated softwood and hardwood). The potential of using residential fencing systems to act as a barrier against radiant heat, burning debris and flame impingement during bushfire was investigated.

A literature survey [Honavar 2004] and a project brief from BlueScope Steel Research Laboratories [Honavar 2003] were conducted to seek the current Australian recommendation on the performance requirements for residential boundary systems in bushfire-prone areas; and the experimental protocols and methods for building elements, including residential boundary systems in bushfire-prone areas. The outcome of the literature review was that currently there is an absence of well-documented and acceptable recommendations on performance requirements, experimental protocols and experimental methods.

Based on the recommendations in these reports, a project proposal was produced by CSIRO Bushfire Research [Leonard 2004] to research and investigate the performance of residential boundary fencing systems. The project proposed experimental methods in a **bushfire simulator** to determine:

- Whether fencing systems will support flame propagation to the extent where structures may be impacted – small-scale and full-scale experiments.
- Ember propagation potential from fencing systems – full-scale experiments.
- The potential of fencing systems to provide barriers to radiant heat and flame during bushfire exposure – full-scale experiments.
- The potential of fencing systems to provide barriers to radiant heat and flame during urban structural fire exposure – full-scale experiments.
- Toxic gas emissions from fencing systems – small-scale experiments.

This report documents the background and the rationale of this research project in Section 3. The methodology developed to asses the performance of the fencing systems is described in Section 4. Three steps have been developed, viz.:

1. Small-scale experiments to test the flammability properties of typical fencing materials.
2. Small-scale toxicology comparative assessments of two fencing materials by measuring a range of toxic gases that may be released during their combustion.
3. Full-scale experiments on different types of fencing systems using a bushfire front flame simulator.

The third part of this report exposes the results of the experiments. The fourth part discusses the results and comment on the performance of the fencing systems.

3 BACKGROUND – LITERATURE REVIEW

This section presents the rationale of this research project. The findings from post-bushfire investigations show the importance of design and building materials for houses exposed to bushfires in Australia. Based on these findings, the potential for residential fencing systems to act as protective barriers in bushfire-prone areas is discussed. The recommendations and the limitations of using fencing systems as protective barriers have been documented from diverse governmental sources (detail in the reports by Honavar [2004; 2005].

3.1 Findings from post-bushfire survey

CSIRO research has shown that the majority of houses, including fencing systems, destroyed in bushfires usually survived the passage of a fire front, but burnt down during the following few hours due to fire spreading from ignition caused by burning debris [Leonard 2003; Blanchi *et al*. 2004; Ahern *et al*. 2004; Chen & McAneney 2004].

A survey and studies after the 2003 bushfires in Canberra showed very high levels of house loss deep into the urban environment [Leonard 2003]. Destroyed homes showed strong clustering [Chen & McAneney 2004]. Most houses were ignited by ember attack and/or house-to-house ignition [Leonard 2003].

The post-bushfire investigation in Canberra showed that in 50% of cases, the bushfire attack mechanism was via embers, and in 35% it was via embers and some radiant heat from surrounding vegetation or other structures [Blanchi *et al*. 2004].

Numerous studies have found that suppression activities by residents during and immediately after fires are important in saving homes. After the bushfires in Canberra, the activities of occupants, neighbours and fire-fighters were also recorded during the survey. It is known that human activity can significantly influence the survivability of structures [Blanchi *et al*. 2004]. The extreme damage in Canberra was in part due to enforced home evacuation, which left most homes undefended [Chen & McAneney. 2004].

Responses and communications with residents who stayed in their homes to fight bushfires and spot fires before and after the passage of the fire front gave testimony to the protection offered by sheet steel boundary fencing systems to stay close to their homes to fight fires.

3.2 Potential of residential fencing systems to act as protection in bushfire-prone areas

Based on the above, it is proposed that fencing systems can offer protection to humans and homes during attack from bushfires and house-to-house ignition (similar to urban structural fires).

During a bushfire, residential boundary fencing may be directly exposed to one or a combination of the following:

- Burning embers from the bushfire before and after the fire front.
- Radiant heat from the fire front.
- Flame attack from the fire front.
- Radiant heat and flame from structure burning.

Burning embers can be carried substantial distances on the convective plume of a fire front, and the concentration of embers increases as the fire front gets closer to a fencing system.

Fencing systems and adjacent buildings can be exposed to burning embers, radiant heat and direct flame contact. The risk of exposure to secondary fires can be substantially reduced by management of vegetation and other combustible materials in proximity to a building, including fencing systems made from combustible materials. Even if the allotment on which a building is constructed is well maintained and leaves and vegetation branches regularly cleared, there is still potential for debris to collect close to or in contact with some combustible building elements (e.g. fencing systems made from combustible materials) during a bushfire.

A fencing system can be attacked by direct flame close to the fire front. Beyond the distance at which there is potential for attack by direct flame, a fencing system can be exposed to substantial radiant heat flux. Radiant heat energy from a bushfire source, which would otherwise be absorbed by a building surface, may be absorbed and/or deflected by radiant heat barriers. Ideally the barrier should be located between the bushfire source and the building.

Radiant heat barriers made from non-combustible materials may be included in building design [NSW Rural Fire Service (RFS) & Planning NSW 2001; Ramsay & Rudolph 2003; Country Fire Services South Australia (CFS SA) & Department of Environment and Planning (DEAP) 2004; Country Fire Authority (CFA) & Ministry for Planning and Environment, Victoria (MPEV) 1990]. The radiant heat barriers may be used as:

- Boundary fencing for houses and other residential-type buildings, including backyard fencing, which front potential bushfire threats.
- Courtyard or fenced-off areas for gardens, barbeque areas and the like, which may assist people to stay close to the house and fight the bushfire threat.

The degree of direct exposure of residential boundary fencing to a bushfire attack is dependent on:

- The distance between the fire front and the fencing system.
- Fuel characteristics.
- Topography.
- Shielding by built environment and natural features.
- Wind.

3.3 Current recommendations for non-combustible residential boundary fencing systems to act as radiant heat barriers

The objective of this section is to document the recommendations for the design, construction and materials for fencing systems in bushfire-prone areas.

3.3.1 Recommendations in the Building Code of Australia

The Building Code of Australia (BCA) is produced and maintained by the Australian Buildings Codes Board [ABCB 2005] on behalf of the Australian Government and each State and Territory Government. The BCA is a uniform set of technical provisions for the design and construction of buildings and other structures throughout Australia, whilst allowing for variations in climate and geological or geographic conditions.

The intent of the BCA is to enable the achievement and maintenance of nationally acceptable standards of structural sufficiency, safety (including safety from building fires and bushfires), health and amenity.

The BCA is published in two volumes:

- Volume One – pertains primarily to Class 2–9 buildings.
- Volume Two – pertains primarily to Class 1 (houses) and Class 10 (sheds, carports, fencing, etc.) buildings.

In Volume One, Section G – Ancillary Provisions, Part G5 – Construction in Bushfire Prone Areas, includes:

- GO5 Objective.
- GF5.1 Functional statement.
- GP5.1 Performance requirement.

The objective, functional statement and performance requirement apply only to:

- Class 2 buildings (buildings with two or more sole-occupancy units).
- Class 3 buildings (places of long-term or transient living for a number of unrelated persons, including guest houses, hostels, residential parts of hotels, schools etc.).

In NSW and South Australia, Part G5.2 Protection, recommends Class 2 or Class 3 buildings in designated bushfire-prone area comply with AS 3959 [Standards Australia 2001].

In Volume Two, Part 2.3 – Fire Safety, includes:

- O2.3 Objective.
- F2.3.4 Functional statement.
- P2.3.4 Performance requirement.

The prescriptive deemed-to-satisfy provisions are included in Part 3.7.4 Bushfire Areas. Part 3.7.4, A. Acceptable construction manuals, states that performance requirement P2.3.4 is satisfied for a Class 1 building located in a designated bushfire prone area if it is constructed in accordance with AS 3959.

AS 3959 is a document that is called up in the Building code of Australia (BCA Volume Two).

Fencing systems are classified as Class 10b buildings. There are no specific provisions including for bushfire prone areas in BCA Volume Two for Class 10b buildings.

Therefore, it is interpreted that currently in BCA Volumes One and Two:

- Performance requirements, including in bushfire-prone areas, are not included for Class 10b buildings.
- Direct reference to the use of fencing systems as radiant heat barriers in designated bushfire-probe areas for the protection of all classes of buildings, is not included.

Also, there are variations in the technical provisions and administrative procedures between the States and Territories and also between local municipal councils. Volumes One and Two of the BCA do not address these variations. Although the BCA does permit alternative solutions to compliance, it does not provide guidance on experimental procedures or exposure conditions that may be used to asses buildings, including fencing systems, in bushfires.

3.3.2 Recommendations in the Australian Standard

The current AS 3959 specifies requirements for the design and construction of buildings in bushfire-prone areas in order to improve their performance when subjected to burning debris, radiant heat and flame contact generated by a bushfire.

The Standard provides a methodology for the assessment of categories of bushfire attack based on:

- Predominant vegetation class:
  — vegetation distance (in each direction from the site for a distance of 350 m);
  — vegetation type (Types 1–28); and
  — vegetation class (Class A–F).
- Distance between the site and the predominant vegetation class.
- Average slope of the land between the predominant vegetation class and the site.

The intent of the assessment is to basically determine the category of bushfire attack for a site. The categories are extreme, high, medium and low.

The category of bushfire attack (e.g. medium, high) determines the level of construction requirements (e.g. Level 1, Level 2) for a building.

For the level of construction, the Standard then refers to the appropriate prescriptive construction requirements for the following different construction elements:

- Flooring systems.
- Supporting posts, columns, stumps, piers and poles.
- External walls.
- Windows.
- External doors.
- Vents and weepholes.
- Roofs.
- Eaves.
- Fascias.
- Gutters and downpipes.
- Verandas and decks.
- Service pipes (water and gas).

Fencing systems are currently not included in the Standard as construction elements that are required to perform in a certain category of bushfire attack, for a certain level of construction, for the following:

- Continue to perform its intended function as boundary fencing.
- Potentially protect other building elements.

3.3.3 Recommendations of State authorities

Recommendations on the potential of fencing systems made from non-combustible materials to act as radiant heat barriers are included in several publications [Ramsay & Rudolph 2003;

CFS SA & DEAP 2004; CFA & MPEV 1990]. These recommendations are of a general nature.

Some specific recommendations are included in the NSW RFS & Planning NSW [2001] *Planning for Bushfire Protection: A Guide for Councils, Planners, Fire Authorities, Developers and Homeowners*. To be able to infer these recommendations, some understanding and interpretation of the structural forms (Class A–F and Types 1–28) of Australian vegetation is required. These may be broadly summarised as grassland, woodland and forest.

The specific recommendations are:

- Radiant heat barriers are suitable for grassland and other similar vegetation situations.
- Radiant heat barriers are less effective for forest and woodland situations where flame heights can be anticipated to be larger than grasslands.
- Heat barriers are unlikely to be effective against burning debris.
- Fencing systems, which serve as heat barriers, provide limited protection from radiant heat to windows.
- Fencing systems should not be relied upon to reduce the need for setbacks or construction standards.
- Fencing systems should be located within about 5 m of the house and should be up to 2 m high to cover most windows and doors on the side facing the bushfire hazard.

3.4 Current limitations in the recommendations for use of fencing systems as radiant heat barriers

The current limitations are:

- Absence of recommendations for fencing systems to perform their intended function when attacked by a bushfire in the current Australian Standard, referenced in the BCA, for construction in bushfire-prone areas.
- Lack of recognition in the current Australian Standard, referenced in the BCA, for construction in bushfire-prone areas of the potential for fencing systems to act as radiant heat barriers to protect homes and similar buildings.
- No current recommendations on exposure levels for fencing systems.
- Fencing systems unsuitable for forest and woodland situations.
- Barriers such as fencing systems are unlikely to be effective against burning debris.
- No specific recommendations, for example, on the distance from buildings for the location of fencing systems for a particular category of bushfire attack, which requires a certain level of construction.
- Fencing systems should be located within about 5 m of a house and should be up to 2 m high on the side facing the bushfire hazard. The basis for this recommendation with specific figures is unknown, as it is not referenced in the source document [NSW RFS & Planning NSW 2001].
- Fencing systems cannot reduce setbacks or construction standards.

The objective of the current research program was to address some of these limitations.

4 METHODOLOGY

The methodology developed for the evaluation of the behaviour of residential boundary fencing systems during bushfires included three parts:

- Small-scale flammability experiments (Section 4.1).
- An air toxics study (Section 4.2).
- Full-scale experiments (Section 4.3).

4.1 Laboratory experiments

The effects of weathering and conditioning on the flammability properties of hardwood and softwood fencing paling materials was investigated, through a series of laboratory-scale experiments using the cone calorimeter. Basic flammability properties such as ignition time and heat release rate (HRR) were measured for old and new treated pine and hardwood paling, weathered to a variety of conditions and moisture contents.

4.1.1 Specimens

Both old and new hardwood palings and old and new softwood palings were sampled for experimental specimens. The old hardwood was classified as messmate (*Eucalyptus oblique*), and was sampled from an in-use fence estimated to be approximately 20 years old. The new hardwood was alpine ash (*E. delegatensis*), purchased direct from a supplier. Both the old and new softwood was treated radiata pine (*Pinus radiata*). The old treated pine was sampled from an in-use fence approximately 10 years old, and the new treated pine was purchased direct from a supplier.

A number of different palings were sampled for each type of timber. For the old hardwood, a significant difference in density and grain structure was observed between different palings. Palings ranged in width from 95–100 mm and thicknesses from 12–14 mm. Samples 100 mm long were cut along the lengths of each paling. These samples were given unique identification numbers such as OPE1, where OP represents old pine, E represents the paling it came from and 1 represents where the sample was located along the paling.

Once cut. the specimens of each type of timber were exposed to the following different conditioning scenarios:

- 23°C and 50% RH – representing typical daytime conditions.
- 40°C and 20% RH – representing hot, dry weather conditions.

The specimens were weighed daily until their mass had equilibrated to the exposure conditions.

After this conditioning, some specimens previously conditioned at 23°C and 50% RH were further conditioned at 40°C and 20% RH for six hours, to simulate the transition from a cooler day to a hot, dry day.

4.1.2 Experimental apparatus

The AS/NZS 3837–1998 cone calorimeter [Standards Australia/Standards New Zealand 1998] is a small-scale oxygen consumption calorimetry apparatus. Specimens, 100 mm square, are supported horizontally on a load cell and exposed to various heat flux levels in ambient air conditions. Ignition is promoted using a spark igniter. Combustion gases are extracted in an exhaust duct where instrumentation measures exhaust gas flow, temperature, O_2, CO and CO_2 concentrations, and smoke optical density. From these measurements, quantities such as HRR, time to ignition and smoke production can be calculated. Samples for toxic gas measurement may also be taken from the exhaust duct.

In this project, specimens were conditioned at different temperatures and RHs using separate conditioning enclosures, which used air-conditioners and humidifiers to achieve controlled conditions. Electronic temperature and humidity meters were used to monitor conditions.

A conductivity timber moisture meter could not be applied to treated pine because of the influence of salts in the timber. Therefore, the moisture content of both softwood and hardwood specimens were measured using a drying oven and laboratory scales.

4.1.3 Procedure

4.1.3.1 Cone calorimeter procedure

Cone calorimeter experiments were carried out in accordance with AS/NZS 3837 with the exception that different sample conditioning was applied. A measured quantity of methanol was burnt on each day of experimentation to calibrate the HRR measurement of the apparatus. Prior to experiments, a PMMA reference specimen was assessed to ensure that all systems were working correctly. Each cone calorimeter experiment was given a unique experimental number. All specimens were assessed in the horizontal orientation with the standard pilot operating. All materials were assessed at an irradiance level of 25 kW/m^2. Specimens were packed to the correct experimental height level using ceramic fibre blanket placed beneath the specimen on top of the specimen holder. All experiments were conducted with the use of an edge frame to retain the specimen and reduce edge effects, as allowed in the Standard. The edge frame reduced the exposed surface area to 0.0088 m^2, and this was the area used in the calculations. The nominal exhaust system flow rate for all experiments was 0.024 m^3/s.

Triplicate specimens of each material were assessed except for wetted specimens. Further experiments were conducted if required for repeatability. Each experiment was continued until the experimental criteria were reached, in accordance with AS/NZS 3837.

4.1.3.2 Moisture content measurement procedure

Moisture content was measured by weighing the original mass of a specimen and then oven drying the specimen and repeatedly measuring the specimens mass until the mass stabilised. The moisture content was then expressed as the following percentage:

$$\text{Moisture }\% = \left(\frac{\text{Original Mass}}{\text{Oven Dried Mass}} - 1 \right) \times 100$$

As drying would affect any cone calorimeter results, a selection of representative specimens were conditioned and measured for moisture content, rather than measuring the moisture content of each specimen assessed in the cone.

4.2 Cone calorimeter air contaminants

Cone calorimeter experiments were conducted with additional toxic gas measurement to make a qualitative and comparative assessment of two fencing materials – CCA-treated pine and COLORBOND steel – by measuring a range of toxic gases that may be released during their combustion. The toxic species that were measured included volatile organic compounds (VOCs), aldehydes, hydrogen fluoride (HF) and trace metals (arsenic, copper and chromium).

This experimentation was only indicative of the combustion gas species released. This experimental method alone does not assess the fire hazard of the materials, or products made from them, under actual fire conditions. Consequently, the results of these experiments should not be quoted in support of claims with respect to the fire hazard of the materials, or products made from them, under actual fire conditions. The results, when used alone, should only be used for research and development, quality assurance or similar industrial needs. A more rigorous program of toxic species measurement would be more time-consuming and expensive, and is not proposed at this stage.

4.2.1 Specimens

The CCA-treated timber and COLORBOND specimens were cut to fit into edge frames to which ceramic fibre blankets were added to obtain the correct experimental level height. The materials were conditioned at a temperature of 23±2°C and a relative humidity of 50±5% prior to being assessed. Each specimen was assessed in triplicate.

4.2.2 Procedure

The materials were combusted using the cone calorimeter, which was operated using the same procedure as for the other cone calorimeter laboratory experiments. All specimens were exposed in the horizontal orientation with the standard pilot operating. Specimens were assessed at an irradiance level of 25 kW/m^2.

Combustion gas sampling was carried out from two sample ports, which were installed in the exhaust duct from the combustion chamber. A heated jacket was installed on the exhaust duct to maintain a duct surface temperature of approximately 200–220°C and to prevent gas condensation onto the duct surfaces. Both sampling ports were packed with small plugs of silanised glass wool to prevent soot from fouling the air sampling devices.

Prior to each exposure, a quantity of methanol was burnt in the cone calorimeter – this yielded a large flame that reached into the exhaust duct and was intended to remove any condensates from previous experiments.

4.2.3 Combustion gases sampled

4.2.3.1 Volatile organic compounds

VOC samples were collected onto multisorbent tubes (Tenax TA, Ambersorb XE340). Before exposure of the CCA-treated timber and the COLORBOND fencing material, 200 ml blank cone samples were taken using a gas syringe to determine residual VOCs in the calorimeter from other experiments. Also, 200 ml blank samples were taken in between each experiment to determine potential residual VOCs from the previous experiment.

For the CCA-treated timber, 200 ml samples were drawn over 1–2 minutes onto the multisorbent tubes using a gas syringe. The first sample was taken before ignition and the second sample was taken 4 minutes post-ignition. The VOCs emitted from the COLORBOND samples were collected onto multisorbent tubes at a sampling rate of 43–60 ml/min for the duration of the experiment, resulting in a volume of 427–600 ml.

Before analysis by GC/FID/MS, sample tubes were loaded with fluoro benzene as an internal standard. The tubes were then thermally desorbed at 280°C in an Environchem Unacon 810A Thermal Desorber, and then onto a DB5MS column in a Varian 3100 GC/FID/Saturn II MS with a GC program from 2°C to 240°C. Compounds were identified by MS and quantified by FID, and calibrated for each VOC using liquid standards in high-purity methanol (which were loaded onto a Tenax (only) tube).

4.2.3.2 Aldehydes

Air from the exhaust duct was sampled via silicone rubber tubing onto 37 mm filters impregnated with 2,4-DNPH for aldehyde measurements. One cone blank sample was taken prior to the combustion of the fencing materials. Samples from the combustion of each material were taken over the entire experimental period at a sampling rate of ~1 L/min, resulting in a collected sample volume of about 10–15 L. The filters were analysed for formaldehyde, acetaldehyde, chloroacetaldehyde, acrolein, crotonaldehyde and n-valeraldehyde by Work Cover NSW using an HPLC method (R. Geyer, Work cover NSW, pers. comm.).

4.2.3.3 Hydrogen fluoride

Samples (600 ml) of HF were collected on a Kittagawa Tube No. 156S with a measurement range of 1.5–90 ppm for 100 ml. A colour change from greenish yellow to pink due to the discolouration of a pH indicator was observed when HF was present; the coefficient of variation for measurements was ~10%.

4.2.3.4 Trace elements (As, Cr, Cu)

A cassette containing a 5 micron PVC filter or glass fibre filter followed by a Na_2CO_3 impregnated glass micro fibre filter was attached to the sampling port to collect the trace elements As, Cu and Cr. As_2O_3, the volatile toxic species that may be released during pyrolysis of CCA-treated timber [Helsen *et al*. 2003; 2004; Kakitani *et al*. 2004], was collected onto the filters impregnated with Na_2CO_3. The samples were collected at a sampling rate of 2 L/min over the entire experimental period, resulting in a sampling volume of about 20–25 L. The filters impregnated with Na_2CO_3 were analysed according to method NIOSH 7901. The other filters were analysed according to method ISO 15202–2. The element concentrations were determined at ICP-AES by CMIT's analytical laboratory (P. Curtis, CSIRO, pers. comm.).

4.3 Full-Scale Experiments

The performance of various fencing systems has been investigated through full-scale bushfire experiments using a bushfire flame front simulator.

Four types of bushfire exposures were performed on these fencing systems using the bushfire flame front simulator. For each experiment, temperatures and radiant heat flux were measured at different locations on the fencing systems, within the fencing area and on a simulated residential building located within the fencing boundary.

4.3.1 Residential objects investigated

For each experiment, the fire performance and interaction between a group of residential objects were investigated. The objects included the fencing system, a simulated residential building, polypropylene children's play equipment and a polypropylene chair placed at set distances inside the fencing boundary.

4.3.1.1 Fencing systems

The following different types of fencing systems were investigated

- COLORBOND steel with traditional roll formed profile infill sheet.
- COLORBOND steel with sawtooth roll formed profile infill sheet.
- COLORBOND steel with sawtooth roll formed profile infill sheets with steel lattice at the top of the fencing.
- Capped open paling hardwood.
- Capped open paling treated pine.
- Closed paling hardwood.
- Closed paling treated pine.

The treated pine was radiata pine (*P. radiata*). The hardwood was yellow stringy bark (*E. muelleriana*) and southern mahogany (*E. botryodes*). All timber fencing panels were conditioned prior to experiments. Timber was placed in a steel shipping container that was maintained at approximately 40°C and 20% RH during the day and approximately 30°C and 50% RH during the night. Typical moisture contents of the installed fencing system after typically two hours of exposure to the ambient conditions of the day achieved were between 10% and 12% for hardwoods and 10% and 11.3% for treated pine.

The design and installation of these fencing systems is shown in Appendix B (drawings) and Appendix C (photographs). Each fencing system was installed in an 'L' configuration with two perpendicular lengths creating one corner. One section was approximately 7.3 m long and ran parallel to the bushfire flame front simulator burner array in a south–east to north–west direction. The second length was approximately 12 m long and ran perpendicular to the burner array. All fencing were approximately 1.8 m high, except for the COLORBOND steel fencing system with lattice on top, which consisted of sawtooth roll formed profile infill sheet to a height of 1.5 m with the additional 0.3 m high steel lattice.

To facilitate rapid construction, all fencing systems were constructed by erecting prefabricated panel fencing sections. For steel fencing the panels were 2400 mm wide and for timber fencing the panels were 2600 mm wide. Each panel was supported and joined to adjacent panels at either side with posts. For steel fencing, COLORBOND steel roll formed posts and rails were used with the panels being screwed together. For treated pine fencing, treated pine posts were used. For hardwood fencing, hardwood posts were used. Timber fencing panels were attached to posts via fencing rails penetrating mortise holes in the posts and secured with screws. Rather than digging posts into the ground, the posts were supported and screwed to steel base plates that were pegged to the ground. All fencing installations were performed by an experienced fencing contractor who was instructed to install each fencing system in the typical way.

For reference purposes, the fencing panels were labelled A to H, as shown in Appendix B.

4.3.1.2 Simulated residential building

A small structure was constructed to simulate a shed/residential building. This building was present for all experiments. The walls and roof of the building were constructed of standard COLORBOND steel fencing panels and was 2.4 × 2.4 m square and 1.8 m high. It had an earth floor. It was located 9.4 m back from the length of fencing parallel to the burner array, and 1.5 m from the fencing perpendicular to the burner array. The wall facing the fencing 1.5 m away was fitted with two windows 900 mm wide × 900 mm high, each glazed with float glass. One window frame was constructed of Oregon timber and the other was aluminium, and both were supplied by a commercial window manufacturer.

4.3.1.3 Play equipment

Three separate pieces of polypropylene children's play equipment were placed at set positions within the fencing boundary for each experiment. This was to provide visual performance indicators for the various fencing systems observed in the experimental program and for items observed in post-bushfire investigations. A plastic wading pool half filled with water was placed approximately 2 m away from panel B, and a plastic chair and trolley were placed approximately 0.5 m away from panel B.

4.3.2 Performance objective of these experiments

The full-scale experiments demonstrated specific mechanisms by which a fencing system can act to protect or endanger a residential property when exposed to a bushfire. The key mechanisms were found to be:

- Providing a radiation barrier: Fencing may provide a significant barrier to radiant heat emitted by a bushfire front. This can be sufficient to prevent combustible items near the fencing from igniting and resulting in fire spread into the property boundary. The amount of radiation shielded increases with fencing height, however the flames at the outside of the fencing may be higher than the fencing, but the fencing may still provide significant shielding to objects lower than the fencing height. The solidity of the fencing is important, as gaps between palings etc. will decrease the shielding of radiant heat. The ability of the fencing to maintain integrity during bushfire exposure is critical. If sections of the fencing burn through or collapse, the radiation barrier fails. Fire spread from bushfire radiation exposure can be more rapid than fire growth from ember attack, thus a suitable fencing may assist in protection against radiant heat fire spread at a time during the bushfire passage when occupant suppression is not practical.
- Lateral flame spread along fencing: Fencing may support lateral flame spread along its length, wicking the fire away from the area of bushfire impact to other potentially combustible areas. An example scenario where this may endanger a residential property is fencing spreading fire along the side of a boundary where the separation distance to buildings can be very narrow. The collapse of a burning section of fencing onto buildings, and sometimes breaking windows was observed.
- Ember attack: The fire performance of fencing materials under ember attack was assessed using burning leaf litter to represent this scenario. The ability of a fencing system to protect objects inside the fencing boundary against attack from windborne embers was not observed in these experiments. Where fencing became involved in fire, only a very small quantity of windborne embers were produced by the fencing material. This was mainly due to the size and density of the fuel compared with foliage and twigs, and also wind speeds conditions were lower than characteristic of extreme bushfire events.

4.3.3 Experimental apparatus

4.3.3.1 Bushfire flame front simulator

The bushfire flame front simulator constructed in the open at the NSW RFS Hot Fire Training Facility, south of Mogo, allows repeatable assessment of different materials in bushfire burn over conditions. The bushfire flame front simulator is designed to recreate actual bushfire flame characteristics (e.g. flame temperature profiles and radiant heat flux) using a grid of liquid propane burners.

Liquid propane is stored in an 8000 L tank permanently installed at the facility. The tank is pressurised by regulated nitrogen to avoid the reduction in flow that occurs when the natural vapour pressure of propane is used as a propellant. Safety features fitted to the supply include over-pressure valves and overflow valves.

The pressurised propane is piped a distance of approximately 30 m to the simulator grid in a buried 75 mm internal diameter pipe.

The burner grid consists of five separate stages to simulate a fire front approach, burn over and continued advancement. However, for this project, only the fire front approach was of interest, so only two stages – pre-radiation burners and on-side immersion burner stages – were used (Figure B2). The fencing systems were built over the top of the unused burner stages.

The pre-radiation burner stage was arranged in a line of four sets of three burners at a distance of 5 m from the north-east facing fencing. This stage simulated the radiant heat exposure from an approaching fire front. Each set of three burners could be individually turned on and off via solenoid valves, and the burner flow could be controlled via control valves.

On-side immersion stage burners were arranged in three rows of six burners set at 350 mm, 1.85 m and 3.35 m from the north–east-facing fencing. During a burn, this phase could only be turned on or off. The flow rate could be controlled by fitting differently sized calibrated jets to the burners. When simulating lower fire intensities with shorter flame depths, the jets in the rear-most rows could be turned off. The total HRR was estimated by summing the calibrated jets used.

The angle and height of the simulator’s flames approaching the fencing was influenced by the ambient wind conditions. Thus, there was a degree of uncontrolled variation in flame angle according to the wind gusts and lulls. The experiments were carried out in north–easterly sea breezes with open-air wind speeds at a height of 2 m of approximately 5–8 km/h. These relatively light breezes are considered to represent the attenuated forest wind under the canopy, and to recreate flame angles similar to actual forest fire flames for the appropriate fire line intensity [Leonard 2003-1].

While effort was made to accurately simulate critical aspects of a bushfire, there remained fundamental assumptions and limitations associated with attempting to simulate a moving fire on a stationary grid, and the use of propane gas to simulate bushfire flames.

4.3.3.2 Instrumentation

Temperature measurement

Temperatures were measured using 1.5 mm Type ‘K’ MIMS thermocouples. Each thermocouple was identified by a separate thermocouple number as shown in Appendix B, which also shows the positions of all thermocouples. Air and surface temperatures were measured at the centre of each fencing panel on both sides of the fencing at different heights. Steel reinforcing mesh was placed over the centre of each fencing panel to support the thermocouples.

Air temperatures at different positions on both sides of the fencing and on the burner grid were measured by thermocouples mounted on masts at heights of up to 3 m above ground level. Thermocouples were also fitted to the simulated residential building to measure air temperatures inside and outside, steel surface temperatures and window surface temperatures.

Heat flux measurement

Heat flux was measured using Medtherm water-cooled Schmidt Boelter total heat flux meters with a sensing range of 0–100 kW/m^2. The total heat flux measured consisted of both radiative and convective heat. Heat flux meters were mounted at the house and windows at different locations on masts on both sides of the fencing facing both horizontally and vertically.

Two heat flux meters were mounted horizontally at the mid-height of fencing panel C adjacent to the burner grid. One faced the rear of the fencing and the other was poked through a hole in the fencing to face the bushfire flame front simulator. This was used to monitor the heat flux output of the bushfire flame front simulator, as well as to measure the effects of radiation feedback a fencing surface received if the fencing system combusted. For these total heat flux meters, radiative heat was the predominant component measured during pre-radiation exposure, however during total flame emersion convective heat was the principal component.

All external cables and cooling lines were protected by placing them in silicon-coated mineral fibre-insulated sheathing or in steel downpipe sections, or by burying them underneath sand.

Data acquisition

The locations of all thermocouples and radiometers are shown in Appendix B. Each was logged at five-second intervals via a Datataker 505 data logger with up to three expansion modules. The data logger and expansion modules were placed in a steel fireproof box located inside the simulated residential building. The data logger had a battery power supply, which was recharged between experiments. An RS232 communications link was created by a radio modem transducer connected to the logger and a matching receiver connected to a monitoring computer in the control area. This allowed for the real-time observation of data, which was simultaneously recorded onto the data logger's internal memory card and a PC in the control area to minimise the potential of data loss.

Moisture content meter

A conductive moisture content meter was used to measure the moisture content of the hardwood during conditioning and prior to exposure. This was not done for the treated pine due to the interference of salts with the measurements. Treated pine samples were taken for each experiment and gravimetric moisture content analysis was performed.

Weather measurement

A range of information relating to climatic conditions was collected prior to and during all experiments. An Oregon WMR112U Cable Free Weather Station and sensors was used to collect weather data and forward it to a base station positioned in the control room, which then logged the information directly to a PC. Data was collected by the sensors at a rate of three recordings per second, and this was logged in the computer database once a minute. Each record in the database is an average of the 180 recordings taken in that minute.

Wind speed was measured and recorded in meters per second, and the wind direction was displayed as a value between 0° and 359°, with 0° representing north, 90° east, 180° south and 270° west. This information, in particular information relating to wind direction and speed, was used to determine appropriate times to perform the exposures. A north–easterly direction was favoured for experimentation, which is represented as 45°, although experimentation was carried out under a range of wind conditions.

Weather conditions during the experiments were varied compared to recent years. Generally the wind conditions are dominated by a local thermally driven sea breeze, which produces strong north–east winds in the afternoons of warmer days.

Where weather data was unavailable at the Mogo site, data from the local Moruya airport was obtained.

In 2005, a warmer open-ocean current moved further down and closer to the coast. It would appear that this increase in sea surface temperature and a slightly lower than average land temperature reduced the frequency and strength of the traditional thermally driven north–east sea breeze.

Audiovisual recording

A minimum of two digital video cameras were used to record each experiment. Digital still pictures before, during and after each experiment were also taken and were time-stamped for appropriate visual recreation of the exposures.

4.3.4 Procedure

The procedure involved a range of different exposure conditions ranging from leaf litter combustion to fuel flame immersion of components of the fencing system.

4.3.4.1 Leaf litter exposure

This simulated an attack from burning embers or leaf litter. Eucalypt leaf litter consisting of leaves and small twigs was conditioned at 40°C and 20% RH. For each exposure, approximately 100 L of leaf litter was spread along the base and rails of the outside of the fencing and 20 L of leaf litter was spread along the base of the inside of the fencing, particularly in the corner. This leaf litter was then ignited using a portable propane burner. The burners of the bushfire flame front simulator were not used for the leaf litter exposure experiments. The experiment was ceased when significant combustion or involvement of the fencing ceased. Leaf litter exposures were not conducted on COLORBOND steel fencing systems as no involvement of the fencing would be expected.

4.3.4.2 Bushfire passage pre-radiation exposure

This level of exposure represents a radiation profile typical of an advancing bushfire that does not reach a point of direct flame contact occurring on a day of Fire Danger Index (FDI) 40 and a fuel load of 15 tonnes/hectare (t/ha). For timber fencing the same quantity of leaf litter as for the leaf litter exposure was distributed and ignited. For steel fencing no leaf litter was applied. The pre-radiation burner stage of the bushfire flame front simulator was then controlled so that the following heat flux measurement readings at fencing panel C were achieved:

- 5 kW/m^2 for 3 minutes.

- 10 kW/m^2 for a further 2 minutes.
- 30 kW/m^2 for a further 2 minutes.
- 10 kW/m^2 for a further 1 minute.
- 5 kW/m^2 for a further 1 minute and then the burners were turned off.

The flame immersion burner stage was not used. The flow rate of the pre-radiation burner stage was manually controlled in response to real-time heat flux readings. An experiment was ceased when significant combustion or involvement of the fencing ceased.

4.3.4.3 Bushfire passage flame immersion exposure

This level of exposure represents a bushfire occurring on a FDI 40 day with a fuel load of 15 t/ha, including a flame immersion from a flame front of 10 megawatts/metre (MW/m) fire line intensity (flame heights typically 5 m). The pre-radiation stage set-up was similar to that for the pre-radiation exposure experiments. The flame immersion stage was also used as follows:

- 5 kW/m^2 pre-radiation stage only for 3 minutes.
- 10 kW/m^2 pre-radiation stage only for a further 2 minutes.
- 30 kW/m^2 pre-radiation stage only for a further 2 minutes.
- Flame immersion stage on for a further 11 seconds.
- Flame immersion stage turned off, but a further 40 seconds was required for all gas to burn out of the lines in this stage of the grid.
- 5 kW/m^2 pre-radiation stage for a further 2 minutes and then the burners were turned off.

Leaf litter was applied to timber fencing, was but not ignited prior to operating the bushfire flame front simulator.

4.3.4.4 Structural fire exposure

This level of exposure was designed to simulate a worst-case structural fire exposure, where a fencing system could increase or decrease the risk of adjacent house ignition. The experiments involved full continuous flame immersion with a fire line intensity of 5 MW/m (flame height 2–2.5 m) for a period of 30 minutes. The flame immersion stage of the bushfire flame front simulator was turned on for 30 minutes. No leaf litter was used.

5 RESULTS AND DISCUSSION

5.1 Small-scale cone calorimeter experiments

The results of all cone calorimeter experiments are summarised in Table 5.

A material's time to ignition under a given irradiance in the cone calorimeter provides a basis for comparing how easily different materials ignite. The vertical bars in Figure 1 show the average time to ignition of different timbers with different conditioning. Cone calorimeter exposures were performed at 25 kW/m^2 under standard experimental conditions, except where specific preconditioning was identified. Error bars are used to indicate the variance between triplicate experiments. Figure 1 clearly shows that the new treated pine was the easiest to ignite, followed by old treated pine and then old hardwood, with new hardwood being the most difficult to ignite. In general, for most timbers, conditioning at 40°C and 20% RH increased a timber's ignitability, followed by conditioning at 23–40°C, with conditioning at 23°C and 50% RH reducing the ignitability the most. Conditioning had a stronger effect on new timbers than older timbers. These results identify a correlation between timber moisture content and increased propensity for ignition, while the aging of timber is significant but dependent on the specific timber variety in question. Of particular interest is the surface moisture content achieved by the 6-hour exposure at 40°C, which created ignition times similar to conditioning at 40°C and 20% RH.

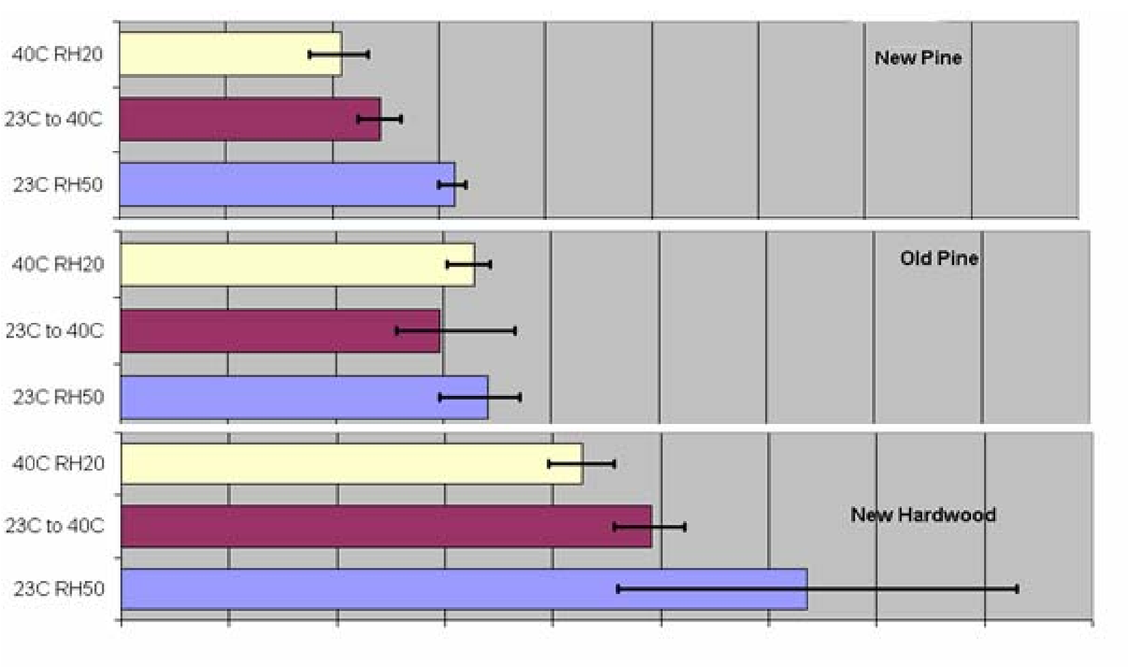

Figure 1. Cone calorimeter time to ignition of different timbers after different conditioning.

The median (of triplicate experimental results) HRR per unit area for each timber and conditioning type is shown in Figure 2. All specimens demonstrated a double peak in HRR. The first peak occurred rapidly after ignition as flames established across the surface of the timber. However, as the material continued to burn, a char layer formed across the burnt surface, which reduced the heat transferred to the unburnt material beneath, and slowed the release of volatile gases to the surface where oxygen is available for combustion. After prolonged combustion and exposure to external heat, cracks developed in the wood char exposing unburnt material, resulting in the second peak. Figure 2 clearly shows that the time between the first peak and the second peak was greater for hardwood than for treated pine. This is because hardwood develops a denser, stable char. This observation supports large-scale observations that hardwood requires a higher level and intensity of radiation exposure to instigate flame spread.

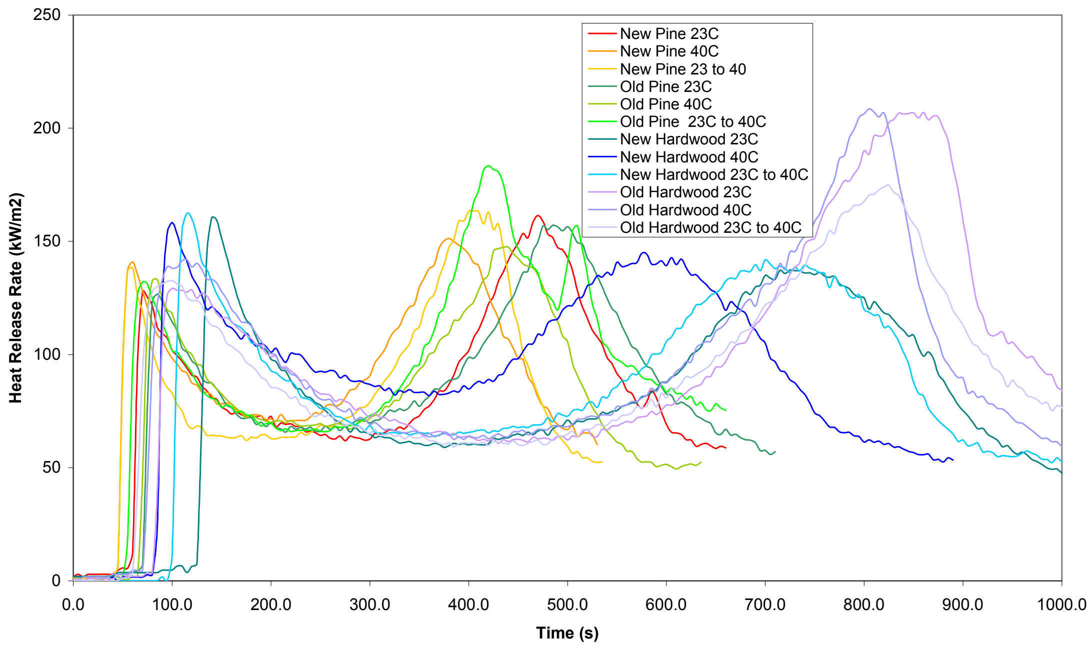

Figure 2. Median cone calorimeter HRR per unit area for each specimen type.

Moisture content measurements showed that both pine and hardwood reached a moisture content of approximately 5% after conditioning at 44°C. Both pine and hardwood reached a moisture content of approximately 10% after conditioning at 23°C. Pine and hardwood specimens transferred from 23°C to 40°C conditions for 6 hours reached average moisture contents of approximately 8%, however surface moisture contents were likely to be closer to 5% in this case. Changing moisture content is the main reason timbers behaviour in fire changes in different temperature and humidity conditions.

COLORBOND steel was also assessed under the same exposure conditions and did not show any signs of ignition.

5.2 Small-scale experiments – air contaminants

Evaluating the risks from air contaminants will depend on the combustion conditions, the quantity of material burnt, the volume of combustion gases generated and its dispersion, and the degree to which site occupants are exposed to the gases. These will vary for each specific situation, and are beyond the scope of this investigation (see Introduction).

5.2.1 Volatile organic compounds

The concentrations of the major VOCs emitted during combustion of both sampling materials are presented in Table 1. The concentrations have been corrected for cone blanks and tube blanks, which were generally very small compared to experimental results.

Table 1. VOC concentrations ($\mu g/m^3$) during cone calorimeter experiments

VOC	COLORBOND	CCA-treated pine	
		At 0–100 s	At 300–380 s
Acetone	310	252	182
Benzene	330	2	38
Toluene	5	6	17
β-pinene	6	95	162
β-pinene	6	42	79
Benzaldehyde	8	<2	<3
Phenol	<20	40	30
Nonanal	14	17	12
Decanal	10	<9	<12
Octamethylcyclotetrasiloxane	11	12	<14
Decamethylcyclopentasiloxane	15	<4	<18
Dodecamethylcyclohexasiloxane	92	3	2
Dodecamethylpentasiloxane	280	18	6
Tetradecamethylhexasiloxane	120	8	<2
Hexadecamethylheptasiloxane	16	ND	<5
TVOC	810	420	590

The results show that:

- The major VOCs emitted during cone calorimeter experiments on the COLORBOND steel fencing material were benzene, acetone and siloxanes. Benzene and acetone were considered to be products of the combustion of the COLORBOND steel coating. BlueScope Steel reported that siloxanes were not used in manufacture, but may have been a minor component of some additives. Further sampling of the cone calorimeter exhaust without material combustion showed that ~30% of the siloxanes measured arose from silane-treated glass wool or silicone tubing used in air sampling. These were subtracted from the reported data.
- The major VOCs released during the combustion of CCA-treated pine included acetone, α- and β-pinene, phenol and benzene.
- The levels of benzene were higher for the COLORBOND fencing material. Benzene has been found to be a common combustion product of plastics [Mansson *et al*. 1994] and bushfire smoke (F. Reisen, Bushfire CRC, pers. comm. 2005). Levels of benzene emitted in bushfire smoke ranges from 30 to 788 μg/m^3. Benzene is a known human carcinogen and in Australia there is a proposed NEPM (http://www.ephc.gov.au/nepms/air/air_toxics.html) that aims at protecting the health of the general population. The monitoring investigation level for benzene (24-hour average of 0.003 ppm) represents a 'level of air pollution below which lifetime exposure, or exposure for a given averaging time, does not constitute a significant health risk'. In Australia there are also exposure standards for atmospheric contaminants in the occupational environment (the 8-hour Worksafe Occupational Exposure Standard for benzene is 0.5 ppm), which are for workplace situations only and would not be applicable for assessing fire-fighters' exposure. However, it is clearly stated that these exposure standards should not be applied in the control of community air pollution (http://www.nohsc.gov.au/OHSInformation/Databases/ExposureStandards/ExposureStandards4AtmosphericContaminants.pdf).
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5.2.2 Aldehydes

The results of aldehyde measurements are presented in Table 2. It can be seen that:

- Formaldehyde was the major aldehyde released during combustion of both materials. Formaldehyde is categorised as a human carcinogen and can cause eye, nose and throat irritation, and in Australia there is a proposed National Environmental Protection Measure (http://www.ephc.gov.au/nepms/air/air_toxics.html).

- The combustion of CCA-treated pine also released measurable amounts of acetaldehyde.
- The concentrations of acrolein, chloroacetaldehyde, crotonaldehyde and n-valeraldehyde were below detection limits.

Table 2. Aldehyde concentrations (μg/m^3) during cone calorimeter experiments

Aldehyde	COLORBOND	CCA-treated pine
Formaldehyde	340	937
Acetaldehyde	<30	170
Acrolein	<30	<24
Chloroacetaldehyde	<30	<24
Crotonaldehyde	<30	<24
n-Valeraldehyde	<30	<24

5.2.3 Hydrogen fluoride

The concentration of HF released during the combustion of both materials was below detection (<0.25 ppm).

5.2.4 Trace elements (As, Cr, Cu)

The levels of trace elements observed during the combustion of the materials are shown in Table 3. Analysis of the particle filter showed that almost no arsenic (<0.4 μg/m^3) was released from the combustion of COLORBOND steel fencing material. However, the ICP-AES analysis determined levels of Cr (5.9 μg/m^3) and Cu (1.2 μg/m^3). Combustion of CCA-treated timber, on the other hand, resulted in the release of measurable concentrations of As (14 μg/m^3), as well as lower levels of Cr (0.2 μg/m^3) and Cu (0.2 μg/m^3) than observed with COLORBOND steel. Arsenic can cause eye, throat and respiratory irritation and is a confirmed human carcinogen.

As shown in Table 3, the levels of As_2O_3 released from both materials were measurable. The blank cone sample resulted in As_2O_3 levels of 50 μg/m^3, whereas As_2O_3 concentrations from the combustion of both materials were 4–5 times higher. It is likely that the levels of As_2O_3 observed were the result of potential contamination from the edge frames or the ceramic fibre blanket used to obtain the correct experimental height in the edge frame. In fact, the same blankets may have been used during experiments conducted with CCA-treated timber and may release As_2O_3 when heated. Further experiments need to be conducted to determine the source of contamination and to determine the levels of potential As_2O_3 released during the combustion of both sampling materials.

Table 3. Trace element concentrations (μg/m^3) during cone calorimeter experiments

Trace metal	COLORBOND®	CCA-treated pine	Timber ash
As	<0.4	14.0	2.2
Cr	5.9	0.5	1.65
Cu	1.2	0.4	1.67
As_2O_3	194	160	

5.3 Full-scale experiments

5.3.1 Experimental observations in date sequence

Key results for each experiment are summarised in Tables 5–10. A summary of the full-scale simulation experiments is included in Table 11. Graphs of the measurements of each experiment are presented in Appendix A. Drawings showing the instrumentation set-up are included in Appendix B. Photographs for each experiment are presented in Appendix C. Summary observations of each experiment are as follows on typical 1.8 m high fencing systems. Also included in the experiments were a 1.5 m COLORBOND steel fencing system and a 1.5 m high COLORBOND steel fencing system with 0.3 m COLORBOND steel lattice.

5.3.1.1 Experiment 1 – flame immersion exposure of COLORBOND steel fencing with traditional roll formed profile infill sheets

For experiments 1 and 2, the simulated residential building was constructed with no roof, windows or rear wall. For later experiments these features were added to the structure.

The pre-radiation stage burners were turned on at the start of Experiment 1. After 6 minutes panels A, B and C were producing significant amounts of smoke. At 7:10 (min:sec) flame immersion stage burners were turned on and flames impinged on the outside of panels A, B, C and D, with flames rolling over the top of the fencing (see Figure 3). Smoke production at the inside of these panels immediately increased. At 7:40 flame immersion burners were turned off. At 13:00 pre-radiation burners were turned off and the experiment ceased.

Figure 3. Experiment 1 – flame immersion exposure of traditional COLORBOND steel fencing.

During the experiment the fencing structure did not sustain any flaming. The COLORBOND steel coating on both sides of panels A, B, C and D were scorched and crazed (see Figure 4). All fencing panels were still standing, however there was slight buckling of the panels that produced small openings at the joints between panels A–B and B–C. There was no damage to the simulated residential building or any of the plastic play equipment.

Figure 4. Experiment 1 – inside view of (left to right) panels D, C, B and A at end of experiment.

5.3.1.2 Experiment 2 – structural fire exposure of COLORBOND steel fencing with traditional roll formed profile infill sheets

Flame immersion stage burners were turned on at the start of the experiment, with flames impinging on panels A, B, C and D. After 1 minute the rear of these panels was producing significant smoke and small flames were observed to intermittently lick between panels A–B, B–C and C–D in the corner. The experiment continued in this manner until the flame immersion burners were turned off at 30:00 minutes. Damage sustained to the fencing was much the same as for Experiment 1 with no major structural damage and only minor buckling at the panel joints. The simulated residential building, plastic play equipment and polypropylene chair (see Figure 5) were only superficially damaged.

Figure 5. Experiment 2 – heat-affected polypropylene chair.

5.3.1.3 Experiment 3 – pre-radiation exposure of COLORBOND steel fencing with traditional roll formed profile infill sheets (with two off-white infill sheets)

Apart from the smoke produced from the smouldering litter, there were no visible impacts of the pre-radiation simulation. The fencing remained completely intact and there was no discernible damage to the exterior of the fencing. Experiment concluded after 10:30.

5.3.1.4 Experiment 4 – flame immersion exposure of COLORBOND steel fencing with traditional roll formed profile infill sheets (with two off-white infill sheets)

The experiment commenced with the lighting of the litter at the base of the fencing on the north–eastern side of panels A, B and C, followed by the north-facing panels. Five minutes of pre-radiation followed this ignition. During this phase the litter continued to smoulder but as would be expected no ignition of the fencing was observed (see Figure 6). By the 7:00, full immersion was under way. The experiment concluded after 10:00 with minimal structural damage observed, however there was crazing and surface coating loss to the exterior surfaces of panels A, B, C and D.

Figure 6. Experiment 4 – leaf litter effect on COLORBOND steel fencing.

5.3.1.5 Experiment 5 – leaf litter exposure of capped open paling hardwood fencing

Leaf litter was ignited along the base and rails of all fencing panels. Most of the leaf litter flamed and then smouldered without any significant involvement of the hardwood. At one location where flames from leaf litter impinged on the bottom of the palings, light surface flaming at the base of the palings occurred (see Figure 7). However, this flaming ceased as the leaf litter burnt out. There was no significant damage to the fencing, play equipment, chair or simulated residential building.

Figure 7. Experiment 5 – leaf litter ignition of capped open paling hardwood fencing.

5.3.1.6 Experiment 6 – pre-radiation exposure of capped open paling hardwood fencing

Leaf litter was initially ignited along the base of panels C, B and A, followed by the longer side panels D, E, F, G and H. At 1:20 the pre-radiation burner stage was turned on and the pre-radiation exposure began. At this stage only smouldering of leaf litter was observed with no real involvement of the hardwood. During the pre-radiation exposure no flaming or smouldering of the fencing was observed. At 9:00 pre-radiation stage burners were reduced to very small flames. At this time some limited smouldering of the fencing at the corner was observed. At 10:00 all burners were turned off and the experiment was ceased. There was no significant damage to the fencing, only scorching of the outside of panels A, B and C (see Figure 8).

Figure 8. Experiment 6 – leaf litter and pre-radiation of capped open paling hardwood fencing.

5.3.1.7 Experiment 7 – flame immersion exposure of capped open paling hardwood fencing

This experiment commenced with the ignition of the pre-radiation burner stage, followed within 30 seconds by the full flame immersion burners. Panels B, C and D ignited almost instantly, with flame extending about 2 m into the air and penetrating through the fencing, damaging the play equipment (see Figure 9). Flame spread to panels A and E was observed, but the majority of the damage was confined to the panels directly exposed to the flame. The flame exposure concluded after 5:40 and the fencing was allowed to burn. During this period flame continued to spread slowly away from the corner until 22:00, when what was remaining of panel B, C and D collapsed.

Figure 9. Experiment 7 – flame immersion exposure of capped open paling hardwood fencing.

The experiment concluded with the almost complete destruction of panels B, C and D. Panel A was 60% destroyed and slow flame spread continued towards the simulated building, but it was deemed unlikely to have reached the residential building.

5.3.1.8 Experiment 8 – leaf litter exposure of closed paling treated pine fencing

At 0:40 flaming of leaf litter was observed at the base of the fencing at the inside corner, with resulting spread to treated pine, with flames approximately 1 m high. Flaming also occurred at the outside of the fencing corner and at the base of panel intersections E–F and H–G. By 1:30 flames in the corner extended to the top of the fencing, and by 3:00 the fire had begun to spread laterally along the fencing from the corner. The intensity of the flames was reduced when wind gusts increased. At this stage the fire had begun to burn through corner fencing palings. At 6:00 all corner palings had been completely burnt, leaving a large hole in the fencing. The fire continued to spread slowly along the fencing, particularly in the south–west direction (along panel D), assisted by the prevailing wind direction. At this time a small fire was also burning a hole through the palings above the mid-height rail at the intersection of panels F and G. By 15:00 half of corner panels D and C had been consumed, with charred rails and posts still standing. Flaming in this area had reduced to small flames at edges of burnt areas because the corner no longer sheltered the burning areas from wind gusts and the burning edges were far enough apart that re-radiation did not occur. At this time the hole at the intersection of panels F and G had grown to one-quarter fencing height. Smouldering at other panel intersections was observed. By 30:00 corner panels D and C were completely consumed. By 40:00 the hole at the intersection of panels F and G extended to the top of the fencing and small flames were observed on panel H adjacent to the windows of the simulated residential structure (see Figure 10). By 50:00 flames on the outside of panel H extended above the top of the fencing. By 60:00 half of panels E and B were consumed and there was increased flaming adjacent to the window with flames penetrating through palings.

Figure 10. Experiment 8 – leaf litter ignition of closed paling treated pine fencing.

By 80:00 all of panel E had been consumed and the hole at the intersection of panels G and F had spread to consume a third of panel G. At this point the majority of the end panel adjacent to the window has been consumed. At 90:00 panel G, adjacent to the residential building, began to slump towards the building and at 100:00 the corner of panel G was leaning against the building and window and continued burning. At 104:00 panel F collapsed outwards and continued burning. At 125:00 flaming of panel G, which was leaning against the building, had increased, and by 132:00 panel G was mostly consumed and was no longer leaning against the building as it was almost reduced to ash.

Inspection of the resulting damage revealed that window 2 in the simulated building had cracked in the top right-hand quarter (see Figure 11). The entire fencing except for panels A and B had either collapsed or been consumed.

Figure 11. Experiment 8 – cracked window 2 after leaf litter ignition of closed paling treated pine fencing.

5.3.1.9 Experiment 9 – pre-radiation exposure of closed paling treated pine fencing

The experiment commenced with the ignition of leaf litter placed around the bottom and on the rails of the fencing. The leaf litter smouldered from these ignition points with no observation of flaming. At 1:30 the pre-radiation burners were ignited and allowed to burn until 10:30. During this period the litter ignition points continued to smoulder, with flame growing from the external corner of panels C and D. This flame spread was in both vertical and horizontal directions.

Also during this period, the ignition of both panels F and G was observed. These ignitions appeared to have been a result of the continued smouldering of the litter positioned on the rails. Flame continued to spread from these ignition points as well as from the exposed corner, causing major structural damage to the fencing along the north-facing panels (see Figure 12). This damage caused the fencing to fall onto the simulated house, smashing window 2 (see Figure 13). This observation is of particular importance as in a real bushfire scenario, total house loss would be imminent unless immediate suppression occurred.

Figure 12. Experiment 9 – pre-radiation exposure of closed paling treated pine fencing.

Figure 13. Experiment 9 – pre-radiation exposure of closed paling treated pine fencing.

5.3.1.10 Experiment 10 – flame immersion exposure of capped open paling treated pine fencing

The experiment commenced with the ignition of the pre-radiation burners. During this pre-radiation phase, there appeared to be some flame contact as wind speed fluctuated. Extensive smoking was observed, but no ignition of the fencing resulted from this contact. A 6:00 there was ignition of the fencing at the corner post, which appeared to be a result of smouldering litter. At 7:30 the flame immersion burners were ignited, immersing the fencing in flames. Flames penetrated under, over and through the fencing, offering no real protection to the play equipment positioned behind the fencing.

Flame spread was observed along the fencing in both directions away from the corner, and severe damage was observed to the directly exposed areas. The fencing appeared to be consumed in the area where flame contact occurred. The experiment concluded with panels A, B, C, D and E being destroyed (see Figure 14), along with the children's play equipment. Burning was ongoing at the time of experiment termination, and it was likely that these flames would have consumed all fencing panels.

Figure 14. Experiment 10 – flame immersion exposure of capped open paling treated pine fencing.

5.3.1.11 Experiment 11 – pre-radiation exposure of - COLORBOND steel fencing with sawtooth roll formed profile infill sheets

The experiment commenced with the ignition of the pre-radiation burners. At 1:30 the burners were increased in intensity to 10 kW/m^2. The fencing showed no signs of deterioration at this point. At 5:00 radiation was increased to 30 kW/m^2, still with no visible impact on the fencing (see Figure 15). No flame contact was observed. The experiment concluded after 9:00 with no structural damage to the fencing.

Figure 15. Experiment 11 – pre-radiation exposure of COLORBOND steel fencing with sawtooth profile.

5.3.1.12 Experiment 12 – pre-radiation exposure of COLORBOND steel fencing with sawtooth roll formed profile infill sheets

The pre-radiation burners were ignited and their output was increased to 10 kW/m^2 at 2:00. No flame contact was observed to this point. Radiation was increased to 30 kW/m^2, and at 5:20 some flame contact was observed, resulting in smoke generation by the contacted panels (A, B and C) (see Figure 16). Radiation was reduced after 7:00 and the experiment concluded at 9:00. No flame penetration was recorded and the fencing remained structurally sound.

Figure 16. Experiment 12 – pre-radiation exposure of COLORBOND steel fencing with sawtooth profile.

5.3.1.13 Experiment 13 – flame immersion exposure of COLORBOND steel fencing with sawtooth roll formed profile infill sheets

The experiment was initiated with the ignition of the pre-radiation burners. After 3:00 the radiation intensity was increased to 10 kW/m^2. No flame contact was observed until an increase in wind speed laid the flames down. Ignition of the remaining pre-radiation burners at 6:00 produced a further increase in the flame size and intensity, causing some smoke emission from the fencing. At 7:00 the flame immersion burners were ignited, covering the fencing in flame. These flames penetrated under, over and, to a small degree, through small gaps between the fencing panels, although they did not cause major structural damage. Smoke was being generated and there appeared to be a slight bowing of the fencing at panel B, directly above a burner. The experiment concluded with the fencing remaining structurally sound, but there was extensive damage to the surface coatings of the fencing. Small gaps had also developed at the joints between panels A, B, and C (see Figure 17).

Figure 17. Experiment 13 – flame immersion exposure of COLORBOND steel fencing with sawtooth profile.

5.3.1.14 Experiment 14 – structural exposure of COLORBOND steel fencing with sawtooth roll formed profile infill sheets

After conducting this experiment, it was realised that larger burner nozzles had been used, producing a fire intensity approximately twice the required rate. A post-mortem of the installed fencing revealed it had been constructed with fewer screws than normally specified. For this reason, this experiment was repeated as Experiment 17.

The immersion burner stage was turned on at the start of the experiment, and after 0:10 a significant amount of smoke was being emitted from the inside of panels A, B, C, and D. At 0:40 flames began licking under panel B. At 1:20 the intersections of panels A–B and B–C began to come apart, and flames licked between them. By 1:50 this separation had become much more severe. At 4:00 panels A and B began to lean backwards away from the burners and at 5:20 panel B collapsed back at a 45° angle, with flames extending 3 m diagonally across the yard. At this time all the plastic play equipment had already melted and the molten seat and chair had ignited. At 7:00 the molten plastic pool ignited. At 8:00 the burners were turned off and the experiment ceased due to the observed collapse (see Figure 18).

Figure 18. Experiment 14 – structural exposure of COLORBOND steel fencing with sawtooth profile.

5.3.1.15 Experiment 15 – flame immersion exposure of 1.5 m high COLORBOND steel fencing with sawtooth roll formed profile infill sheets

No leaf litter was distributed around the fencing for this experiment. The pre-radiation burner stage was turned on at the start of the experiment. At around 5:00 panels B and C began to emit smoke. At 6:00 flames from the pre-radiation burners began leaning more towards the fencing and the smoke emission increased. The flame immersion burners were turned on at 7:00, and flames from the burner were observed to roll over the top of the fencing more than for the taller fencing. Flame immersion burners were turned off at 7:30 and the fencing ceased smoking at 8:30. The pre-radiation stage burners were turned of at 9:30.

There was no structural damage to the fencing, however the coatings on both sides of panels A, B, C and D was scorched and crazed. There was no damage to the simulated residential structure or plastic play equipment (see Figure 19).

Figure 19. Experiment 15 – flame immersion exposure of traditional 1.5 m high COLORBOND steel fencing.

5.3.1.16 Experiment 16 – flame immersion exposure of 1.5 m high COLORBOND steel fencing with sawtooth roll formed profile infill sheets with 300 mm steel lattice on top

This experiment showed similar results to Experiment 15, except flames did not roll over the top of the fencing as much. Panels B and C began to emit smoke at 5:00 during exposure to the pre-radiation burners. The immersion burners were turned on at 7:00 and flames were observed to intermittently lick under the fencing. The flame immersion burners were turned off at 7:30 and the panels continued to smoke for about one minute. At 9:30 the pre-radiation burners were turned off and the experiment was ceased.

The damage was similar to that for Experiment 15, with only scorching and crazing of the COLORBOND coating (see Figure 20).

Figure 20. Experiment 16 – flame immersion exposure of 1.5 m high COLORBOND steel fencing with lattice top.

5.3.1.17 Experiment 17 – structural exposure of COLORBOND steel fencing with sawtooth roll formed profile infill sheets

The flame immersion burners were turned on at the start of the experiment, with flames impinging on panels A, B, C and D. The rear of these panels began emitting smoke from this time. After the first minute of exposure the panels had slightly buckled at the joints between panels A–B, B–C and C–D, with small flames licking through the openings. However, the fencing remained standing and did not sustain any further structural damage throughout the exposure. The flame immersion burners were turned off at 30:00. There was no damage to the simulated residential building, but there was some damage to the plastic chair and toy trailer (see Figure 21).

Figure 21. Experiment 17 – structural exposure of COLORBOND steel fencing with sawtooth profile.

5.3.1.18 Experiment 18 – leaf litter exposure of closed paling hardwood fencing

At 2:00 smoke from smouldering leaf litter was evident, but no flaming of the timber could be observed. At 2:30 small flames from the leaf litter at the inside fencing corner were observed, but with limited involvement of the hardwood. The flames extended from the base to 0.5 m high. By 4:00 the flaming had extinguished with smouldering of corner and post continuing (see Figure 22), and by 10:00 smouldering had ceased. There was no significant damage to the fencing except for minor charring at the base of the corner.

Figure 22. Experiment 18 – leaf litter ignition of closed paling hardwood fencing.

5.3.1.19 Experiment 19 – pre-radiation exposure of closed paling hardwood fencing

At the start of the experiment, a small amount of smoke was still being produced by the smouldering leaf litter from the previous experiment. More leaf litter was distributed and ignited along panels D, E, F and G. Leaf litter was also ignited along panels A, B and C. At 1:50 the pre-radiation burners were turned on. By 8:00 the pre-radiation burners were at their peak, and leaf litter and fencing timber on the outside of the corner started flaming, extending above the top of the fencing. At 9:30 flames from the pre-radiation burners were reduced and the flames at the corner decreased. By 10:00 a lot of smoke was coming from the corner, but there were no visible flames. The pre-radiation burners are turned off at 11:00 and the corner continued smoking. By 18:00 there were flames visible at the base of the corner on the inside, and by 25:00 these flames have grown to extend to the mid-height of the fencing. By 38:00 the flames reached the top of the fencing and had spread very slowly laterally from the corner along panel C. By 45:00 the palings had burnt out in the corner, extending halfway along panel C. From this point, the flames decayed with no further significant spread until all flaming ceased at 70:00 and the experiment was ceased. There was no resulting damage to the simulated residential building or the play equipment. There was no collapse of the fencing, but flaming had led to the consumption of all palings in the corner intersection of panel C and D, extending half way along panel C (see Figure 23).

Figure 23. Experiment 19 – leaf litter and pre-radiation exposure of closed paling hardwood fencing.

5.3.1.20 Experiment 20 – flame immersion exposure of closed paling hardwood fencing

After igniting pilots for the bushfire flame front simulator, the igniter operator proceeded to ignite leaf litter along both sides of fencing panels D to H. No leaf litter was ignited along panels A to C. At 1:20 the pre-radiation burner stage was turned on. At this time smoking of leaf litter along panels D to H was observed, with no involvement of the fencing timber. The front of fencing panels A, B and C had begun to lightly smoke. By 7:00 there was still no involvement of the fencing timber. At 8:30 the flame immersion burner stage was turned on and the rear of panels A, B and C began to produce a significant amount of smoke, with surface flaming at the front where the burners impinged. At 8:54 the immersion burners were turned off. Panels A, B and C continued to produce significant smoke. At 11:30 the pre-radiation burners were turned off while panels A, B and C continued to smoke. However, by 15:00 the rate of smoke production had significantly reduced and at 20:00 the experiment was ceased.

There was no significant resulting damage to the fencing except for scorching of the outside of panels A, B and C (see Figure 24). No significant flaming had been sustained. There was no damage to the simulated residential building, plastic play equipment or chair.

Figure 24. Experiment 20 – flame immersion exposure of closed paling hardwood fencing.

5.3.1.21 Experiment 21 – flame immersion exposure of closed paling treated pine fencing

Leaf litter was ignited along fencing panels D to H, as for experiment 20. At 1:32 the pre-radiation burner stage was turned on. By 3:40 there was smoke from smouldering leaf litter and treated pine along the length of panels D to H. At 5:30 flaming of the fencing timber was observed at the outside of the corner at panels C and D, and by 6:00 the flames extended to the top of the fencing. By 7:00 flames began spreading laterally along the outside of panels C and D from the corner, and by 7:40 flaming extended along the entire outside of panel C and halfway along the outside of panel D. At 8:30 the flame immersion stage burners were turned on, with flames 4–5 m high leaning towards the fencing. The outside of panels B and C instantly became involved in flame. At 9:00 the immersion burners were turned off, but were still bleeding from supply lines. At this time most palings on panel C had been consumed, leaving a large hole. However, most of the panel D palings were still intact. The outside of panel B was still flaming at mid-rail height. At 10:00 flaming was observed at the intersection of panels D–E and E–F, and panels B and C were flaming on both sides. By 11:00 flames at the intersection of panels D–E and E–F extended to the top of the fencing. At 11:10 the pre-radiation burners were turned off and panels B and C continued flaming. By 12:00 the majority of the palings in panels B and C were burnt through with charred rails and posts still standing, and most of panel D was involved in flame (see Figure 25). By 14:00 flaming of panels A, B and C had ceased, but flaming at other points on the fencing continued. At 15:40 panel D collapsed and the paling at the intersections of panels D–E and E–F had been consumed. At 18:30 panel E collapsed. At 26:00 panel F collapsed. At this stage panels G and H adjacent to the window were flaming. At 34:00 panel G collapsed outwards away from the simulated building. Panel H continued flaming and collapsed onto the simulated building at 47:00. At 49:00 the window that the burning fencing was leaning against broke. This appeared to be due to thermal stress as burning timber was in direct contact with the window. At 60:00 the remaining smouldering material was suppressed and the experiment was stopped.

Figure 25. Experiment 21 – flame immersion exposure of closed paling treated pine fencing.

All of the fencing panels except for half of panel A were consumed. Damage to the residential objects consisted of the chair being completely melted down but not consumed, the toy trailer had melted down to 20% of its original height, and the front edge of plastic wading shell had strands of plastic drooping but no significant damage.

5.3.1.22 Experiment 22 – structural exposure of closed paling hardwood fencing

The immersion stage burners were turned on at the start of this experiment. Flames immediately impinged on the outside surfaces of panels B and C, with flames penetrating through the palings and emerging from the rear of the panels (see Figure 26). After 30 seconds of this exposure the rear of panels B and C began producing significant amounts of smoke. The burner flames leaned towards the fencing and impinged on most of the outside of panel D due to the prevailing wind. At 2:20 mast 1 on the grid softened and fell over due to the high temperatures. By 4:00 the majority of the rear of panels B and C were involved in flame.

Figure 26. Experiment 22 – structural exposure of closed paling hardwood fencing.

By 6:00 many gaps started to appear in panels B and C as palings were consumed. At this stage all the plastic play equipment had melted and there were flames on the inside of panel D. By 8:00 all the palings on panels B, C and D had been consumed with charred posts and rails still remaining, and at 8:50 panel A collapsed. At 9:40 the remains of panel D collapsed. The edge of panel E ignited at 11:30 and by 20:00 half the palings on panel E had been consumed. After this there was no significant flame spread. At 30:00 the burners are turned off. Panels A, B, C and D and half of panel E were destroyed. All plastic play equipment was destroyed. There was no damage to the simulated residential building.

5.3.1.23 Experiment 23 – leaf litter exposure of capped open paling treated pine fencing

Small flames were observed to grow on the leaf litter at the inside fencing corner and spread to treated pine palings from the time of ignition. By 5:00 flames extended to a height of 1 m and penetrated through the corner palings, burning both sides of the fencing, depending on wind gusts. Limited smouldering was also observed at other posts. At 7:00 flames at the corner reached the top of the fencing. Flames were also observed on the outside at the intersection of panels D and E, which penetrated through palings. Smouldering also occurred at the base of the end of the fencing (panel G). By 10:00 flames at the intersection of panels D and E extended to the top of the fencing on both sides. The corner was still burning. By 17:00 flames were observed at the mid-height rail on panels A and B. At 21:00 panel D collapsed (see Figure 27).

Flaming continued slowly at the edges of panels E and C with no significant further lateral flame spread. After a further hour there had been no significant further flame spread and the experiment was ceased.

Figure 27. Experiment 23 – leaf litter exposure of capped open paling treated pine fencing.

5.3.2 Experimental observations by fence type

5.3.2.1 Performance of COLORBOND steel fencing systems

COLORBOND steel fencing was not tested under leaf litter exposure as it was assumed that a non-combustible material would not exhibit flame spread properties.

Pre-radiation exposures of COLORBOND steel fencing resulted in no apparent structural damage. In some cases, there was minor scorching and crazing of the steel surface coatings. The measured heat fluxes for Experiment 12, a typical COLORBOND steel pre-radiation experiment, are shown in Figure 28.

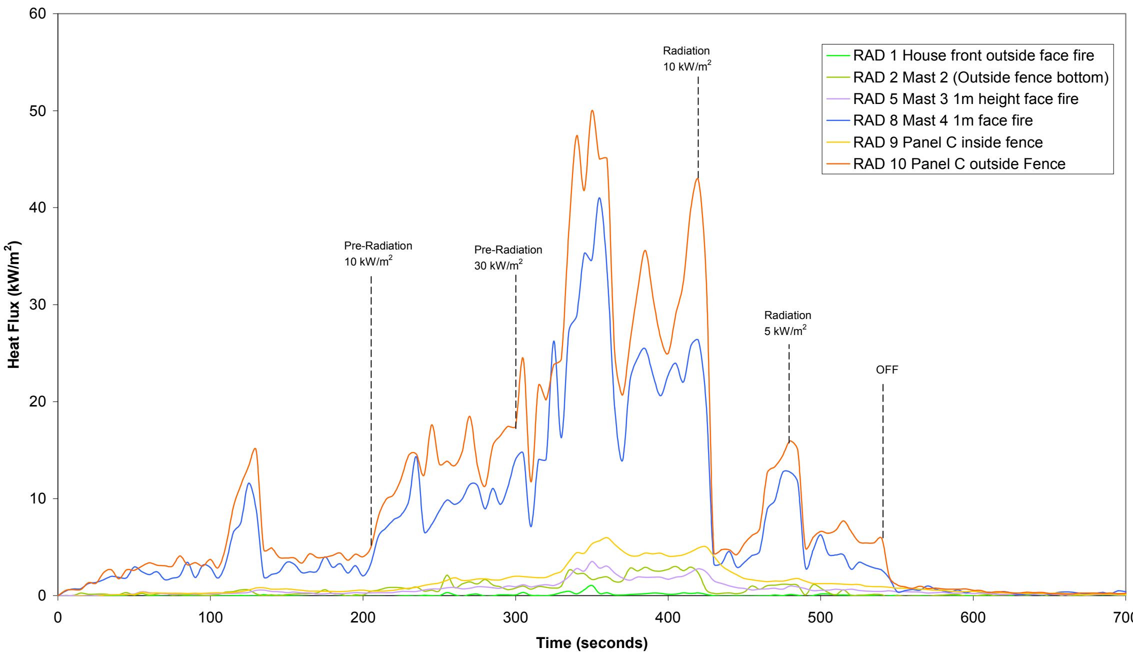

Figure 28. Experiment 12 – heat flux measurements for pre-radiation exposure of COLORBOND steel fencing.

Figure 28 demonstrates the typically good performance of COLORBOND steel fencing as a radiant heat barrier under pre-radiation exposure. At fencing panel C, which was directly exposed, the peak heat flux on the front face of the fencing was 63 kW/m^2, whilst at the back face it was 4 kW/m^2. At 1 m back from the burner grid the peak heat flux at radiometer (RAD) 8 outside the fencing was 41 kW/m^2, whilst inside the fencing at RAD 5 it was 3.5 kW/m^2. At a distance of 9.4 m from the burner grid (near the simulated building) the peak heat flux at RAD 2 outside the fencing was 3 kW/m^2, whilst at RAD 1 inside the fencing it was 1 kW/m^2. The critical heat flux for ignition of many typical combustible elements is >20 kW/m^2. In all pre-radiation experiments the COLORBOND succeeded as a radiation barrier, maintaining heat flux levels within the fencing boundary below 20 kW/m^2 at all times.

Flame immersion experiments on COLORBOND steel fencing resulted in no major structural fencing failure. However, in all cases there was slight buckling and separation of the joints of panels and posts. There was also severe scorching and crazing of the surface coatings on both sides of panels exposed to direct flame contact. The measured heat fluxes for Experiment 13, a typical COLORBOND steel fencing flame immersion experiment are shown in Figure 29.

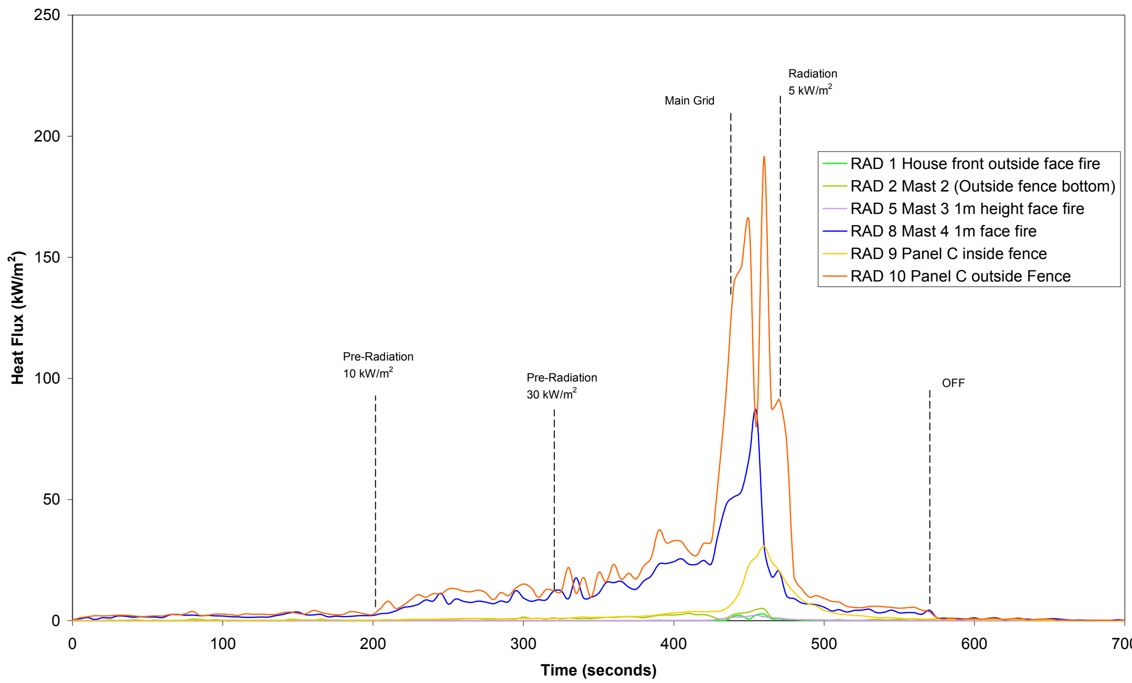

Figure 29. Experiment 13 – heat flux measurements for flame immersion exposure of COLORBOND steel fencing.

Figure 29 demonstrates the typically good performance of COLORBOND steel fencing as a radiant heat barrier under flame immersion exposure. At panel C, the front face of the fencing was immersed in flames resulting in a peak heat flux well in excess of the heat flux meters' accuracy limit of 100 kW/m^2, whilst at the back face the peak heat flux measured was 31 kW/m^2. At a distance of 1 m back from the burner grid the peak heat flux at RAD 8 outside the fencing was also in excess of the accuracy limit of 100 kW/m^2, whilst inside the fencing at RAD 5 it was 21 kW/m^2. At a distance of 9.4 m from the burner grid (near the simulated building) the peak heat flux at RAD 2 outside the fencing was 5 kW/m^2, whilst RAD 1 inside the fencing it was 3 kW/m^2. The burner flames were higher than the fencing and some limited flames penetrated under fencing and through separated joints, and thus objects inside the fencing received radiant heat directly from flames. However, the view factor in which the object saw of the flames was significantly reduced by the fencing. The fencing also shielded against direct flame contact and convective heat. Although heat fluxes inside the fencing exceeded 20 kW/m^2, the likelihood of ignition was significantly reduced by the fencing and there was no damage or ignition of the play equipment or simulated building.

Structural fire exposure experiments on COLORBOND steel fencing showed similar results to the flame immersion exposures, except for Experiment 14 where panels B and C failed structurally. This isolated failure was due to below standard construction using less than the recommended screws, and the use of larger than standard burner nozzles producing a more intense fire. This result highlights the importance of quality of construction on the performance of fencing systems. For all other experiments there was only slight separation at fencing panel joints and surface coating damage. The measured heat fluxes for Experiment 17, a typical COLORBOND steel fencing structural fire exposure experiment, are shown in Figure 30.

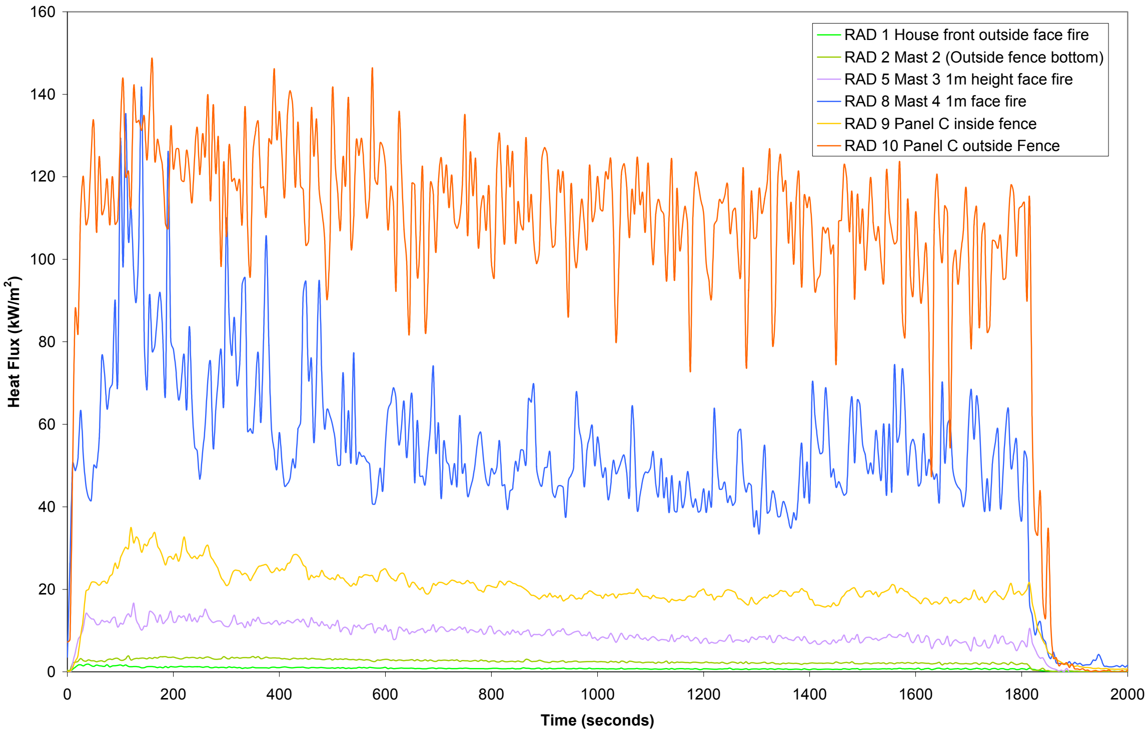

Figure 30. Experiment 17 – heat flux measurements for structural fire exposures of COLORBOND steel fencing.

Figure 30 demonstrates the typically good performance of COLORBOND steel fencing as a heat barrier under structural fire exposure. Fencing front face heat flux was not measured to avoid damage to instruments from prolonged flame immersion. However, the peak heat flux at the back face was 35 kW/m^2. At a distance of 1 m back from the burner grid, the peak heat flux at RAD 8 outside the fencing was in excess of the measurement range of 100 kW/m^2, whilst inside the fencing at RAD 5 it was 17 kW/m^2. At a distance of 9.4 m from the burner grid (near the simulated building) the peak heat flux at RAD 2 outside the fencing was 4 kW/m^2, whilst at RAD 1 inside the fencing it was 2 kW/m^2. As the heat exposure was prolonged there was some melting of the play equipment in these exposures. However, there was no ignition of the plastic (except for Experiment 14 due to poor fencing construction) and there was no damage to the simulated building. Thus, the fencing significantly reduced the likelihood of fire spread and asset damage within the fencing boundary.

5.3.2.2 Performance of hardwood fencing systems

Leaf litter exposure experiments on hardwood fencing demonstrated that isolated hardwood fencing was unlikely to become significantly involved, spread flame laterally or fail as a barrier. Any limited combustion ceased shortly after the ignited leaf litter had burnt out.

Pre-radiation exposures on hardwood fencing demonstrated that burning leaf litter combined with pre-radiation is more likely to spread to involve the hardwood, but lateral spread along the fencing is unlikely. In one case only charring of the outside of the fencing resulted. However, in another experiment (Experiment 19) the hardwood at the intersection of panels C and D became involved, with flames reaching the top of the fencing with very little lateral flame spread prior to burning out. The measured heat fluxes for Experiment 19 are shown in Figure 31.

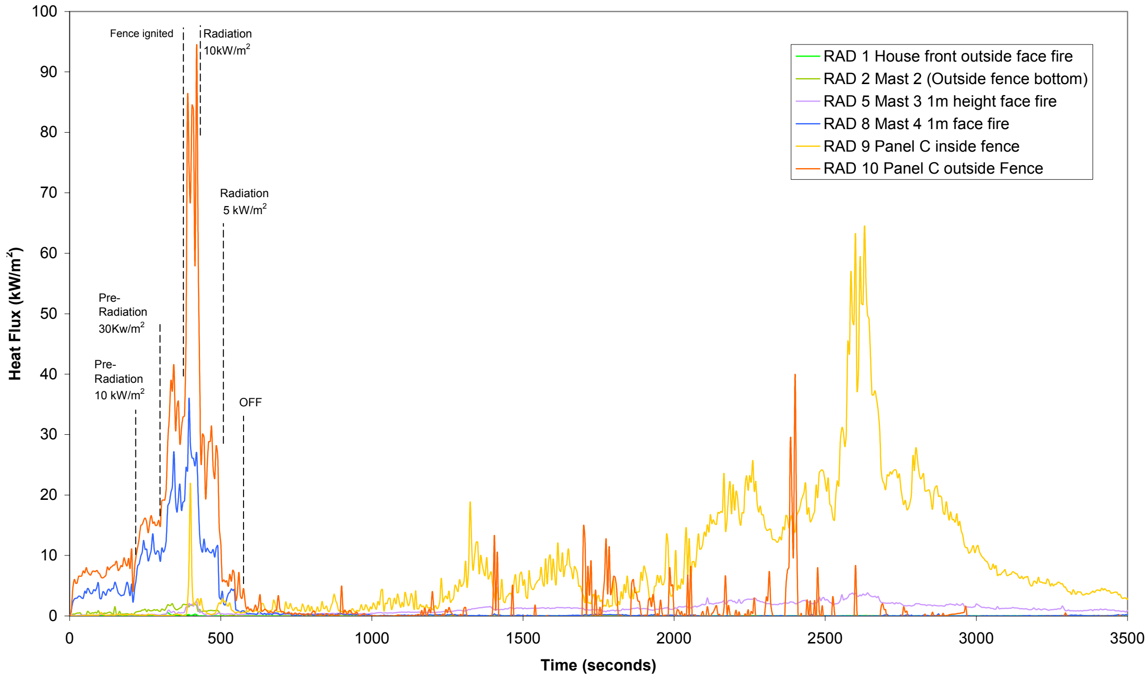

Figure 31. Experiment 19 – heat flux measurements for pre-radiation exposure of closed paling hardwood fencing.

Figure 31 demonstrates the performance of hardwood fencing as a heat barrier under pre-radiation exposure. During the burner exposure the fencing front face peak heat flux was 95 kW/m^2, whilst at the back face it was 22 kW/m^2. However, after the burners were turned off the fire at the corner grew and a peak of 65 kW/m^2 was measured at the back face. At a distance of 1 m back from the burner grid the peak heat flux at RAD 8 was 36 kW/m^2, whilst inside the fencing at RAD 5 it was 3.8 kW/m^2. Similar observations were made in Experiment 6 where the open paling fencing showed a similar level of performance. At a distance of 9.4 m from the burner grid (near the simulated building) the peak heat flux at RAD 2 outside the fencing was 2.1 kW/m^2, whilst at RAD 1 inside the fencing it was 0.5 kW/m^2. There was no damage to objects within the fencing boundary. This demonstrates that under pre-radiation exposure a hardwood fencing performs well as a heat barrier, with some risk of flame propagation to elements immediately adjacent to the fencing boundary.

Flame immersion exposure of a hardwood fencing also demonstrated its good performance as a heat barrier. The outside surface of the hardwood was observed to catch fire during the burner immersion. However, after the immersion burners were turned off the majority of flames on the fencing rapidly ceased. There was only charring of the external surface and small holes burning through at some points, without further flame spread. The measured heat fluxes for bushfire flame immersion experiment 20 are shown in Figure 32.

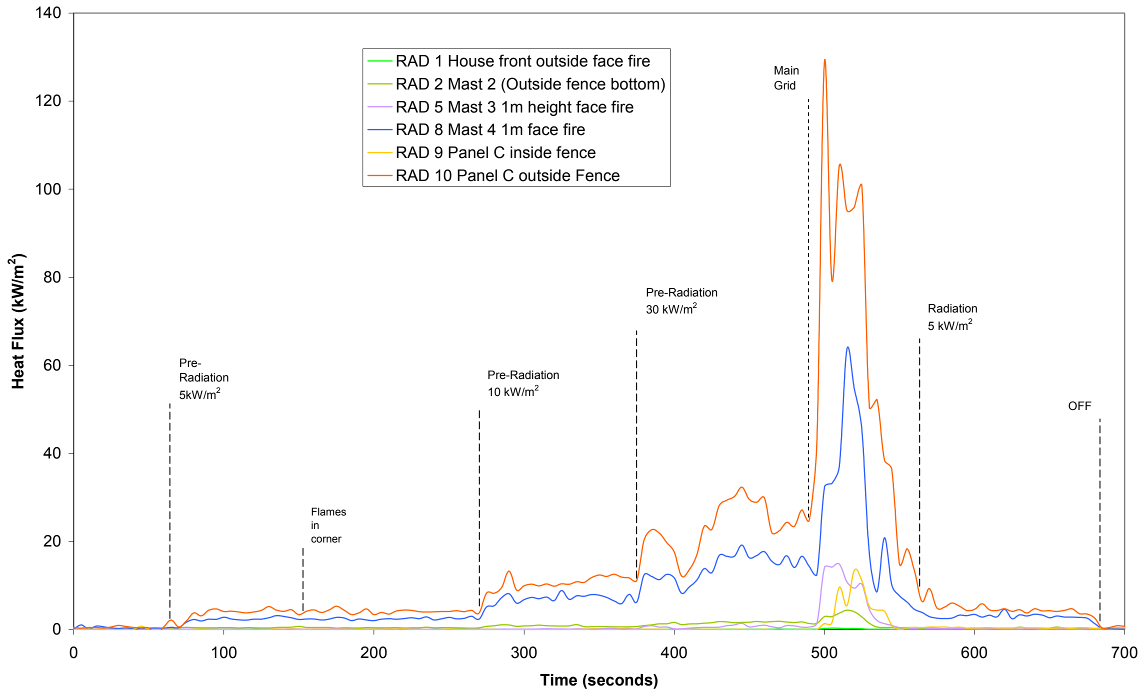

Figure 32. Experiment 20 – heat flux measurements for flame immersion exposure of closed paling hardwood fencing.

Figure 32 demonstrates that with flame at the outside of the fencing, the peak heat flux at the rear face of the fencing was 13 kW/m^2. There was no damage to play equipment or the simulated building and no lateral flame spread, indicating that hardwood fencing will reduce the likelihood of fire spread into the fencing boundary given a flame immersion exposure. In contrast, open paling hardwood fencing provided little barrier during the flame immersion phase of the exposure, and flames were observed to flow through the fencing structure, providing extreme radiation and flame contact to the play equipment and instrumentation immediately behind the fencing. Once the flame and radiation abated in Experiment 7, flame propagation was again observed to cease. Figure 33 shows the lack of flame attenuation exhibited by open paling fencing systems, with RAD 9 tracking closely to the incident radiation, with radiation measured 1 m within the fencing boundary reaching 50 kW/m^2.

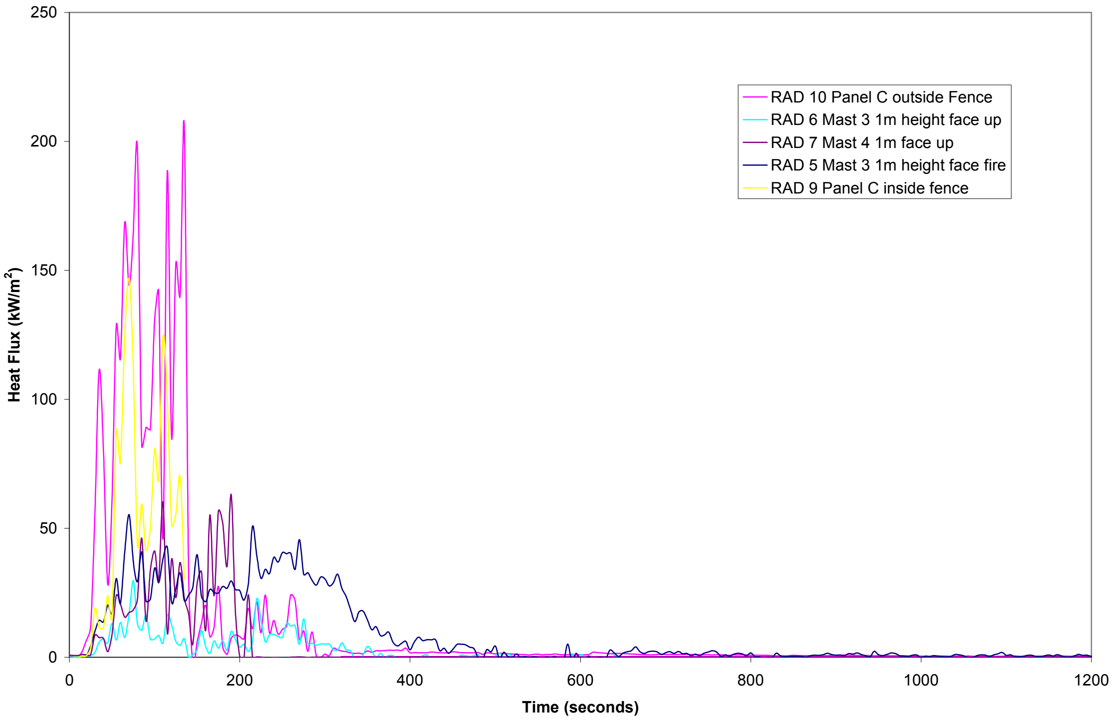

Figure 33. Experiment 7 – heat flux measurements for flame immersion exposure of capped open paling hardwood fencing.

Structural fire exposure of hardwood fencing resulted in loss of the fencing where directly immersed in burner flames. The measured heat fluxes for a typical structural fire experiment (Experiment 22) are shown in Figure 34.

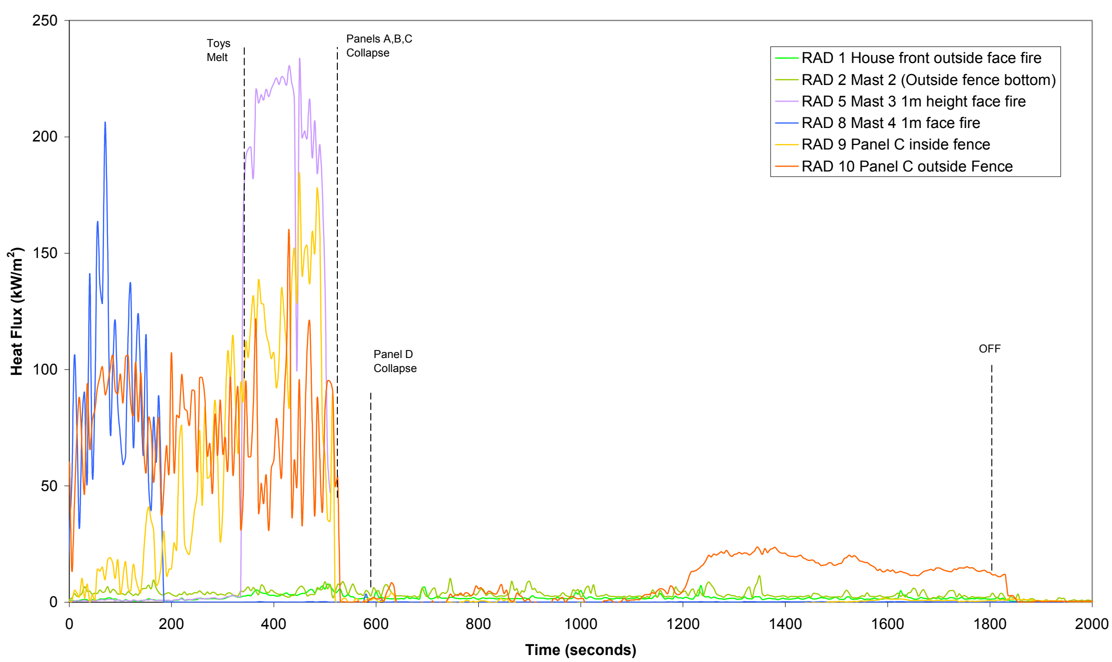

Figure 34. Experiment 22 – heat flux measurements for structural fire exposure of closed paling hardwood fencing.

Figure 34 shows that the hardwood fencing initially performed as a heat barrier. However, due to the prolonged external flame exposure, palings started to burn through at 5:30. At that time, the heat flux 1 m behind the fencing rapidly increased from 4 kW/m^2 to >100 kW/m^2, resulting in melting and ignition of the play equipment. In all cases, the heat flux at the simulated building did not exceed 8 kW/m^2, resulting in no damage to the building. Over the 30-minute burner exposure there was no significant lateral flame spread along the fencing. No observations were made to determine if continued smouldering over a very long period would result in slow lateral spread, however this experiment demonstrated that the risk of hardwood timber fencing wicking fire to other combustibles is low under the defined experimental conditions.

5.3.2.3 Performance of treated pine fencing systems

Leaf litter exposure experiments on closed paling treated pine fencing demonstrated that treated pine is easily ignited by burning leaf litter when compared to hardwood. Once ignited, the treated pine is likely to support slow lateral fire spread via flaming and smouldering. In two cases, the fire wicked along the fencing and reached the simulated building. After 90 minutes, the flaming fencing eventually collapsed onto the building, breaking a window. This demonstrated how a treated pine fencing is likely to wick fire to other combustible elements if left unattended after leaf litter fire exposure. Under these exposures, virtually all of the timber material was eventually consumed.

A pre-radiation exposure experiment on closed paling treated pine fencing demonstrated how the likelihood of treated pine ignition and lateral flame spread is increased with the presence of external radiant heat. The treated pine fencing maintained integrity, acting as a heat barrier during the burner exposure. However, after the burners were turned off, fire continued to slowly spread laterally along the fencing, eventually reaching the simulated building. The flaming fencing collapsing onto the building, once again causing window failure. The measured heat fluxes for Experiment 9, the pre-radiation experiment on closed paling treated pine fence, are shown in Figure 35.

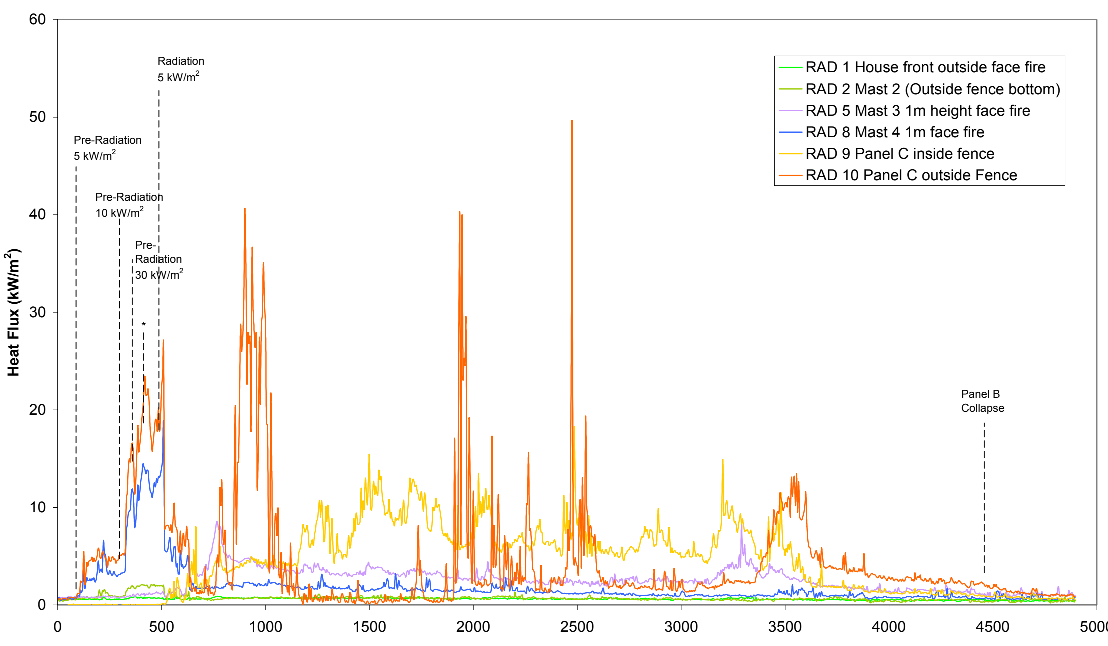

Figure 35. Experiment 9 – heat flux measurements for pre-radiation exposure of closed paling treated pine fencing.

Although the resulting heat fluxes at the inside of the fencing boundary were not extremely high, the collapse of the burning fencing as the fire spread along it, increased the likelihood of fire spread to other combustible items. Various instruments showed the sporadic peaks and localised flame intensity following the radiation exposure. Under these exposures virtually all of the timber would eventually be consumed.

Flame immersion exposures of closed paling treated pine fencing demonstrated that it failed as a heat barrier under this scenario. In all experiments, the entire face of the exposed fencing ignited when exposed to flame immersion, with the majority of the palings burning through during the flame immersion period, unlike the hardwood which did not significantly burn through. The treated pine slowly wicked fire along the fencing after the flame immersion burners were turned off. The measured heat fluxes for Experiment 21, a flame immersion experiment on closed paling treated pine fencing, are shown in Figure 36.

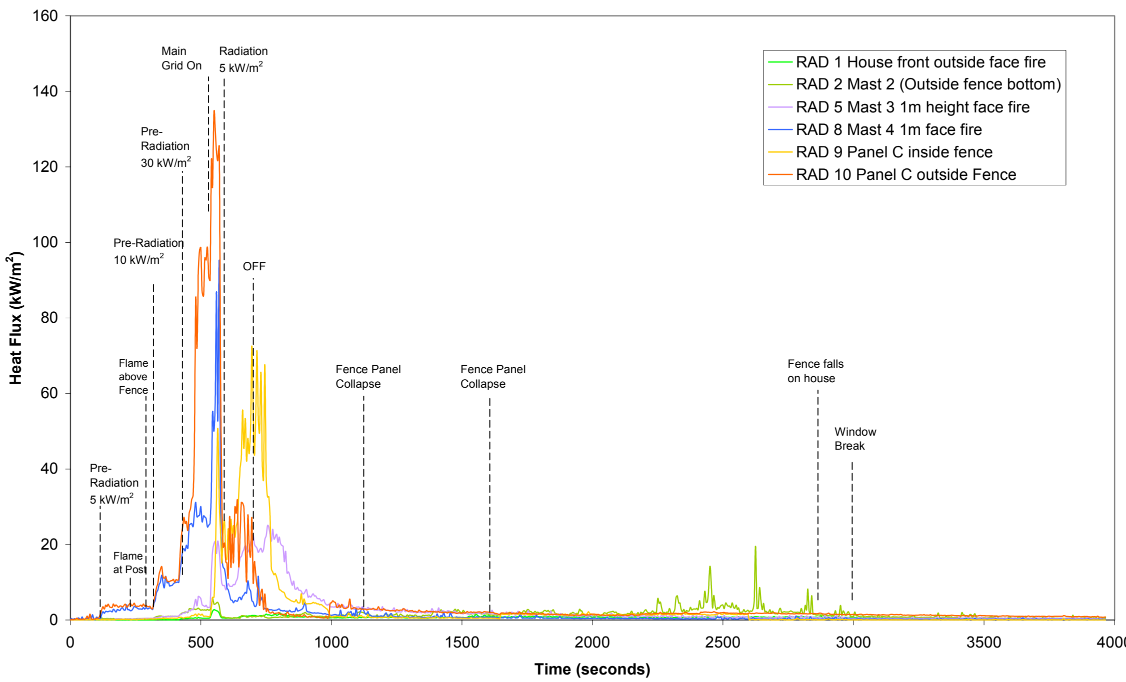

Figure 36. Experiment 22 – heat flux measurements for flame immersion exposure of closed paling treated pine fencing.

Figure 36 demonstrates that once the palings burnt through, heat flux at the rear face of the fencing increased to >60 kw/m^2 and the heat flux 1 m behind the fencing increased to 25 kW/m^2. This demonstrated a high likelihood of fire spread into the fencing boundary. Of particular note also is the incident radiation imposed in the house front face at around 2500 seconds, which provided compelling experimental evidence of the thermal exposure provided by fencing combustion in close proximity to a structure (note that plain glass windows are likely to break at radiation levels >12.5 kW/m^2).

Capped open paling treated pine fencing showed no improvement in performance, exhibiting an even lower barrier to the initial radiation load. Figure 37 shows examples of this where RADs 5 and 6 experienced full flame immersion during the flame exposure period.

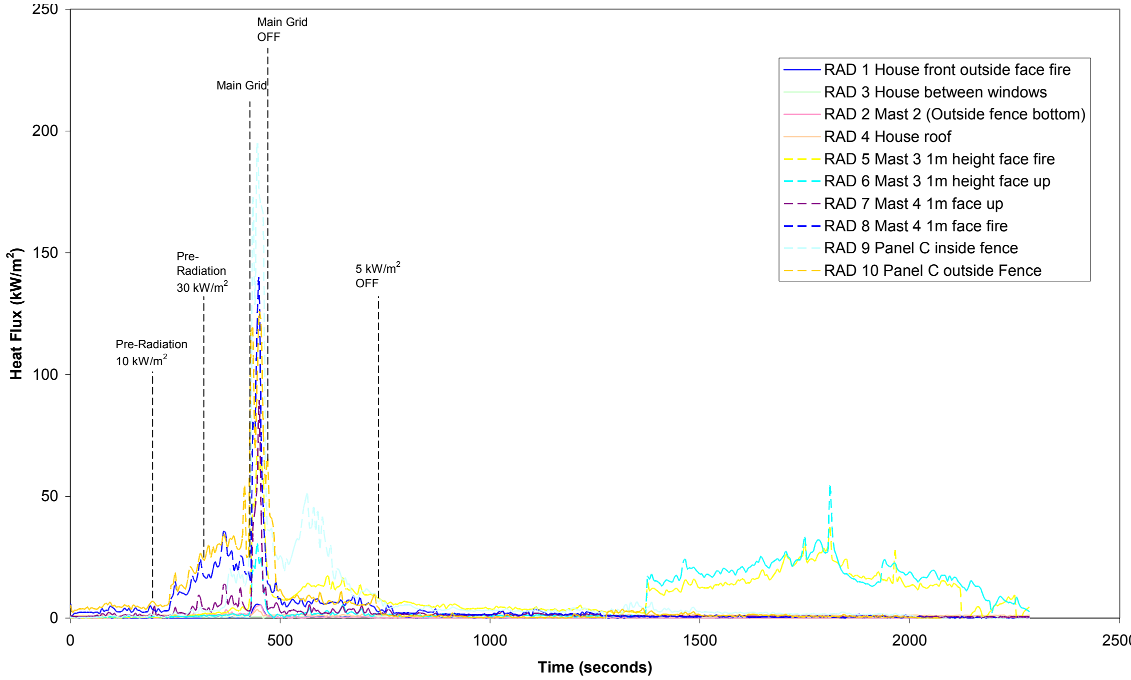

Figure 37. Experiment 10 – heat flux measurements for flame immersion exposure of capped open paling treated pine fencing.

5.4 Influence of specific COLORBOND steel fencing features

5.4.1 Radiation attenuation of different COLORBOND steel panel colours

Specific COLORBOND steel panel colours were used in different exposures in an attempt to ascertain whether colour makes a significant difference to the radiant heat transfer through the fencing system. This is best quantified by the ratio of heat received immediately behind the panel compared to the heat impacting on the panel. For the purpose of discussion, we will call this the radiation attenuation ratio. Two specific experiments were performed using two off white infill sheets; other infill sheets were dark blue. Any correlation between the emissivity of the paint system and its radiation attenuation ratio would have been observed in these experiment comparisons. Table 4 shows the average radiation attenuation ratio for each experimental exposure.

Table 4. Radiation attenuation ratio versus panel colour

Experiment	Panel colour	Average radiation attenuation ratio
3	Off-white	22
4	Off-white	13
11	Dark blue	9
12	Dark blue	8
13	Dark blue	10
15	Dark blue	7
16	Dark blue	7

Although variable, the data shows some correlation between the average radiation attenuation ratio and panel colour. Observing the radiation attenuation ratio as it varies throughout the experiment also revealed that the ratio drops to about 5 after the panels experience direct flame contact, independent of the original colour of the panel. Figures 38 and 39 demonstrate this effect and also show the variability of the radiation attenuation ratio itself. Much of this variation was due to the transitory nature of the incident flame and the thermal mass effect of the fencing panels.

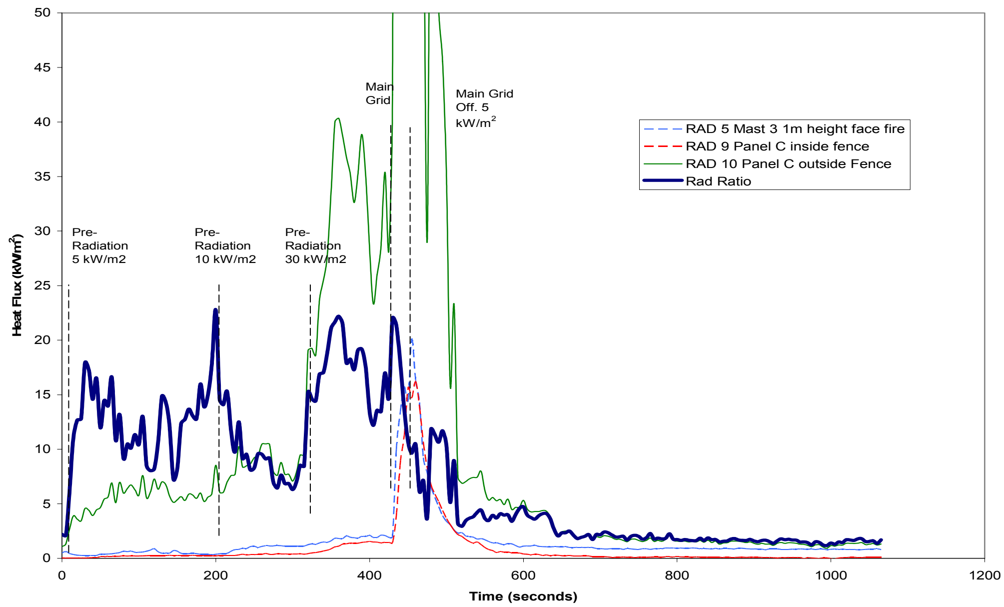

Figure 38. Experiment 4 – radiation attenuation ratio of off-white infill sheets.

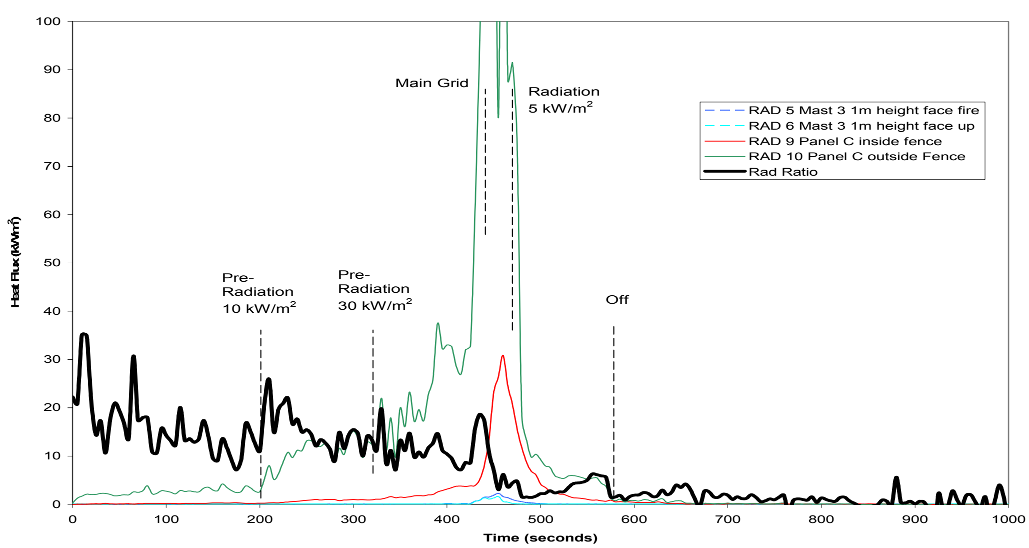

Figure 39. Experiment 13 – radiation attenuation ratio of dark blue infill sheets.

5.4.2 Influence of fencing height on radiation transfer

Fencing configurations were also setup to assess the specific influence of fencing height on the radiation levels experienced behind the fencing. Much of the fundamental understanding of this effect can be easily modelled, especially with the knowledge gleaned in Section 5.4.1 of the specific back-face re-radiation that occurred in the full-scale experiments. Experimental justification for the specific benefits of higher fencing was difficult to determine, as the radiation levels 1 m behind the fencing and at the location of the structure were so low during the radiation exposure phase that experimental comparison was not possible.

6 CONCLUSIONS

6.1 Air toxic conclusions

The cone calorimeter experiments provided a comparative indication of the fire release of the air contaminants measured. This experimental method alone does not assess the fire hazard of the materials, or products made from them, under actual fire conditions. **Consequently, the results of these experiments should not be quoted in support of claims with respect to the fire hazard of the materials, or products made from these materials, under actual fire conditions.** The results, when used alone, should only be used for research and development, quality assurance or similar industrial needs. A more rigorous program of toxic species measurement would have been more time consuming and expensive, and was beyond the scope of this investigation. Within these constraints, it has been determined that the combustion of both materials released measurable levels of contaminants, as follows:

- The major air toxics released during the combustion of both sampling materials were benzene and formaldehyde – both human carcinogens.
- COLORBOND steel fencing material released higher levels of benzene, but lower levels of aldehydes than CCA-treated pine.
- The only aldehydes emitted at levels above the detection limit were formaldehyde for both materials, and acetaldehyde for CCA-treated pine.
- The major issue related to the combustion of CCA-treated pine is the release of significant levels of arsenic, as well as the high arsenic content in the timber ash (2.2% by weight). Arsenic can cause eye, throat and respiratory irritation, and is a confirmed human carcinogen. Note, that the National Environmental Protection Measure (NEPM) (http://www.ephc.gov.au/nepms/air/air_toxics.html , refer to NEPC 1999) provides health-impact criteria for arsenic in soils in the range of 0.01–0.05%, and so the dispersion of CCA-treated pine ash could lead to site contamination, especially where large quantities of the material has been burnt.

Two human carcinogens (benzene and formaldehyde) were detected in the air toxicity experiments conducted on COLORBOND steel. Note that, while these gases were detected, the risks they present would depend on the levels of exposure to nearby occupants, which is unknown. In fact, evaluating risks from these gases will depend on the combustion conditions, the quantity of material burnt, the volume of combustion gases generated and its dispersion, and the degree to which site occupants are exposed to the gases. These will vary for each specific situation, and it is not possible to predict levels of these gases in real situations from cone calorimeter measurements.

For real fires in Australia, there are exposure standards that are relevant. In the proposed NEPM for benzene, which aims at protecting the health of the general population, the 24-hour average monitoring investigation level is 0.003 ppm. The monitoring investigation levels represent 'levels of air pollution below which lifetime exposure, or exposure for a given averaging time, does not constitute a significant health risk'.

There are also exposure standards o hat assess atmospheric contaminants in the occupational environment (http://www.nohsc.gov.au/OHSInformation/Databases/ExposureStandards/ExposureStandards4AtmosphericContaminants.pdf). The Worksafe occupational exposure standard for benzene is an 8-hour average of 0.5 ppm. These standards apply to workplace situations only and would not be applicable for assessing fire fighters' exposure. However, it is clearly stated that these exposure standards should not be applied in the control of community air pollution.

More extensive experiments could be conducted under full-scale fencing and bushfire conditions for a quantitative risk assessment of:

- The toxic gases released during combustion of these fencing materials.
- The impact of air emissions of arsenic.
- The exposure of site occupants (whether fire agency or general public) to arsenic from the ash from CCA-treated pine.
- The contamination of building sites from arsenic.

6.2 Small-scale experiments

This experimental investigation confirmed that COLORBOND steel fencing panels do not ignite and contribute significant heat release during the cone calorimeter exposure. Both pine and hardwood materials provide significant heat release during these exposures. The ranking of performance of these materials in descending order are: COLORBOND steel (insignificant heat release0, new hardwood, old hardwood, old pine and new pine.

Of particular interest was the effect moisture content had on the time to ignition for all these materials. In particular, the observation that a material exposed for six hours to 40°C and 20% RH had similar fire properties to the same material when conditioned at the same conditions until moisture equilibrium was achieved. This highlights a significant point that the fire behaviour of these specimens was influenced more by the surface moisture content rather than the average moisture content of the specimens, and hence the weather conditions on the day of fire impact will have a significant effect on the fire performance of timber elements. In all cases, conditioning at 23°C and 50% RH generated longer ignition times.

6.3 Large-scale experiments

- COLORBOND steel: This has the best performance as it is a non-combustible material, it maintained structural integrity as a heat barrier under all experimental exposure conditions, and it did not spread flame laterally or contribute to the fire intensity during exposure. The fencing reduced radiation levels within the fencing boundary to below 5 kW/m^2 immediately behind the fencing system during all radiation exposures, and reduced the radiant heat exposure on a structure 9m from the fencing by at least a factor of two.
- Hardwood: Although combustible, closed paling hardwood fencing maintained a radiant heat barrier during radiation-only exposures, resulting in a greater than three times reduction in radiant heat received at the structure. In exposures where flame contact of the fencing occurred, flame emission from the fencing provided additional radiant heat exposure on the structure. Open paling hardwood fencing systems were effective in attenuating incident radiation when flames did not contact the fencing systems, however they provided little barrier during direct flame contact. Neither fencing configuration supported lateral flame spread to the extent that would expose the structure to direct flame contact. Under structural fire exposure conditions, the fencing quickly burnt away leaving no barrier to the impinging flames.
- Treated pine: This had the worst performance, as its integrity under leaf litter attack resulted in potential for loss of the adjacent structure due to lateral flame spread. Its performance as a heat barrier was good until ignition of the fencing occurred, after which point additional heat impact was received by all elements behind the fencing. Significant risk of house loss occurred during all experimental exposures, either through thermal exposure or mechanical impact as the fencing collapsed onto the structure. Under structural fire exposure conditions, the fencing quickly burnt away leaving no barrier to the impinging flames.

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SUMMARY TABLES

Table 5. Summary cone calorimeter results

Material	Temp., RH	Spec. no.	Expt no.	Ign. time (s)	End of expt (s)	Initial mass (g)	Mass remaining (g)	Ave. mass loss rate (g/m²s)[a]	Total heat evolved (MJ/m²)	Peak HRR (kW/m²)	Time of peak HRR (s)	Average HRR[a]			Ave. EHC (MJ/kg)	Ave. CO (kg/kg)[b]	Ave. CO_2 (kg/kg)[b]
												Over 60 s	Over 180 s	Over 300 s			
New treated pine	23°C, 50%	D6	643cA25	65	625	44.1	9	9.1	60.3	171.5	474	118.3	99.2	94.4	10.8	0.005	0.53
		E2	643cC25	62	630	44.7	7.7	7.3	51.8	156.8	470	100.4	83.5	76.4	12	0.015	0.77
		E7	643cD25	61	645	41.5	10.4	6	41.9	120.8	70	99.6	77	68.2	11.2	0.021	1.10
		mean		62.7	633.3	43.4	9.0	7.5	51.3	149.7	338.0	106.1	86.6	79.7	11.3	0.014	0.80
		stdev		2.1	10.4	1.7	1.4	1.6	9.2	26.1	232.1	10.6	11.4	13.4	0.6	0.008	0.29
	40°C, 20%	C8	643dA25	42	526	36.4	9.3	8.9	38.9	134.2	52	102.5	76.1	75.9	8.4	0.008	0.73
		E3	643dB25	47	525	40	8.3	7.4	45.9	149.3	380	107.8	88.3	88.5	12.3	0.015	1.05
		F6	643dC25	36	600	41.7	10	6.4	50.5	131.5	50	109.6	90.2	84.1	13.7	0.014	1.14
		mean		41.7	550.3	39.4	9.2	7.6	45.1	138.3	160.7	106.6	84.9	82.8	11.5	0.012	0.97
		stdev		5.5	43.0	2.7	0.9	1.3	5.8	9.6	190.0	3.7	7.7	6.4	2.7	0.004	0.22
	20–40°C	D3	643eA25	49	636	43.8	11	8.8	50.8	135.4	60	106.3	81.5	74.7	9.1	0.005	0.66
		C7	643eB25	45	520	37.7	7.7	7.1	43.1	162.1	405	98.6	76.5	77	12.2	0.016	0.92
		E6	643eC25	53	550	41.1	7.7	7.6	50.9	167.8	415	110.5	90.6	88.6	13	0.019	0.95
		mean		49.0	568.7	40.9	8.8	7.8	48.3	155.1	293.3	105.1	82.9	80.1	11.4	0.013	0.84
		stdev		4.0	60.2	3.1	1.9	0.9	4.5	17.3	202.1	6.0	7.1	7.5	2.1	0.007	0.16
Old treated pine	23°C, 50%	OPD8	644bA25	72	660	48.6	12.3	6.9	55.3	156	485	99.8	82.1	78.4	12.8	0.010	1.02
		OPF1	644bB25	59	655	46.8	8.7	7.2	54.3	149.2	490	105.1	85.5	78.2	12.3	0.018	1.07
		OPE5	644bC25	74	695	58.5	13.1	8.3	57.8	156.2	515	94.6	80.1	75.4	10.4	0.006	0.98
		mean		68.3	670.0	51.3	11.4	7.5	55.8	153.8	496.7	99.8	82.6	77.3	11.8	0.011	1.02
		stdev		8.1	21.8	6.3	2.3	0.7	1.8	4.0	16.1	5.3	2.7	1.7	1.3	0.006	0.05
	40°C, 20%	OPF6	644aA25	69	595	47.55	12	7.6	47.9	146.4	435	108.8	86.3	83.1	11.1	0.011	1.02
		OPE8	644aB25	67	705	58.62	16.5	7.4	57.3	134	80	111.9	93.6	86.1	11.3	0.010	1.07
		OPD1	644aC25	61	625	45.37	10.3	7	49.4	151.2	410	102.2	82.2	80.5	12	0.023	1.04
		mean		65.7	641.7	50.5	12.9	7.3	51.5	143.9	308.3	107.6	87.4	83.2	11.5	0.015	1.04
		stdev		4.2	56.9	7.1	3.2	0.3	5.1	8.9	198.1	5.0	5.8	2.8	0.5	0.007	0.03
	20–40°C	OPD5	644cA25	51	555	44.2	10.1	7.6	48	163.4	440	106.3	86.4	82	11.7	0.012	1.00
			644cB25	54	635	46.64	9	7.4	58.7	180.6	420	105.9	85.5	81.3	13.7	0.021	1.07
		OPF3	644cC25	73	615	47.38	13.2	7.1	46.5	132.3	85	108.3	85.2	79.6	11.1	0.010	1.02
		mean		59.3	601.7	46.1	10.8	7.4	51.1	158.8	315.0	106.8	85.7	81.0	12.2	0.014	1.03
		stdev		11.9	41.6	1.7	2.2	0.3	6.7	24.5	199.4	1.3	0.6	1.2	1.4	0.006	0.04

Material	Temp., RH	Spec. no.	Expt no.	Ign. time (s)	End of expt (s)	Initial mass (g)	Mass remaining (g)	Ave. mass loss rate $(g/m^2s)^a$	Total heat evolved (MJ/m^2)	Peak HRR (kW/m^2)	Time of peak HRR (s)	Average HRR[a]			Ave. EHC (MJ/kg)	Ave. CO (kg/kg)[b]	Ave. CO_2 (kg/kg)[b]
												Over 60 s	Over 180 s	Over 300 s			
New hardwood	23°C, 50%	HE13	645bA25	92	955	69	15.9	7	85.6	162.4	105	131.7	109.5	95.9	13.5	0.019	1.01
		HA10	645bB25	166	1000	68.8	12.1	7.6	76	159.9	180	129.1	99	83.5	10.3	0.012	0.94
		HB9	645bC25	127	965	62.2	11.5	6.8	75.6	151.7	140	120.6	94.6	81.2	12.1	0.013	0.81
		HB10	645D25	123	930	64.8	11.4	7.5	76.6	155.8	135	134.1	100.3	85.2	11.5	0.015	0.82
		mean		127.0	962.5	66.2	12.7	7.2	78.5	157.5	140.0	128.9	100.9	86.5	11.9	0.015	0.90
		stdev		30.3	29.0	3.3	2.1	0.4	4.8	4.7	30.8	5.9	6.3	6.5	1.3	0.003	0.10
	40°C, 20%	HB1	645cA25	79	710	57.8	11.9	8.3	68.7	175.7	510	131.4	103.8	94.1	12.1	0.010	1.09
		HC1	645cB25	91	860	66.6	15.3	7.6	79.3	162.7	100	138.8	111.3	96.2	12.6	0.010	1.10
		HA5	645cC25	86	815	60.6	12	7.5	76.3	150.5	100	127.7	111.1	100.8	12.9	0.011	1.10
		mean		85.3	795.0	61.7	13.1	7.8	74.8	163.0	236.7	132.6	108.7	97.0	12.5	0.010	1.10
		stdev		6.0	77.0	4.5	1.9	0.4	5.5	12.6	236.7	5.7	4.3	3.4	0.4	0.001	0.01
	20–40°C	HB4	645dA25	91	845	58.6	10	7.3	72.5	157.8	105	124.6	98.5	85.9	12.6	0.025	1.05
		HB3	645dB25	104	805	59.2	11.4	7.7	67.7	155.8	120	128	96.7	84.6	11.3	0.017	1.02
		HC3	645dC25	100	960	67.9	11.8	7.3	80.1	154.2	115	127.2	102.2	87.7	11.8	0.012	1.03
		mean		98.3	870.0	61.9	11.1	7.4	73.4	155.9	113.3	126.6	99.1	86.1	11.9	0.018	1.03
		stdev		6.7	80.5	5.2	0.9	0.2	6.3	1.8	7.6	1.8	2.8	1.6	0.7	0.007	0.02
Old hardwood	23°C, 50%	OHA1	646aC25	74	915	87.8	22.3	8.7	79.3	199.2	760	103.4	85.4	72.3	9.9	0.014	0.94
		OHC2	646aD25	82	1175	101.9	22.4	8.2	110.8	206.2	860	108	103.2	90.6	12.4	0.031	1.06
		OHC7	646aE25	100	1025	100.7	25.6	9.1	94.1	185.5	850	119.4	108.3	92.3	10.3	0.013	0.91
		mean		85.3	1038.3	96.8	23.4	8.7	94.7	197.0	823.3	110.3	99.0	85.1	10.9	0.019	0.97
		stdev		13.3	130.5	7.8	1.9	0.5	15.8	10.5	55.1	8.2	12.0	11.1	1.3	0.010	0.08
	40°C, 20%	OHC9	646bA25	84	1020	101.02	30.5	8.5	85.2	189.8	850	124.2	104.1	86	9.9	0.017	0.91
		OHA5	646bB25	54	940	84.64	23.8	7.8	79.8	162.7	690	115.6	92.7	79.3	11.2	0.012	0.96
		OHC10	646bC25	73	1045	102.6	29.5	8.7	96	206.7	805	125.8	112.5	95.3	10.9	0.016	0.94
		mean		70.3	1001.7	96.1	27.9	8.3	87.0	186.4	781.7	121.9	103.1	86.9	10.7	0.015	0.94
		stdev		15.2	54.8	9.9	3.6	0.5	8.2	22.2	82.5	5.5	9.9	8.0	0.7	0.003	0.03
	20–40°C	OHA11	646cA25	61	890	84.45	22.2	8.7	81.8	189.5	735	113.5	95.3	82	10.7	0.013	0.92
		OHC3	646cB25	9	930	99	25.9	9.4	99.3	233.2	760	0.9	77.8	81.6	11.1	0.013	0.90
		OHC4	646cC25	62	1170	102.1	29	7.5	101.2	172.8	825	108	101.3	87.7	12.1	0.030	0.90
		mean		44.0	996.7	95.2	25.7	8.5	94.1	198.5	773.3	74.1	91.5	83.8	11.3	0.019	0.91
		stdev		30.3	151.4	9.4	3.4	1.0	10.7	31.2	46.5	63.5	12.2	3.4	0.7	0.010	0.01

[b] Calculated from ignition.
[a] Calculated from start of experiment.

Table 6. Summary of moisture content as a percentage by mass (%MC)

Specimen	Room	Original	Final	%MC
OHB2	44^{0}C	117.1	111	5.2
OHB1	44^{0}C	119.9	113.6	5.3
OHA2	44^{0}C	71.9	68.9	4.2
OHA1	44^{0}C	71.2	68.2	4.2
NP2	44^{0}C	49.3	46.7	5.3
NP1	44^{0}C	57.4	53.6	6.6
Average				**5.1**
OHB4	23^{0}C	126.7	114	10.0
OHB3	23^{0}C	125.2	112.8	9.9
NP4	23^{0}C	55.7	49.5	11.1
NP3	23^{0}C	55.1	49.1	10.9
OHA3	23^{0}C	72	65.1	9.6
OHA4	23^{0}C	72.9	66.1	9.3
Average				**10.1**

Table 7. Summary of results of leaf litter experiments

Expt	Type of fencing	Key observations	Resulting damage	Time of failure	Wind direct-ion & speed
5	Hardwood, capped open paling	No significant involvement of fencing except for light flaming at base of paling in one location, which ceased when leaf litter burnt out.	None	N/A	357°N to 75°E @ 3.4 m/s
8	Treated pine, closed paling	Immediate ignition of pine, with slow flame spread and smouldering tthat eventually consumed majority of fencing. Window cracked at approx. 90 min due to impact of fencing and resulting direct flame contact. Increased flaming occurred where protected from wind, i.e. inside corner. Treated pine easily supported smouldering and low intensity flaming. Once flames spread to top of fencing, lateral spread by smouldering and flames was much slower.	Entire fencing except for panels A & B consumed or collapsed. Window failed due to collapse of fence panel onto the window.	Half corner panels C & D consumed in 15 min. Corner panels C & D completely consumed in 30 min. Half panels E & B consumed in 60 min. Panel G slumped against house & window in 90 min. Panel F collapsed in 100 min.	360°N @ 2.6 m/s
18	Hardwood, closed paling	Started smouldering with small flames 0.5 m high at inside corner mostly due to leaf litter with limited involvement of hardwood at 2 min. Flames burnt out by 4 min.	None	N/A	320°N @ 2.1 m/s
23	Treated pine, capped open paling	Immediate ignition of pine. Increased flaming occurred where protected from wind at inside corner. Treated pine easily supported smouldering and low intensity flaming. Once flames spread to top of fencing, lateral spread from corner by smouldering and flames was much slower. Limited smouldering and consumption of palings near post between panels A & B. Panel D collapsed. Further spread ceased, but effected by wind and early collapse of whole panel.	Palings/railing consumed at corner. Panel D collapsed. Limited palings consumed at intersection of panels A and B.	Panel D collapsed in 20 min.	1°N to 86°E @ 3.55 m/s

Table 8. Summary of the results for pre-radiation exposure

Expt	Type of fencing	Resulting damage	Peak measurements (time of peak measurement in parentheses)														Wind direction and speed
			At house		Mast 2		Outside fencing			Inside fencing			1 m behind fencing		1 m behind fire front		
			RAD 1 (kW/m^2)	TC 2 (°C)	RAD 2 (kW/m^2)	TC 17 (°C)	RAD 10 (kW/m^2)	TC 50 (°C)	TC 51 (°C)	RAD 9 (kW/m^2)	TC 46 (°C)	TC 48 (°C)	RAD 5 (kW/m^2)	TC 43 (°C)	RAD 8 (kW/m^2)	TC 40 (°C)	
3	COLORBOND, 2 off-white infill sheets	No damage	0.8 (360)	33.3 (395)	3 (325)	48.3 (325)	43.6 (405)	154.8 (385)	189.7 (380)	2.1 (415)	52.5 (395)	54.1 (395)	2.3 (400)	39.2 (395)	/	175.4 (325)	298°NNW to 116°E @ 2.4 m/s
4	COLORBOND, 2 off-white infill sheets	Minimal structural damage, but charing and crazing to exterior surfaces of panels A, B, C, D	3.3 (450)	42.2 (460)	6.3 (450)	39.7 (460)	240.0 (440)	708.5 (455)	953.6 (460)	16.2 (460)	178.6 (460)	163.7 (460)	20.1 (455)	64.4 (460)	/	520.0 (455)	297°NNW to 77°NE @ 2.12 m/s
11	COLORBOND, sawtooth profile	No damage	0.4 (110)	34.8 (330)	2.7 (335)	37.4 (345)	23.6 (325)	137.1 (325)	147.9 (325)	2.2 (335)	48.4 (310)	60.6 (310)	1.0 (330)	42.3 (310)	16.2 (330)	140.8 (335)	357°N @ 3.6 m/s
12	COLORBOND, sawtooth profile	No damage	1 (350)	37.1 (280)	3 (405)	38.5 (480)	50 (350)	228.3 (350)	251.9 (350)	6 (360)	55.1 (360)	60.7 (340)	3.5 (350)	43.3 (360)	41.0 (355)	251.2 (355)	71°NE @ 3.6 m/s
6	Hardwood, capped open paling	Charing of panels A, B, C, D	1.9 (340)	42.5 (375)	6.0 (370)	68.8 (375))	63.2 (380)	194.4 (380)	254.8 (380)	3.8 (375)	114.6 (380)	145.4 (380)	3.4 (375)	48.5 (380)	/	254.7 (380)	334°N to 70ºNE @ 3.57 m/s
19	Hardwood, closed paling	Consumption of fencing at corner join of panels C & D and extending along panel C	0.5 (325)	28.5 (165)	2.1 (410)	31.5 (430)	94.5 (420)	237.1 (425)	409.9 (425)	64.5 (2630)	402.5 (1380)	640.6 (2595)	3.8 (2640)	49.6 (2505)	36.0 (395)	92.4 (430)	320°N @ 2.1 m/s[a]
9	Treated pine, closed paling	Panels B, C, D destroyed; significant damage to joint of panel F–G; panel G fell on simulated residence, breaking window	0.9 (375)	41.6 (1755)	2.0 (465)	50.3 (235)	40.6 (900)	481.0 (2585)	575.5 (3260)	15.3 (1500)	155.7 (2500)	672.6 (1855)	8.5 (765)	69.4 (1505)	14.5 (410)	88.2 (540)	203°NNW to 156°ESE @ 1.8 m/s

[a] Wind conditions measured at Moruya weather station; all other conditions measured at Mogo experiment site.

Table 9. Summary of result for flame immersion experiments

Expt	Type of fencing	Resulting damage	Peak measurements (time of peak measurement in parentheses)														Wind direction and speed
			At house		Mast 2		Outside fencing			Inside fencing			1 m behind fencing		1 m behind fire front		
			RAD 1 (kW/m^2)	TC 2 (°C)	RAD 2 (kW/m^2)	TC 17 (°C)	RAD 10 (kW/m^2)	TC 50 (°C)	TC 51 (°C)	RAD 9 (kW/m^2)	TC 46 (°C)	TC 48 (°C)	RAD 5 (kW/m^2)	TC 43 (°C)	RAD 8 (kW/m^2)	TC 40 (°C)	
1	COLORBOND	Surface damage to panels A, B, C, D; some separation of panels at joins	/	/	/	23.8 (405)	211.5 (385)	980.6 (400)	989.2 (400)	16.1 (400)	49.8 (420)	89.7 (405)	12.8 (400)	40.2 (405)	/	70.4 (400)	57°NE to 143°ESE @ 2.4 m/s
4	COLORBOND, 2 off-white infill sheets	Surface damage to panels A, B, C, D; some separation of panels at joins	3.3 (450)	42.2 (460)	6.3 (450)	39.7 (460)	240.3 (440)	708.5 (455)	953.6 (460)	16.2 (460)	178.6 (460)	163.7 (460)	20.1 (455)	64.4 (460)	/	520 (455)	353°N to 77°NE @ 2.1 m/s
15	COLORBOND, 1.5 m high	Surface damage to panels A, B, C, D; damage sustained to both sides	2.0 (440)	37.1 (385)	5.2 (455)	36.6 (540)	150 (445)	859.9 (460)	831.9 (460)	21.8 (460)	171.8 (465)	218.5 (455)	19.4 (460)	67.5 (450)	92.8 (455)	383.2 (455)	320°N @ 2.1 m/s*
16	COLORBOND, 1.5 m + lattice	Surface damage to panels A, B, C, D	2.0 (455)	31.1 (460)	4.9 (450)	37.9 (530)	138.2 (445)	733.9 (450)	941.4 (440)	28.5 (450)	195 (465)	396.7 (455)	14.9 (440)	67.6 (455)	178.4 (455)	827.6 (455)	320°N @ 2.1 m/s[a]
13	COLORBOND, sawtooth profile	Surface damage to panels A, B, C, D; some separation of panels at joins	2.7 (460)	28.5 (445)	4.9 (460)	38.2 (270)	191.6 (460)	793.8 (450)	1005.8 (450)	30.8 (460)	129.4 (465)	150.3 (460)	20.6 (445)	64.9 (460)	159.3 (455)	355.5 (460)	10°NE @ 1.2 m/s
10	Treated pine, capped open paling	Panels A, B, C, D, E destroyed; play equipment destroyed	5.7 (445)	45.2 (805)	5.1 (450)	65.1 (385)	125.6 (450)	666 (470)	794.5 (460)	193.6 (445)	964.7 (455)	1125.7 (450)	68.9 (445)	151.9 (445)	138.3 (450)	699.8 (450)	8°N to 141°ESE @ 2.1 m/s
20	Hardwood, closed paling	No significant damage sustained; charing to outside of panels A, B, C; hole burnt at joints A–B and B–C	2.5 (505)	37.7 (520)	4.4 (515)	33.0 (520)	128.9 (500)	435.0 (520)	1016.0 (520)	13.4 (520)	79.8 (520)	368.6 (525)	14.2 (505)	51.5 (520)	63.6 (515)	81.3 (525)	290ºNW @ 2.1 m/s[a]
21	Treated pine, closed paling	All fencing consumed with the exception of panels A and G; panel G fell onto simulated residence	2.8 (550)	44.3 (805)	19.5 (2625)	767.1 (3865)	134.4 (550)	627.5 (515)	1045.1 (555)	72.5 (695)	898.2 (780)	840.2 (695)	25.0 (755)	232.3 (810)	95.1 (570)	137.3 (575)	290°NW @ 2.1 m/s[a]

[a] Wind conditions measured at Moruya weather station; all other conditions measured at Mogo experiment site.

Table 10. Summary of results of structural fire experiments

Expt	Type of fencing	Resulting damage	Peak measurements (time of peak measurement in parentheses)											Wind direction and speed
			At house		Mast 2		Inside fencing			1 m behind fencing		1 m behind fire front		
			RAD 1 (kW/m^2)	TC 2 (°C)	RAD 2 (kW/m^2)	TC 17 (°C)	RAD 9 (kW/m^2)	TC 46 (°C)	TC 48 (°C)	RAD 5 (kW/m^2)	TC 43 (°C)	RAD 8 (kW/m^2)	TC 40 (°C)	
2	COLORBOND	No significant structural damage; some minor buckling at joints	0.8 (390)	24.7 (620)	/	33.6 (430)	16.0 (625)	80.8 (620)	107.4 (490)	10.2 (390)	190.3 (615)	/	544.1 (370)	64°NE to 140°ESE @ 2.4 m/s
7	Hardwood, capped open paling	Panels B, C, D destroyed; 60% of panel A destroyed	4.8 (215)	76.5 (220)	11.6 (205)	113.6 (215)	/	1090.6 (115)	1041.4 (70)	55.2 (70)	335.1 (255)	/	819.6 (280)	348°N to 92°E @ 4.4 m/s
14	COLORBOND, sawtooth profile	Damage to panels B and C; play equipment destroyed	4.1 (320)	51.4 (125)	6.2 (235)	62.3 (125)	34.7 (420)	259.3 (145)	324.3 (470)	20.6 (140)	125.2 (465)	136.5 (145)	769.8 (140)	10°NE @ 1.2 m/s
17	COLORBOND, sawtooth profile	Charing to exposed surfaces; minimal structural damage; some melting of plastic toys	1.9 (40)	31.8 (115)	3.9 (115)	36.8 (840)	35.0 (120)	180.7 (125)	225.8 (155)	16.7 (125)	66.7 (120)	126.5 (110)	211.6 (120)	320°N @ 2.1 m/s[a]
22	Hardwood, closed paling	Panels A, B, C, D and 50% of E destroyed; toys destroyed	7.9 (505)	147.6 (515)	11.3 (1350)	147.4 (905)	184.5 (450)	1066.8 (435)	1124.0 (465)	/	755.3 (550)	206.0 (70)	659.7 (30)	N to E @ 2.5 m/s

[a] Wind conditions measured at Moruya weather station; all other conditions measured at Mogo experiment site.

Table 11. Summary of full-scale simulation experiments

Experiment **Fence type**	Leaf litter ignition	Pre-radiation exposure 5k W/m² 3 m 20 s 10 kW/m² 1m 40 s 30 kW/m² 2 m 10 kW/m² 1 m 5 kW/m² 1 m	Flame immersion Pre-radiation (same as previous experiment) + full grid 11 s	Structural fire 30 min full grid
COLORBOND	No experiment	Experiment 3 (date 11/03) + litter Experiment 4 (date 11/03) + litter	Experiment 1 (date 8/03) Experiment 4 (date 11/03) + litter	Experiment 2 (date 8/03)
COLORBOND, 1.5 m high COLORBOND, 1.5 m + lattice			Experiment 15 Experiment 16 (date 01/04)	
COLORBOND, sawtooth profile		Experiment 11 (date 31/03) Experiment 12 date (31/03)	Experiment 13 (date 31/03)	Experiment 14 (date 31/03) Experiment 17
Hardwood, capped open paling	Experiment 5 (date 11/03) no ignition	Experiment 6 (date 11/03) start ignition and stop	Experiment 7 (date 11/03) fully ignited	Experiment 7
Treated pine, capped open paling	Experiment 23 ignition		Experiment 10 embers not ignited + radiation + full grid	
Hardwood, closed paling	Experiment 18 (date 05/04)	Experiment 19 (date 05/04)	Experiment 20 (date 08/04)	Experiment 22 (date 08/04)
Treated pine, closed paling	Experiment 8 (date 14/03) ignition	Experiment 9 (date 15/03) ignition	Experiment 21 (date 08/04)	