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Description of bushfire performance of buildings and its verification

CSIRO Research Report

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SUMMARY

This report presents the description of bushfire performance of buildings and its verification by CSIRO Bushfire flame front simulation test method. The test method and apparatus was developed by CSIRO to simulate radiant heat, flame immersion and burnover exposures for bushfires in large-scale.

The description of bushfire performance was based on ISO 'Framework for specifying performance in buildings'. The test method may be applied to evaluate the performance of buildings but can also be modified for evaluating the performance of vehicles and other infrastructure when exposed to these bushfire conditions. The test method and outcomes may be used to support a performance based alternative solution to existing deemed to satisfy solutions prescribed by the Building Code of Australia and related reference test standards[]. It may also be used to support additional building solutions that may be developed as Acceptable Construction Manuals.

1 Description of bushfire performance of buildings

1.1 Introduction

This part discusses the issues associated with the description of bushfire performance of buildings. These include the objectives, the principles and the parameters of the performance description as well as the methods for evaluation of the solution(s). These are described in accordance with ISO 'Framework for specifying performance in buildings' (ISO 2013).

1.2 Objective of Performance Description

The description of performance must be related to a user need or objective. There are a number of possible user needs, such as the need for a safe shelter or the need to reduce property damage. Underlying all these needs, however, is the need to reduce the likelihood of ignition in a bushfire event. For the purpose of this report, the objective is considered to be the need for reducing the likelihood of ignition. This is far less complex and more universal as an objective.

The likelihood of ignition includes the likelihood of ignition due to the environmental conditions generated by a bushfire event and the likelihood of ignition to and from the neighbouring buildings.

1.3 Principle of Performance Description

Similar to the description of structural performance, the description of bushfire performance of buildings involves: (i) the description of the bushfire actions that contribute to the likelihood of ignition, (ii) the description of measures used to reduce the likelihood of ignition to buildings and (iii) the description of the methods used to evaluate the solutions.

In Australian regulatory context (NCC Vol.1 & Vol.2 2013), the descriptions of the actions are known as 'performance requirements', the descriptions of the measures to reduce the likelihood of ignition are known as 'solutions' and the description of the methods used to assess whether the 'solution' meets the 'performance requirements' are known as 'assessment methods'.

The description of bushfire actions (similar to other structural actions such as wind, snow and earthquake etc.) are based on simplified models describing temporal, spatial and directional properties of the actions. There are two main aspects of the description: physical and statistical. Physical description provides the information that characterised the action. Statistical description provides the data on how the physical description varies with situations. Action is generally described in terms of a high percentile value of the physical data in the region of 90-95 percentile values. These will be described in more detail in Section 1.4.

The description of measures to reduce the likelihood of ignition can be approached in two ways. It could be by standardized processes or by rational design from first principles. In regulatory context, they are known as 'Deemed-to-Satisfy' Solution (DTS) and Alternative Solution (AS). They will be described in more detail in Section 1.5.

The description of the methods used to evaluate the solution varies with the solutions and available technical knowledge for their assessment. Generally they are based on calculation or testing or a combination of both. In a regulatory context, a number of methods of assessment are deemed to be acceptable. These will be described in more detail in Section 1.6.

1.4 Parameters for describing bushfire actions

1.4.1 GENERAL

The risk of ignition is caused by three types of actions: embers, radiant heat or flame action that could be generated by a bushfire and in certain cases nearby built structures. These actions either work individually or in combination to ignite the building and/or its contents. The contents of the building combined with the combustible building elements represent a fuel load much higher than is generally found in the forest. Hence the completeness of building destruction we see in the aftermath of bushfire events (Leonard & Blanchi 2005). Buildings that are only partially damaged are found relatively rarely and in each case the partial damage is usually attributed to occupant or brigade activity in suppressing the fire and preventing further involvement (McArthur 1997, Leonard & Blanchi 2005).

Assisted by wind, burning embers, radiant heat, flames or convective heat may:

(i) enter the building and directly ignite its contents,

(ii) enter the building envelope and ignite combustible elements within the cavities of the building envelop and later ignite the building contents,

(iii) cause the building façade or façade elements to break distort or yield, leading to one of the above processes, and

(iv) ignite the façade of the building leading to one of the above processes.

These mechanisms have an exposure hierarchy; ember attack is the most prolific and has the greatest reach. In some circumstance radiation from a large flame front can also accompany ember attack and in few cases direct flame contact can accompany radiation and ember attack. Flame exposure, radiant heat and ember attack have different length scales for which they cause loss relevant to land use. Their combined effect is observed in house loss statistics, typical upper limits of their combined effect for worst-case bushfires in southern Australia are given in Table 1.

Table 1 Indicative distances between hazardous vegetation and loss from bushfire for severe bushfires (Ahern and Chladil 1999; Leonard, Blanchi et al. 2009)

Mechanism	*Indicative distance for 80% of all house losses (m)*	*Indicative maximum distance for house ignition from forest (m)*
Combined actions	100	700

Distance of a building to the bush is therefore an important parameter in describing the building performance. It affects the severity of the ember actions as well as the severity of radiant heat and flame actions.

1.4.2 EMBERS ACTIONS

(A) PHYSICAL ASPECTS

Ember attack is a generalised term used to describe fine fuel elements emitted by a bushfire that are carried by wind to land on various objects in the surrounding landscape. Their main impact is to act as ignition sources. They can also accumulate to represent a considerable localised flame source. The elements follow the wind and fall out of the air in regions of low wind. These fine fuel elements may be in various stages of flaming, glowing, burnt or unburnt at any stage of transportation and deposition. Once deposited, elements can form flaming ignition sources in such places as building cavities, building interior, crevices, gutters, corners or decks on buildings; ground vegetation, shrubs or unburnt bushland (Ramsay, McArthur et al. 1986; Blanchi and Leonard 2008).

It should be noted that fine fuel debris can be deposited at times other than a fire event. This build up can occur over many years and represent a considerable accumulated fine fuel load that becomes dry and readily ignitable at the same time and for similar reasons that bushfires become active in the landscape. Because accumulation of fine fuel debris is via wind transport the regions where this accumulation occurs are similar to those where burning embers may arrive in a bushfire event. Over many surveys involving human accounts and researcher observations of ignition points, ember attack has been observed to have ignited a wide variety of combustible elements on and within structures. Internal walls, roof space, sub floor and occupied spaces have all been subject to ember ignition as have combustible external features of the building (Ramsay 1987, Leonard & Blanchi 2005).

Ember attack can be prevalent before the arrival of a fire front, is present during the arrival of the fire front, and is always present for a period after the fire front has passed.

Factors affecting ember intensity include:

- Proximity to burning vegetation or buildings.
- Wind speed and duration.
- The effects of hotness and dryness of wind on the moisture content of fine fuels.
- Vegetation type.
- Presence or absence of objects between the ember source and buildings that can trap or block embers.
- Topography that can support strong flame front convection that lifts embers and projects them further across the landscape.

Under hot, dry and windy weather conditions more fine fuel and bark will be susceptible to ignition and transportation (Ellis 2000). Each combination of vegetation type and fire weather conditions will create a different ember profile and therefore different urban susceptibility to ember attack.

(B) STATISTICAL ASPECTS

Under extreme circumstances, embers can travel a long distance (20 km). Short distance embers are often found in prolific numbers and tend to have greater impact. Typically this mechanism is responsible for over 90% of ignitions leading to building loss in an urban environment. More severe fire weather and persistent wind conditions will support embers activity deep within urban environments as urban fuels become new localised ember sources (Leonard and Blanchi 2005).

1.4.3 RADIATION AND FLAME ACTIONS

(A) PHYSICAL ASPECTS

Radiant heat is the primary mechanism by which flames transfer some of their heat energy to the surrounding environment. Convection and conduction also play a part in transferring energy to buildings during periods of flame immersion. Structures can be subjected to significant radiation from large flame bodies of burning hazardous vegetation or buildings on adjacent land parcels. The major determinants of radiant heat exposure are flame size and proximity to the object. For a detailed review on radiant heat see Sullivan et al. (2003).

Factors that influence the severity of radiant heat exposure to a location include:

- Size of the flame body (both height and width)

- Distance between the flame body and the location
- Intervening elements between the flame body and the location
- Shape and orientation of the flame body
- Shape and orientation of the forest edge
- Speed of the advancing flame front
- Prevalence of heavy fuel elements that also act as flame sources.

As a simple rule, radiation intensity reduces as the inverse square of distance.

(B) STATISTICAL ASPECTS

Statistical aspects are best discussed in three distinct phases: pre-immersion, immersion and post immersion.

(i) Pre- immersion

Pre-immersion is the phase in which a fire front is approaching a structure and is represented by increasing radiation. The radiation at any particular time is a function of the flame body temperature and the distance between the flamer body and the building. The rate of increase is defined by the rate of approach of the fire front; the faster the approach the quicker the increase and briefer this phase will be. Ignitable objects such as timber are most susceptible to a slow build up as it allows time to heat and dry out the timber surface prior to ignition. Other materials may by susceptible to a brief sudden exposure that induces a thermal shock in the object (eg glass). These materials may need to also be exposed to a rapid radiation profile.

The flame body emissive temperature is determined by the principles of combustion physics. It is considered to have a reasonable upper bound of 1200 K under the range of variables applicable to forest fuel fires Sullivan et al. (2003). AS 3959 Appendix B assumes a maximum flame temperature of 1090 K. The difference in these two values is principally due to the application of a radiation reduction factor that attempts to account for multiple conservative inputs into the AS3959 calculation process.

Figure 1 presents the radiant heat vs time curve for what is considered to be the worst long term heating scenario. Appendix A provides more details on the derivation of the curve.

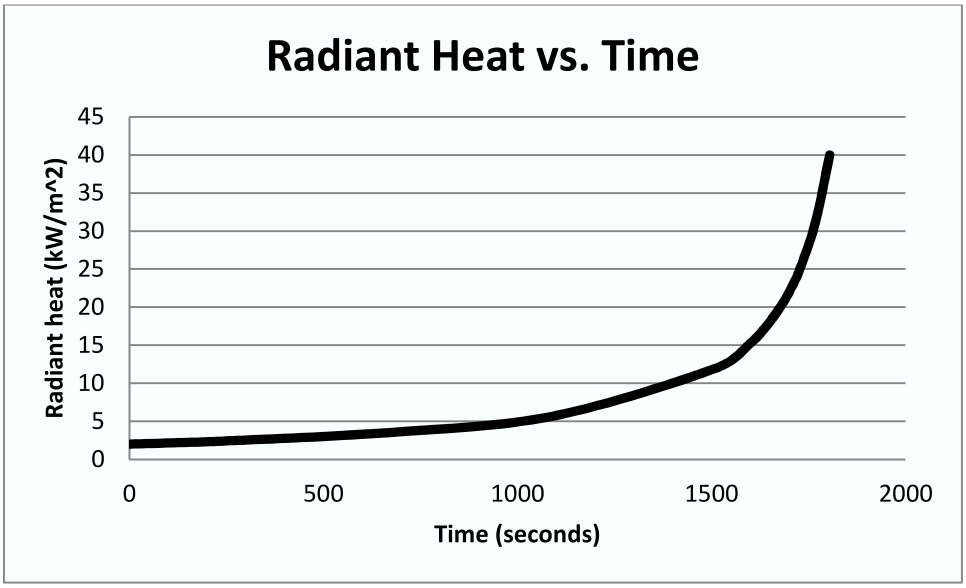

Figure 1 Radiant heat vs. Time for pre-immersion

(ii) Immersion

During the immersion phase, all three modes of heat transfer between the flame and the building come into play. The main issues concerning the immersion phase are:

1. The duration of the phase, and
2. The flame body emissive temperature (as per previous section)
3. The emissivity of the flame body.

The maximum immersion time has been determined from a range of field studies. See Appendix B for details. For cases with FDI>=40, the maximum duration of the immersion phase is 104 sec. Therefore 110 sec. was selected as a reasonable upper percentile value for specifying the flame immersion time.

(iii) Post-immersion

Sullivan (2001) provided a predictive curve of the total power emitted by heavy fuels in the period following the passage of the main fire front and an estimate of the time decay profile from heavy fuels immediately adjacent to forest. This curve is sufficiently conservative to be emulated by the following time radiation steps:

- Step 1 – 5 kW/m^2 for 200 sec.
- Step 2 – 2.5 kW/m^2 for 700 sec.

The inclusion of the period in which the flames die down as fuels burn out following the immersion phase makes it unnecessary to include a transition phase between the end of the flame immersion phase and the onset of the post radiation phase (from heavy fuel elements). This phase does not include the exposure potential that may arise from man-made fuel elements such as buildings, vehicles or fences.

(iv) Full exposure curve

A reasonable worst case full exposure curve can be obtained by combining the above three phases as shown in Figure 2.

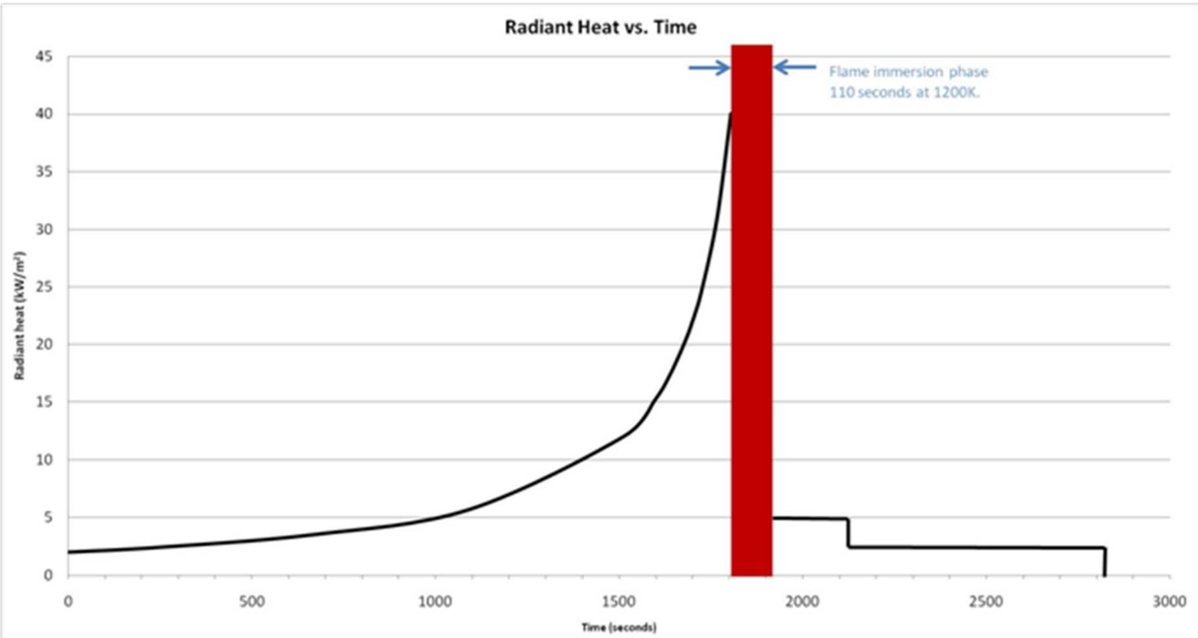

Figure 2 Full exposure curve for radiation and flame action

(v) Variations of the curve

The curve of Figure 2 represents the worst case for each phase assuming the structure is immediately adjacent to the forest fuels. For other conditions, the curve could vary from that proposed.

If the structure is assumed to be at a further distance or if the exposure condition is less severe, the resultant curve could have a shorter radiation build up, a narrower flame immersion phase and a lower intensity post radiation phase. If the separation is greater than the flame length itself then the curve will plateau at a radiation level less than $40kW/m^2$ and persist for a period no greater than the flame immersion phase, then decay into the post radiation phase.

(vi) Comparisons with other exposure curves

The radiant heat vs time profile presented in Figure 2 is not the only exposure that has been proposed for bushfire action modelling. A substantial body of research data exists on the performance of building components in Standard Fire Tests (SFT). These tests, for which test facilities exist throughout Australia and the world, are designed to model a slowly evolving cellulose material fire in an essentially closed compartment. The resulting temperature and radiation experienced by a test element comprising one surface of a rectangular box is of concave –down form, with an exposure lasting typically a minimum of 30 minutes. A discussion of this curve, and how it compares with the profile presented in Figure 2, is contained in Poon and England (2002).

1.5 Parameters for the description of methods to reduce the likelihood of ignition

1.5.1 IGNITION DUE TO EMBER ACTIONS

Reduction of the likelihood of ignition due to ember actions can be achieved through combination of the following:

- Locate the building to distance it from forest fuel sources (as 80% of all ember related loss occurs within 100 m of forest fuels).
- Eliminate exterior near-building sources of fuels, such as surface fuels, firewood, vehicles, vegetation, furnishings etc.
- Eliminate combustible building elements that may be exposed to embers such as combustible decks.
- Eliminate combustible surfaces where embers can attach and ignite, e.g. rough sawn timbers such as western red cedar.
- Eliminate gaps that are sufficiently large to allow embers to enter and ignite combustible internal building elements (gaps less than 2 mm are considered acceptable according to (Manzello 2009)
- Eliminate combustible materials in the structure behind claddings that have or may develop larger gaps through which embers may pass.

These measures are largely prescriptive.

1.5.2 IGNITION DUE TO FLAME/RADIATION ACTIONS

The exposure can be reduced by either increasing the distance between the flame body and the building or retaining intervening elements between the flame body and the building such as vegetation, fences, buildings and terrain. These approaches are very effective in creating a shielding effect because radiation travels in straight lines and decays rapidly with distance. They can influence both the time radiation profile and the peak radiation level experience by a building.

Reduction of the likelihood of ignition due to flame/radiation actions can be achieved through a combination of the following:

- Protecting or minimising building components that are most vulnerable to flame/radiation actions such as glass
- Selecting appropriate building systems especially cladding materials that provide adequate resistance to flame /radiation actions

1.6 Evaluation

1.6.1 EVALUATION OF LIKELIHOOD OF IGNITION

For a particular site, the likelihood of ignition is a function of many factors including:

- General bushfire danger level of the area
- Availability of vegetation as fuel sources
- Distance of building from vegetation
- Slope of the land

These factors are usually combined into a single bench mark to indicate the level of exposure a location on a particular site may receive. This is then linked to assumptions surrounding the mode of failure of a building which can either be complex or simple.

In Australian regulatory context, this benchmark for classification of sites exposure level is known as ‘Bushfire Attack Level’ (BAL) which is and estimation of the peak radiant heat flux exposure level received at a given location (AS 3959). The assumed failure thresholds are not explicitly states in AS3959 but are limited to a simple threshold approach that focuses in the expected peak radiation threshold.

1.6.2 EVALUATION OF MEASURES TO REDUCE THE LIKELIHOOD OF IGNITION

(A) MEASURES TO RESIST EMBER ATTACK

The general strategy to resist ember attack is to find safe places for embers to land. This may include one or a combination of:

- stopping the entry of embers in places where there are combustible materials by screening or other forms of protection of openings

- using non-combustible materials in areas where embers are likely to reach

These measures are largely prescriptive so their evaluation is not an issue. However, their effective implementation involves activities such as maintenance which require continuous participation by the building owners/occupiers well outside the reach of the regulators.

(B) MEASURES TO RESIST RADIATION OR FLAME ATTACK

There are two general methods to evaluate measures to resist radiation or flame attack:

- Component evaluation – where each construction element is to be evaluated for its fire resistance and non-combustibility which can be assessed with appropriate fire tests. Prototype evaluation - where a prototype building is exposed to a radiation profile representing the passing of a bushfire through the building such as that proposed in Figure 2 in order to evaluate the building resistance as a whole.
- In the Australian regulatory context, the component evaluation approach has been adopted by Australian Standard AS 3959 which has been reference in the National Construction Code (NCC)

as a Deemed-to- Satisfy (DTS) provision. The full scale prototype testing approach is also acceptable under the Performance provisions of the NCC as an Alternative Solution, and could be developed into a Verification Method in the future.

- The full scale prototype testing approach has some advantages in removing the uncertainty of component to component exposure within a built system.

2 Bushfire Flame Front Simulation Test Method

2.1 Scope

This report provides a test method for evaluating the performance of complete buildings, vehicles and other infrastructure in large scale when exposed to some or all of the follow bushfire attack mechanisms:

- Radiation exposure from an approaching flame front
- Flame immersion
- Flame underburn
- Radiation from a receding flame front
- Radiation from burnout of residual fuels

The method does not attempt to emulate ember penetration or simultaneous severe wind loading, although the effects of ember accumulation and ignition can be emulated in some cases.

2.2 Objective

The objective of this report is to detail a test method and apparatus that may be used to evaluate performance of complete building, vehicle or other infrastructure systems in large scale when subjected to bushfire radiant heat and flame immersion exposures.

The objectives of a particular test will be dependent upon stakeholder agreement but may include.

- Determination of performance in terms of ignition, damage or spread of fire
- Determination of performance in terms of continued serviceability
- Determination of performance in terms of occupant survivability within interior spaces

2.3 Principle

The test equipment comprises an array of Liquid Propane burners which are controlled to simulate the following types of bushfire exposures:

- The bushfire approach phase, where radiation loads from the approaching fire are the main threat;
- The bushfire flame immersion phase, where heat transfer and ignition may occur by direct flame contact both on the windward and leeward sides as well as beneath the test specimen
- The receding phase, where the bushfire has passed the test specimen and radiant heat loads subside both on the windward and leeward sides.

The test method does not specifically simulate exposure to wind born embers. However, burning timber cribs or combustible debris may be appropriately conditioned and located to simulate collection and ignition of burning debris by embers.

A large scale flame exposure is generated which enables the testing and evaluation of specimens as complete large scale systems rather than smaller individual components.

2.4 Application

This test method can be applied to complete large scale systems rather than smaller individual components.

The test method has previously been applied to the following specimen systems:

- Complete buildings incorporating all typical construction.
- Vehicles including passenger cars and fire fighting vehicles with and without specifically designed crew protection systems
- Water tanks
- Fencing systems
- Power pole systems

The application is not limited to the above systems.

2.5 Limitations

2.5.1 WIND

Tests are conducted in open air due to the size of the flame exposures used and the opportunity for more complete flame engulfment of the test specimen using ambient wind exposure.

Worst case wind speeds in real bushfires can be very high to the point that they are damaging in their own right. It would be dangerous and impractical to attempt to simulate the combined effect of fire and wind over a wide range with the facilities available. Previously performed large scale experimentation using the test apparatus has found that high wind speed can reduce the effective thermal load on the structure due to flame turbulence and convective loss. Hence the approach taken is to apply the thermal exposure under moderate wind conditions to ensure a worst case flame engulfment and to then consider the implications of wind related damage as a separate engineering based assessment.

The optimum steady wind speed during testing is in the range 1.2-6.0 m/s. A narrower wind range can be specified during stakeholder discussions for specific infrastructure elements.

2.5.2 SPECIMEN SIZE

The maximum specimen size is limited to approximately 2.5 m deep for a full burnover profile (eg simulating a burnover of a vehicle surrounded by forest).

For an exposure consisting of only the fire approach and immersion (eg simulating a house at an urban/ bushland interface), the specimen depth normal to the flame front is not limited. Maximum specimen width parallel to the flame front is approximately 12 m, but will be reduced when test objectives include an expectation that flames will engulf its ends and related corner details. Previous experimental configurations show that a specimen width of 9 m or less allows for full engulfment of the specimen ends.

RADIANT HEAT AND FLAME PROFILES

Due to tests being conducted in open air conditions, high wind speed and wind fluctuations can influence the flame size and angle. This can affect the radiant heat and flame immersion received by the specimen. This is addressed by the following measures:

- Only undertaking testing under moderate wind conditions (1.2-6.0 m/s);
- Measuring and recording wind conditions during testing;
- Measuring and recording total heat flux exposure throughout the test and adjusting radiation burner settings accordingly.

2.5.3 EMBERS

The test method does not specifically simulate exposure to wind born embers. However, where required by the specific test objectives, burning timber cribs or combustible debris may be located on and within cavities to simulate collection and ignition of debris by embers.

2.5.4 CONDITIONING

The requirement for conditioning of specimens varies both with specimen behaviour and stakeholder requirements. When infrastructure systems contain elements that are hygroscopic it is advisable that these elements be appropriately conditioned and moisture content qualified. These levels should be at or lower than levels experienced on the worst case scenarios under which the infrastructure is expected to perform. Where this cannot be achieved due to the impracticality of conditioning on the particular test subject, this must be clearly identified as a limitation of the test.

2.6 Safety Precautions

Users must be aware of the following possible hazards relating to this test:

- Exposure to high levels of radiant heat, convective heat and direct flame contact or toxic/harmful smoke, gas and other residues resulting from combustion;
- Storage and release of flammable gas under pressure;
- Mechanical and manual handling hazards relating to construction/installation, testing and removal of test specimens

This report does not provide a safety assessment or safe operating procedures. A safety assessment should be undertaken for each test to identify and manage all potential risks to health, safety and the environment and identifying all safety equipment or precautions required to suitably address the risks.

2.7 Test Apparatus

2.7.1 BUSHFIRE FLAME FRONT SIMULATOR

(A) LIQUID PROPANE SUPPLY

Liquid propane is stored in an 8000 litre tank permanently installed at the test site. The tank is pressurised by regulated nitrogen to avoid vapour development in the gas supply system as is normal when the vapour pressure of propane is used as a propellant. Prior to the nitrogen pressurisation of the tank, propane is vented to atmosphere to cool the propane to a vapour pressure of 600kPa. The vessel is then pressurised to 800kPa.

The pressurised liquid propane is then piped to the simulator grid in a buried 75 mm internal diameter pipe, a distance of approximately 30 metres. The large diameter keeps pressure drop to a minimum. The pipe diameter and supply pressure are a practical compromise between keeping supply pressures moderate and ensuring liquid propane arrives at the nozzle outlets.

Two-phase flow occurs if the pressure of propane falls below the vapour pressure of the liquid. A drop in pressure is unavoidable as liquid flows downstream in a pipe. Local low-pressure zones on the inside of sharp corners can also cause local points of vaporisation. In the gas phase, the total mass of propane that will flow through the nozzles at a given pressure is greatly reduced. The problem of two-phase flow is that it causes a reduction in overall discharge rates of the main burner grid and creates short intervals where portions of the flame body are not sufficiently hot and opaque (with the correct soot mass fraction). Two-phase flow is also caused if hot spots develop due to insufficiently insulated pipes near the burner heads or even exposure to the sun. To reduce this possibility, clean sand is heaped over all pipes prior to testing.

(B) BURNER GAS FLOW CONTROL

The main supply line delivers liquid propane to a series of valves for each stage of the burner grid, which are operated from a control panel in a nearby building. A safety cut-off button is installed on the control panel that will shut the main valve cutting supply to all stages simultaneously.

(C) BURNERS

Burner nozzles used are mounted on 150 mm vertical stems off the manifolds. This allows the manifolds to be covered with sand to a depth of 50 to 100 mm for heat insulation. Simple straight drilled orifice brass nozzles of different sizes can be screwed in as required to achieve the required flow rate of liquid propane. The nozzle size used to achieve the bushfire flame front exposure curve detailed in section 1.4.3 delivers approximately 16 MW/m of fire line, which is considered sufficient to create flame significantly taller than a 5 m tall test specimen and hence effectively immerse it. For the purpose of flame shaping, each burner has a convex-down deflector approximately 150 mm in diameter mounted 150 mm above the jet (see Figure 3). Higher gas flow rates will produce a larger flame body but is unlikely to result in a more severe direct exposure to a 5 m tall test specimen as the excess heat energy would be expressed well above the specimen. The burners are ignited by pilot flames that are lit prior to the start of the test.

Figure 3 Gas delivery from main grid burners

(D) GRID LAYOUT

Figure 4 shows the grid layout with each of the burner stages defined in table 3. Table 3 also shows the order of activation of each of the optional burner phases.

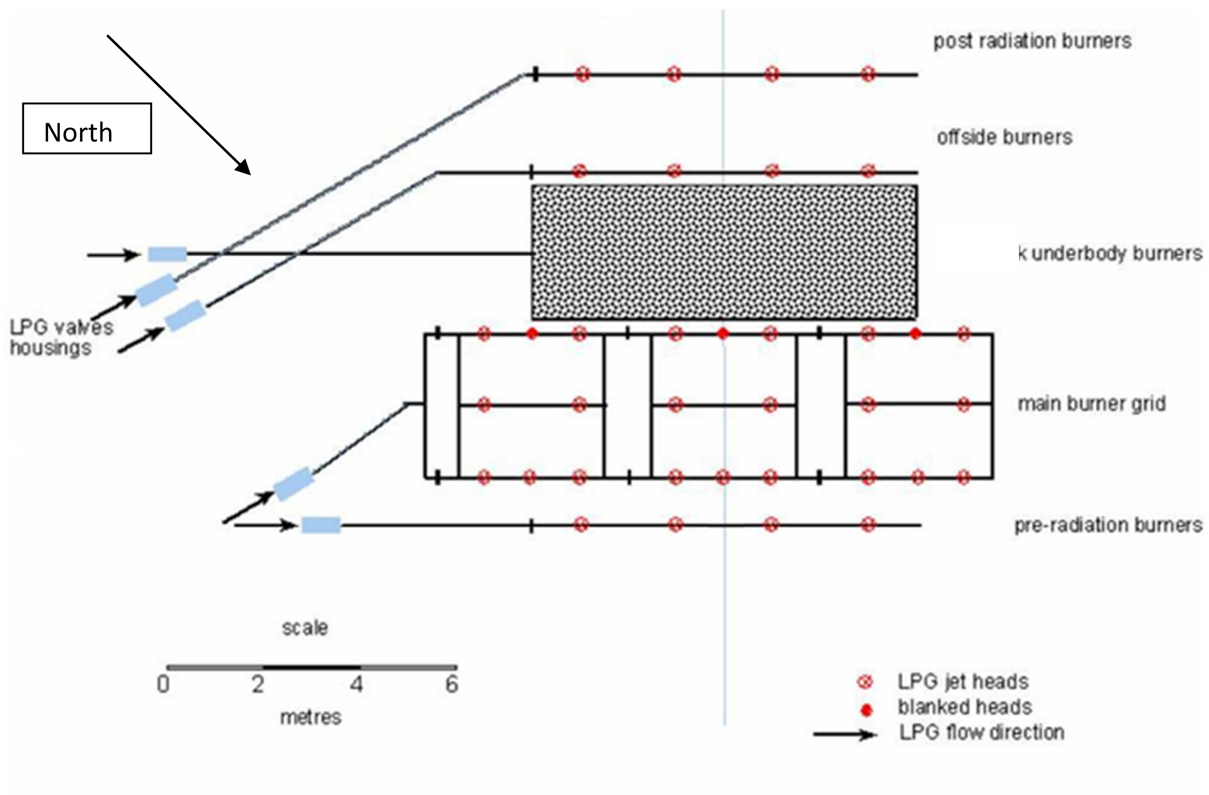

Figure 4 Bushfire flame front simulator burner grid layout.

Table 2 Grid burner stages

Burner Stage	Simulation	Configuration
Pre-radiation burners	pre-radiation approach of the bushfire	One row of 4 groups of 3 burners positioned approximately 5 m from the near side of the exposed specimen. Each of the three burners in the group has a selected jet size. By utilising a combination of the 3 burners the radiant heat on the front side of the test specimen can be adjusted.
Main burner grid	the on-side aspect of the flame immersion phase	Three rows of 50 mm manifold set back 0.35 m, 1.85 m and 3.35 m from the front of the test specimen. Each row has 6 risers. Each row is fitted with differently sized jets. When simulating lower fire intensities with shorter flame depths the jets in the rear most rows may be blanked off.
Underbody burners	the flame immersion due the combustion of the litter fuel under the fire tanker	A separate gaseous propane line is used and the gas diffuses up through a 20 mm grade stone bed producing a low scattered flame. The flow is controlled by a standard gas regulator to simulate a grass fire burning beneath a test specimen with a fuel load of 2 t/ha
Offside burners	the offside aspect of the flame immersion phase	Single row manifold with 4 risers. The diameter of the jets is selected so the total power approximates that of the main burner grid.
Post-radiation burners	the receding of the fire front	Three risers from a 50 mm pipe parallel and set back 4 m from the off side of the fire tanker

2.8 Instrumentation

Instrumentation is required for two purposes:

- To measure radiation and temperature conditions so that the test equipment may be adjusted to deliver the intended thermal exposure to the test specimen.
- To measure thermal effects in specimen elements for assessment against threshold criteria.

The location and quantity of instrumentation will be dependent on the test specimen and the aims of the particular test. The following provides guidance on suitable types of instrumentation and the minimum requirements for instrumentation.

NOTE: For infrastructure such as power poles and the like, not all of the following instrumentation will be relevant. In such cases instrumentation suitable to meet the objectives of the test should be determined.

2.8.1 CALIBRATION OF MEASURMENTS

All instrumentation used should either be provided with accredited calibration certificates or alternatively calibration checks must be performed against calibrated equipment or known physical conditions/constants to verify the calibration of equipment prior to use.

2.8.2 HEAT FLUX MEASURMENT

Total heat flux sensors must be installed at the following locations:

- The external vertical surface of test specimen which is closest to the burner grid. At least two heat flux sensors located at the external surface of the test specimen are recommended for redundancy
- 365 mm from the non-fire side within 200 mm of the centre of any glazed element. Where there are multiple glazed elements heat flux sensors may be limited to a portion of the glazed elements which are considered to be of most significance.
- 365 mm from the non-fire side of uninsulated materials which are considered to pose a risk of excessive heat transfer to the occupiable interior of the test specimen.

Water cooled Schmidt-Boelter heat flux sensors with a measurement range of 0 - 100kW/m^2 are appropriate.

NOTE: Total heat flux sensors are used to measure radiant heat in stages of the test where the radiant heat component is the dominant mode of heat transfer.

2.8.3 TEMPERATURE MEASUREMENT

All temperatures may be measured using Type K thermocouples which are 1.5 mm diameter, Mineral Insulated Metal Sheath (MIMS) with stainless steel (AISI 310) sheath and magnesium oxide powder insulated. These are suitable for temperatures up to approximately 1050 ^{o}C. Other types of thermocouples or temperature measurement devices may also be suitable.

NOTE: The thermocouple type suggested above is considered to be suitable for the following reasons:

- They have been successfully used in previous tests on fire tankers, houses, water tanks, fences and power poles.
- The thermocouple probe can be bent and threaded through material
- The probe is protected along its length against the high temperatures that are likely to be experienced
- The probes have been found to provide similar temperature measurement to the standardised disc thermocouples used in AS 1530.8.2
- Where surface temperature is required the thermocouple can be held by screws and bent to give a positive contact to the surface as shown in Figure 5. It is recommended that a continuous length of at least 30 mm from the tip should be pressed against the surface to ensure good thermal contact.
- They are significantly lower in cost than higher temperature Type N, R or S thermocouples

Figure 5 Examples of thermocouples used for measuring surface temperatures (clockwise from top left: stud, plasterboard, roof truss, glass window)

The purpose of the temperature measurement is to determine the temperature of the outside of the test specimen and the adjacent air, the variation of the temperature through to the inside of the specimen and the internal air temperatures within the occupiable interior space if applicable

As a minimum, thermocouples must be located as follows:

- Exterior air temperature at outside surface – at least five thermocouples must be located with the tip approximately 40 mm from the exterior surface of the test specimen on the front face (facing the burner array) and distributed to determine any significant variations in exposure temperature across the exposed face of the test specimen
- Construction cavity temperatures – at least five thermocouples must be located to measure cavity temperatures within the test specimen construction which is facing the fire exposure. Where multiple layers of construction (eg external cladding, cavity insulation and interior lining) a thermocouple should be located at the interface of each layer. Thermocouple positions should be selected giving consideration to the location of materials at risk of ignition and likely paths of heat transfer through the cavity.
- Occupiable interior surface temperatures - at least five thermocouples must be located to measure temperatures of interior surfaces within any occupiable space. Consideration should be given to the different materials of construction and likelihood of heat transfer though these materials.
- Occupiable interior air temperatures – air temperatures should be measured at vertical height intervals of not more than 0.5 m within the approximate centre of the occupiable internal space
- Interior glazed surface temperatures – a thermocouple should be located within 200 mm of the centre of each glazed surface on the non-exposed side of glazed elements. The purpose is to roughly indicate glass failure temperature.

NOTE: Application of thermocouples to the exposed side of glazed elements may result in shielding and thermal gradients within the glass that can promote early failure.

2.8.4 TOXIC GAS MEASUREMENT

Toxic gas measurement is only required where assessment of occupant tenability within internal spaces is a test objective.

The following sections provide recommended strategies for toxic gas measurements. However measurement techniques may be modified to meet the objectives of a particular test.

Leakage tests

Immediately before conducting the bushfire flame front simulation test (eg the day before) a leakage test should be carried out to measure the leakiness of the enclosure in terms of air changes per hour. This will influence the degree to which external air toxics (from external LPG combustion) ingress into the building.

During the leakage test the test specimen must be in a test-ready condition with all doors, windows and other openings closed and seals in place.

During the leakage test it is recommended that an axial fan (approximately 25 mm) be operating in the centre of the enclosure to fully mix the interior air.

Carbon monoxide (CO) is carefully released into the enclosure and controlled to achieve a concentration of 50-100 ppm inside the enclosure.

The CO concentration decay is then monitored for a period of up to 1 hour. CO concentration has been successfully monitored for this purpose using Q-TRAK indoor air quality meters fitted with an electrochemical gas sensor.

Multiple measurements at different external wind speeds may be taken if considered necessary. The application of a 50 Pascal negative pressures to the building envelop is also an option to emulate the air exchange rate achieved during high wind exposure events.

Toxic gas measurements during bushfire flame front simulation test

It is recommended that both CO and respirable particles sampled from the external flame zone should be measured during the test to quantify the amounts of these toxic gases generated from the gas burner grid. The external flame zone gas sample point is typically located 300 mm in front of the exposed external surface of test specimen and approximately 1.2m above ground level. The purpose of this is to identify if ingress of burner grid air toxics to the enclosure becomes significant.

The internal enclosure air at a central point within the enclosure should also be sampled for gas analysis during the tests.

Sample air should be pumped from each sample location via non-reactive sample tubes to 10 litre sample chambers located a safe distance from the test specimen. A pump flow rate of 15 l/min is typical. Gas sample transport delay time should be measured prior to commencement of the test by introducing a puff of CO to the sample point and timing the delay to measurement.

Independent gas analysis equipment or “grab bag samples” may be sampled from the sample chamber.

The following gas species and measurement techniques should be considered. The actual species measured may be dependent upon gases to be expected from the materials of construction. Sampling equipment references are noted as examples only, and should be carefully considered with respect to the expected concentration of each gas species during the test.

- Carbon monoxide – measurement by electrochemical sensor (Q-TRAK) or gas infrared detection may be suitable.
- Respirable particles - measurement by optical particulate measurement techniques may be suitable, for example by TSI Dustrak instrument (continuous over test, range 0-180 mg/m^3) or TSI Sidepak (continuous over test, range 0-20 mg/m^3).

- Carbon Dioxide - measurement by electrochemical sensor (Q-TRAK) or gas infrared detection may be suitable.
- Hydrogen chloride, hydrogen cyanide, hydrogen bromide, hydrogen fluoride and nitrogen dioxide - measurement by electrochemical sensor, gas infrared detection or calorimetric gas detection tubes (Kittagawa) may be suitable.
- Key VOCs – measurement by collection of gas samples and later laboratory analysis by GC/MS may be suitable
- Formaldehyde – measurement by calorimetric gas detection tubes (Kittagawa) may be suitable.

The frequency of gas sampling should be determined to ensure that critical events such as flame immersion or failure of the test specimen's barrier integrity can be identified.

2.8.5 WIND AND AMBIENT CONDITIONS

Wind speed and direction at the test facility should be measured and logged through the duration of the test. A weather station consisting of a vane anemometer and wind direction vane with a sensitivity of at least 0.1 m/s and downloadable logged recording is suitable for this purpose.

Ambient air temperature and relative humidity should be measured and recorded immediately prior to the test.

2.8.6 RECORDING OF MEASURED DATA

Outputs of all heat flux sensors, thermocouples and other instruments without individual logging capability should be logged using electronic data acquisition equipment at time intervals not greater than 5 seconds.

The outputs of heat flux sensors indicating radiant heat flux to the exterior of the test specimen should be displayed in real time during the test to enable the burner grid operator to control flow rates to achieve the required heat flux exposure.

2.8.7 AUDIO VISUAL RECORDING

Both still and audio visual records of the test should be made.

Video cameras from a number of positions both outside and inside the test specimen are recommended during the test.

Photos should be taken documenting the test specimen construction, instrumentation and the test.

Photos should also be taken documenting the condition of the test specimen and its dismantled components after the test.

2.9 Reporting of results

The report shall include:

(a) The name and address of the testing laboratory;
(b) The name and address of the sponsor of the tests;
(c) The name of the manufacturer and or any project contributors ;
(d) Identification of all stakeholders responsible for agreeing upon the final test procedure and performance criteria.
(e) A complete description of the test specimen. This should include all material details, construction details and methods of installation. It is preferred that full and detailed drawings should be provided by the test sponsor.
(f) A complete description of the agreed test procedure
(g) The agreed performance criteria, if applicable
(h) A complete description of the agreed measurements and instrumentation
(i) The date of test and operator's name;
(j) Records of all test results including measurements, observed significant events during the test and inspection of the test specimen after the test.
(k) All measurements presented as either tables or graphs.
(l) Concluding statements regarding the performance of the test specimen and comparison to acceptance criteria if applicable.
(m) The reasoning for adoption of alternative flame front exposure profiles, or acceptance criteria if different to those suggested in this report.

2.10 Acceptance criteria

If the purpose of the test is to assess the risk of ignition of the test specimen then the following acceptance criteria are suggested:

2.10.1 STRUCTURAL ADEQUACY

Failure in relation to structural adequacy and may be deemed to have occurred upon any of the following:

- Collapse of the test specimen
- Measured temperatures of structural elements exceeding pre-determined limits for structural adequacy

  Note: Depending on the test objectives, failure of replaceable components may be acceptable provided they are separately identified in the test report.

2.10.2 BARRIER INTEGRITY

Large openings in the building envelop must not occur. In particular, any failure of glazing, doors, penetrations and other openings should be observed.

Where resistance against ember attack is a criterion, the formation of an opening larger than 3 mm wide from the fire-exposed face to the non-fire-exposed face through which an ember can pass is not acceptable.

2.10.3 THERMAL INSULATION

Mean and maximum temperature rises should not be greater than 140 K and 180 K, respectively, on the non-fire side during test, except for glazed/uninsulated areas for which the radiant heat flux limits are applicable.

Radiant heat flux 365 mm from the non-fire side of the specimen should not exceed 15 kW/m^2 from glazed and uninsulated areas during the test.

NOTE – the purpose of this criterion is to minimise risk of fire occurring in the interior via heat transfer through a barrier.

2.10.4 CONTINUED SERVICABILITY OF INFRASTRUCTURE

Any criteria regarding the continued serviceability of infrastructure will be particular to the type of infrastructure tested and must be agreed by all stakeholders prior to testing.

APPENDIX A – Derivation of the radiation-time curve for the pre-radiation phase

In order to derive a credible worst case pre–immersion profile, it is necessary to estimate the size and temperature of the flame body and its speed of travel towards the building. To assess the speed, 16 time radiation profiles were generated using assumptions provided in AS3959 method B using FDI >40. These cases are listed in Table 3 with relevant parameters including surface fuel load, overall fuel load and effective slope to produce the radiant heat vs. time curves shown in Figure 1 Radiant heat vs. Time for pre-immersion. The methodology used to produce the curves is Method B Appendix of AS 3959-2009 with the following modifications:

- The flame body is assumed to have an emissive temperature of 1200^0 K
- Full flame length as predicted by Luke and McArthur (1978)
- No separation distance between vegetation and building

These modifications are aimed at producing a more extreme radiant heat vs. time curve in keeping with the practice of describing actions in terms of higher percentile value of the physical data. FDI 40 is selected as the benchmark because there is no record of appreciable loss on days of FDI 40 or less (Blanchi 2010). Profile 16 is the worst case scenario at FDI 40 and is adopted to represent the pre-radiation phase. The profile begins at a radiation level of 2 kW/m^2 which is the point at which occupant would find it difficult to stay outside the building and ends at 40 kW/m^2 which is the point where flame impingement is imminent. The worst case time required for the build-up from 2 to 40 kW/m^2 is 1800 sec (30 minutes). The general principle observed was that the less intense slower moving fire fronts provided the longest time radiation profile which coincided with shorter flame lengths. Only 2 out of 18 cases examined required a longer time for build-up but for these case the FDI was below 40.

Table 3 Range of input parameters to show range of potential time radiation curves

Number	FDI	Surface Fuel Load	Overall Fuel load	Effective Slope °
1	50	25	35	30 (d/s)
2	50	5	15	30 (d/s)
3	50	25	35	0 (flat)
4	50	25	35	5 (u/s)
5	50	25	35	10 (u/s)
6	50	25	35	15 (u/s)
7	50	5	15	0 (flat)
8	50	15	25	15 (u/s)
9	100	5	15	15 (u/s)
10	90	5	15	15 (u/s)
11	50	10	20	15 (u/s)
12	50	8	18	15 (u/s)
13	60	5	15	15 (u/s)
14	50	6	16	15 (u/s)
15	50	5	15	15 (u/s)
16	40	5	15	15 (u/s)
17	30	5	15	15 (u/s)

18	20	5	15	15 (u/s)

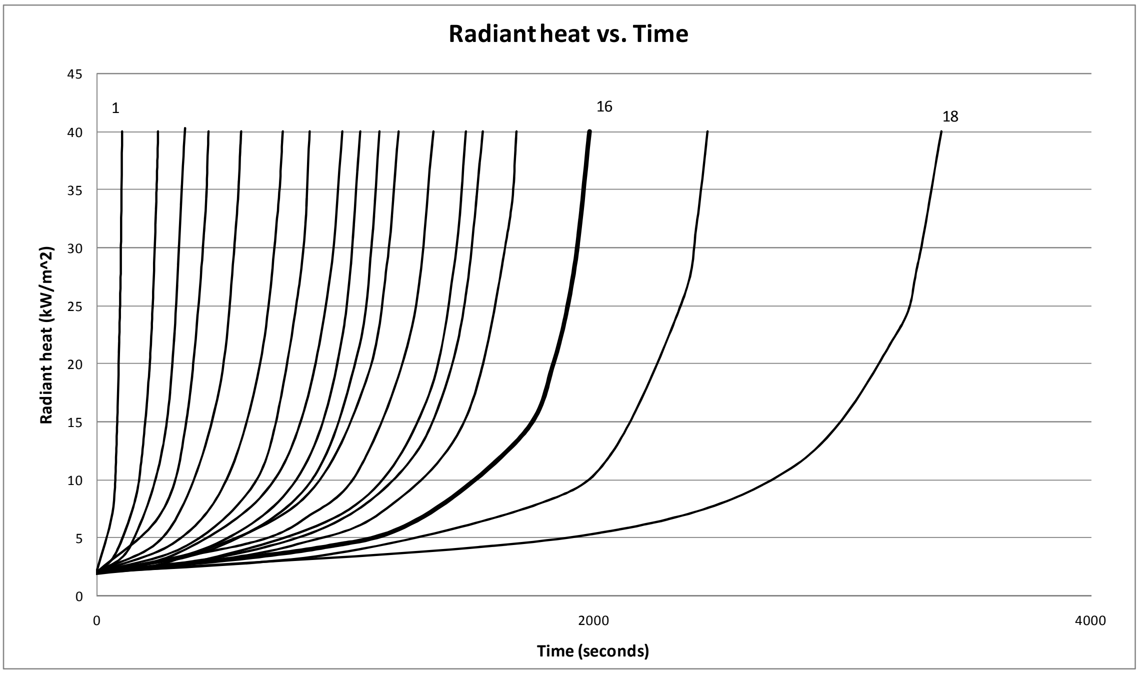

Figure A1: Graph of radiation time curve

APPENDIX B – Duration of immersion phase

To obtain an upper percentile value of the duration of the immersion phase, 15 theoretical cases were studied covering a wide range of input parameters where McArthur Mark5 (1967) is used to calculate both the flame length and rate of spread. In each case one is a trade-off for the other, hence taller flames which reach the structure sooner are also faster moving so they travel over the structure more quickly. The outcomes are presented in Table 4 for worst case scenarios within the assumption limits. As with radiation modelling it is clear that the slower and shorter flame lengths provide the longest potential flame immersion. The maximum immersion time for cases with FDI>=40 is 104 seconds being example 3. Thus 110 sec. represents a reasonable upper percentile value for specifying flame immersion time.

Table 4 Flame immersion times for worst case scenarios.

Example No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
FDI	20	30	40	50	50	60	50	50	50	70	80	100	50	120	50
Surface Fuel load (t/ha)	5	5	5	5	10	5	15	25	20	5	5	5	20	5	25
Overall Fuel Load (t/ha)	15	15	15	15	20	15	25	35	30	15	15	15	20	15	35
Slope °	0	0	0	0	0	0	0	0	0	0	0	0	0	0	15(d/s)
ROS (km/h)	0.12	0.18	0.24	0.3	0.6	0.36	0.9	1.5	1.2	0.42	0.48	0.6	1.2	0.72	4.22
Flame length (m)	3	4	5	6	11	6	16	26	21	7	8	9	18	11	61
Flame Immersion time (seconds)	128	112	104	99	97	96	96	95	95	94	92	89	88	88	85

APPENDIX C – Observed ignition points

The following lists locations of observed ignition points from three surveys (Ramsay 1995, Blanchi and Leonard 2005).

(i) External ignition points

- Timber decks;
- Eave fascia boards and/or gutters;
- Timber window frames;
- Timber stairs;
- Timber door frames;
- Rough sawn western red cedar cladding;
- Gapped board around stumps;
- Exposed timber beams (eave structure);
- Veranda, supporting beam;
- Door mats;
- Fabric veranda roofs;
- Timber shingle roofs;
- Plastic roof panels;
- Veranda/pergola;
- Timber frame behind a/c unit;
- Bitumen roof membrane;
- Canvas awning;
- Timber wall frame elements;
- Plastic veranda roof;
- Weather boards.

(ii) Ember entry points:

- Door jams;
- Windows that are not tight fitting;
- Gaps in roofing systems;
- Gaps in under floor enclosure;
- Gaps in flooring systems;
- Flues and chimneys;
- Gaps in building facades particularly at the interface of boards or sheets and where they terminate at corners or other building elements.

(iii) Ember accumulation points:

- Re-entrant corners;
- Roof valleys;
- Gutters;
- Unprotected sub-floor areas;
- Wall cavities;
- Roof cavities;
- Under decks;
- Between decking boards above bearers;
- Door thresholds;
- Window frames;
- Corner of decks adjacent to walls or glazing.

3 References

Ahern, A., & Chladil, M. (1999). How far do bushfires penetrate urban areas? *Proc. Australian Disaster Conf. 1999, Disaster Prevention for the 21st Century*. Canberra: Emergency Management Australia.

AS 1530.8.1-2007 : methods for fire tests on building materials, components and structures - tests on elements of construction for buildings exposed to simulated bushfire attack - radiant heat and small flaming sources. Sydney, Australia: standards Australia, 2007.

AS 1530.8.2-2007 : Methods for fire tests on building materials, components and structures - Tests on elements of construction for buildings exposed to simulated bushfire attack - Large flaming sources. Standards Australia

AS 3959-2009 *Construction of buildings in bushfire prone areas*.(Inc. Amend. 1) Standards Australia.

Blanchi, R., & Leonard, J. (2008). Property safety: judging structural safety. In J. Handmer & K. Haynes (Eds.), *Community Bushfire Safety* (pp. 77–85).

Blanchi, R., & Leonard, J. E. (2005). *Bushfire at the urban interface: lesson from the Otways Fires (1983), Sydney Fires (1994) and Canberra Fires (2003). Bushfire CRC report CMIT(C)-2005-373*.

Blanchi, R., Lucas, C., Leonard, J., & Finkele, K. (2010). Meteorological conditions and wildfire-related houseloss in Australia. *International Journal of Wildland Fire*, *19*(7), 914–926.

Ellis, P. (2000). *The aerodynamic and combustion characteristics of eucalypt bark- a firebrand study*. *A Thesis submitted to the Dept. of Forestry Australian National University for the Degree of Doctor of Philosophy*.

ISO(2013) Framework for specifying performance in buildings ISO/TC59/SC3 N565

Leonard, J., & Blanchi, R. (2005). *Investigation of bushfire attack mechanisms involved in house loss in the ACT Bushfire 2003*. CSIRO Manufacturing & Infrastructure Technology.

Leonard, J., Blanchi, R., Leicester, R., Lipkin, F., Newnham, G., Siggins, A., … Barwick, M. (2009). *Building and Land use planning research after the 7th February 2009 Victorian bushfires. Preliminary findings*. Melbourne: Interim report USP2008/018 - CAF122-2-12 . Retrieved from http://www.bushfirecrc.com/managed/resource/bushfire-crc-victorian-fires-research-taskforce-final-report.pdf

Luke McArthur, A.G., R. H. (1978). *Bushfires in Australia. Reprinted with corrections 1986*. Canberra Publishing and Printing Co.

Manzello, S. L., Park, S.-H., & Cleary, T. G. (2009). Investigation on the ability of glowing firebrands deposited within crevices to ignite common building materials. *Fire Safety Journal*, *44*(6), 894–900. Retrieved from http://www.sciencedirect.com/science/article/B6V37-4WH0JRY-2/2/c93bb86ccb5fc7607bd857e767b0fb45

McArthur, A. G. (1967). *Fire behaviour in eucalypt forests*. *Leaflet No. 107.* Comm. of Australia For. & Timber Bur.

McArthur, N. A. (1997). A protocol for surveying bushfire building damage. (B. J. McKaige, R. J. Williams, & W. M. Waggit, Eds.)*Bushfire '97*. Darwin 8-10 July 1997: CSIRO.

NCC Vol.1 (2013) National Construction Code Series Volume 1, Building Code of Australia 2013, Class 2 to 9 buildings. Canberra: Australian Building Codes Board.

NCC Vol.2 (2013) National Construction Code Series Volume 2, Building Code of Australia 2013, Class 1 and 10 buildings. Canberra: Australian Building Codes board.

Poon, S.L. and England, J.P.(2002), Literature Review of Bushfire Construction Materials and Proposed Test Protocols for Performance Assessment, WFRA Project No. 20551, Warrington Fire Research, Guidelines for Evaluation and Specification of Bushfire Fire Research, Australia, 2002.

Ramsay McArthur, N.A. Dowling, V.P., G. C. (1987). Preliminary results from an examination of house survival in the 16 February 1983 bushfires in Australia. *Fire and Materials*, *11*, 49–51.

Ramsay, G. C., McArthur, N. A., & Dowling, V. P. (1986). Building survival in bushfires. *Fire Science'86. The 4th Autralian National Biennial Conference*. 21-24 October, Perth.

Sullivan, A. L., Ellis, P. F., & Knight, I. K. (2003). A review of radiant heat flux models used in bushfire applications. *International Journal of Wildland Fire*, *12*(1), 101.

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