NSW ADVANCES IN APPROACHING PERFORMANCE BASED ASSESSMENTS OF RESIDENTIAL DEVELOPMENTS IN BUSHFIRE PRONE AREAS

Grahame Douglas, Lew Short and Zhenxiang Tan
NSW Rural Fire Service, Sydney, Australia

Abstract

The construction of buildings in bushfire-prone areas in Australia needs to comply with the requirements of the Building Code of Australia (BCA). The BCA is a fully performance based code which obtains its statutory power through the EP&A Act 1979 and EP&A Regulation 2000 in NSW. The BCA contains both Performance Requirements and Deemed to Satisfy (DTS) Provisions which are applicable to Class 1, 2 and 3 buildings that are proposed for construction in bushfire-prone areas and AS 3959 *Constructions of buildings in bushfire-prone areas* is referenced by the BCA as the Deemed to Satisfy (DTS) construction standard. Although the BCA accepts alternative solutions, it provides little guidance in regard to the verification methods which can be used to formulate and evaluate alternative solutions. Due to the lack of guidance in evaluating alternative solutions for the construction of buildings in bushfire-prone areas, the use of alternative solutions which could introduce new building design or building material may have been restricted also being very difficult for the authority having jurisdiction to examine the appropriateness of the alternative solutions formulated and evaluated by using inappropriate verification methods. In view of this, the authors have proposed a verification method for formulating and evaluating alternative solutions for the construction of buildings in bush fire prone areas. This paper explores the details of the proposed verification method.

Introduction

Bushfires pose severe threats to life, property, and the environment in rural and urban interface areas. In NSW, more than 250 residential houses were destroyed during the mid-December 1993 to January 1994 fires and a total 109 residential houses were destroyed in the 2001/2002 bushfires. In excess of 500 houses were lost on 18 January 2003 bushfires in Canberra. The high severity and frequency of bushfire events have drawn increased attention from both government and the general public. As a result, a number of bushfire protection reforms have been made in NSW. One of these reforms is that the construction of Class 1, 2 and 3 buildings in bushfire prone areas needs to comply with the Building Code of Australia (BCA).

Figure 1. BCA Structure

The BCA is a fully performance-based code. The performance requirements are the only requirements which a building solution need to comply with. As shown in Figure 1, the compliance of the performance requirements can be realised through either Deemed-to-Satisfy (DTS) Provisions or Alternative Solutions. When the DTS solutions are sought, the standard AS 3959-1999 *Construction of Buildings in Bushfire Prone Areas* should be referred to as the relvant *construction practice*. In NSW, AS 3959 -1999 was amended on 1 January 2002 via a NSW variation to the Building Code of Australia (BCA). This variation introduced a more applicable site assessment methodology through *Planning for Bush Fire Protection 2001*(PBP) to replace Section 2 of the Standard. Similar to the standard site assessment methodology, the methodology in the PBP is also a matrix-based qualitative approach. Based on vegetation type, slope and separation distance, the level of bushfire attack and the associated construction level can be readily determined by looking up the assessment matrix. For instance, if the predominant vegetation type of a development site is of forest and the effective slope is 10 degrees, then the level of bushfire attack to which a development sited at 40m from the edge of the vegetation might be exposed is **Extreme** and therefore a **Level 3** construction is required for the compliance with AS 3959 -1999. According to the pre-defined performance criteria, the development constructed to Level 3 construction should be able to withstand significant ember attack and a radiant heat flux up to 31kW/m^2 . For the purpose of determining the DTS provisions for a development, the existing qualitative assessment method is considered to be adequate. However, it becomes inadequate when used for formulating and evaluating alternative solutions because of its qualitative nature.

When an alternative solution is sought, the proposed alternative solution needs to satisfy the performance requirement defined in the BCA for compliance. The current performance requirements for construction of buildings in bushfire prone areas required by the BCA is that Class 1, 2 and 3 buildings must be designed and constructed to reduce the risk of ignition from a bushfire while the fire front passes. It is obvious that the above performance requirement is qualitative and open for interpretation. In addition, the BCA doesn't provide any clear guidance in formulating and evaluating alternative solutions for construction of buildings in bush fire prone areas. This situation has restricted the use of new building design, building material and building components as alternative solutions. This becomes even more pronounced when a proposed development is assessed as falling within the 'flame zone; which is currently out of the scope of AS 3959 -1999. In view of this, the authors have proposed an assessment method which can help fire agencies, architects, councils and consultants to formulate and evaluate alternative solutions for construction in bush fire prone areas. The details of this assessment method are explored in the flowing sections.

Verification Method

Figure 2 shows the steps involved in the verification method. As shown in Figure 2, the method can be summarised into the flowing steps:

Step 1 Obtain Site Specific Data

The purpose of obtaining site-specific data is to prepare the input data required by flame length modelling and radiant heat flux modelling. These data include the information related to vegetation, topography and fire weather such as vegetation type, effective slope, site slope, distance between development site and vegetation, FDI and so on.

Table 1 Rate of Spread Equations

Vegetation	Rate of Spread (km/hr)
Forest & Woodland (Noble et al. 1980)	R=0.0012 *FDI*w *exp (0.069*slope)
Shrub & Heath (Catchpole et al. 1998)	$R= 0.023 * V^{1.21} * VH^{0.54} * \exp(0.069 * slope)$
Grassland (Noble et al. 1980)	R = 0.13*FDI * exp (0.069* slope)
Note: FDI = forest fire index w = surface fuel load (t/ha) slope = effective slope (degrees) VH = average height of vegetation (m) V = average wind speed at 10m above ground, defaulted as 45km/h	

Step 2 Calculate Rate of Spread

The objective of rate of spread modelling is to provide the inputs required by fire intensity calculation or flame length modelling. Depending on vegetation classification, the rate of fire spread shall be modelled by one of the equations shown in Table 1.

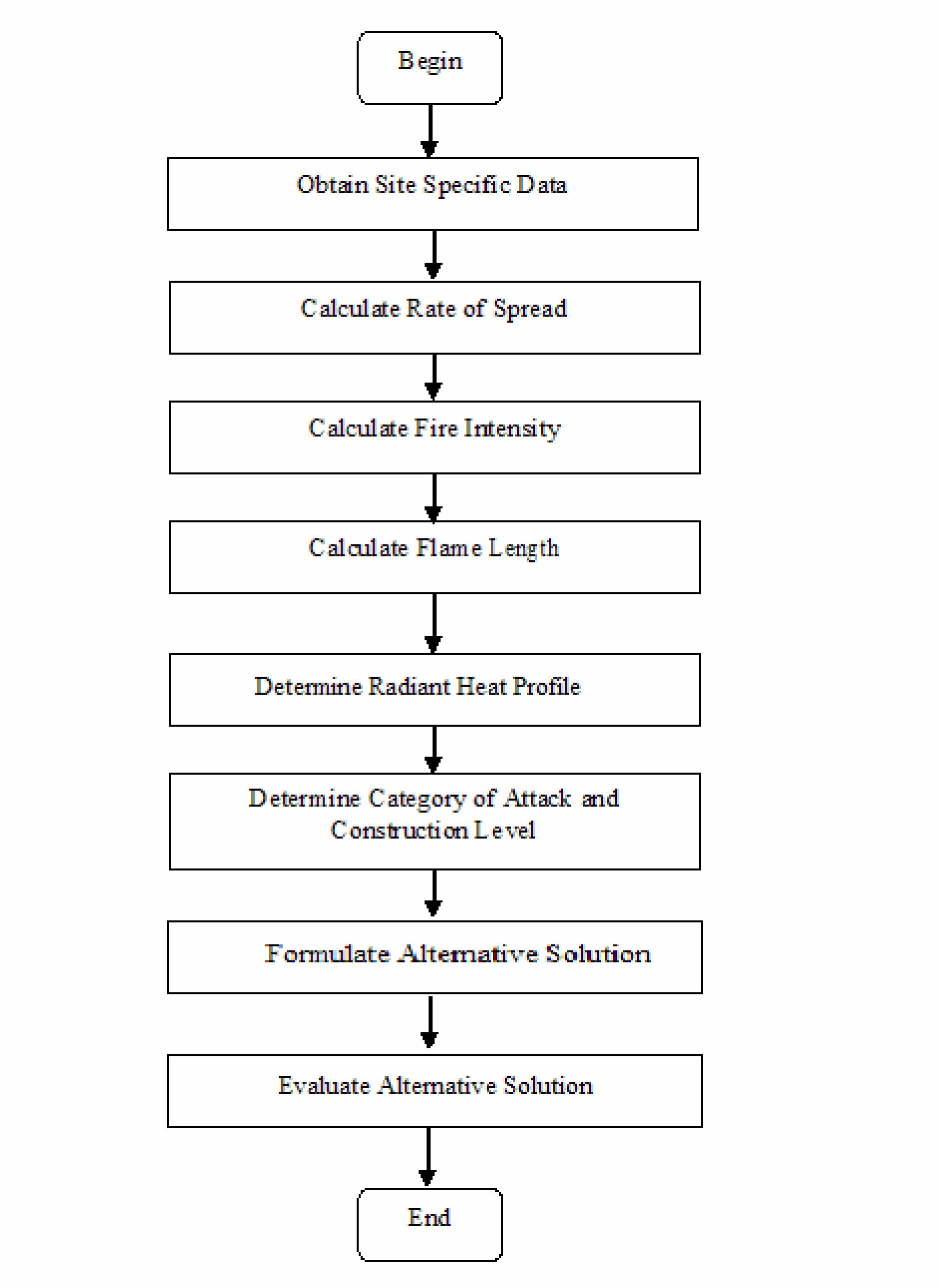

Figure 2. Flowchart of Verification Method

Step3 Calculate Fire Intensity

The objective of fire intensity calculation is to provide the input required by modelling flame length for grasslands, shrub and heath. Fire intensity shall be calculated by using the well-known Byram Equation which is mathematically expressed as (Byram 1959):

$$I = H*W*R/36$$

Where

I =fire intensity (kW/m)

H =heat of combustion (kJ/kg), approximated as 18,600 kJ/kg
W = overall fuel loads (t/ha)

Step 4 Calculate Flame Length
The objective of flame length modelling is to estimate flame length required for flame contact check and the subsequent radiant heat flux modelling. Depending on the types of vegetation, flame length shall be modelled by using one of the empirical flame length equations shown in Table 2.

Table 2 Flame Length Equations

Vegetation Classification	Flame Length Lf (m)
Forest & Woodland (RFS PBP 2001)	$L_f = (13R+0.24W)/2$
Shrub & Heath (Alexander 1982)	$L_f = 0.0775*I^{0.46}$
Grassland (Nelson 1980 in Ellis 2000)	$L_f = 1.192(I/1000)^{0.5}$

Step 5 Determine radiant heat profile
The radiant heat level to which a development in a bushfire prone area may be exposed in the event of a bushfire increases gradually when fire front is approaching to the development and reaches the maximum at the edge of the bushfire hazard. If the purpose of radiant heat fluxes prediction is for determining level of bushfire attack and the associated construction level for a site with specific conditions, then the maximum radiant heat to which the development may be exposed needs to be predicted only. However, for the purpose of formulating and evaluating an alternative solution, it is necessary to determine the radiant heat–time profile so that the performance of the proposed alternative solution under radiant heat attack can be evaluated against this profile. Figure 3 shows a sample radiant heat profile based on the assumption that flame length =19.8m, flame width= 100m, flame emissivity =0.95, flame temperature =1200K, initial fire front distance=124m, final fire front distance =26m and flame reside time =120s. As shown in Figure 3, the radiant heat profile comprises three development stages, that is, growing stage, stabilising stage and decaying stage, which correspond to the three different movement stages of fire front i.e. approaching stage, passing stage and leaving stage.

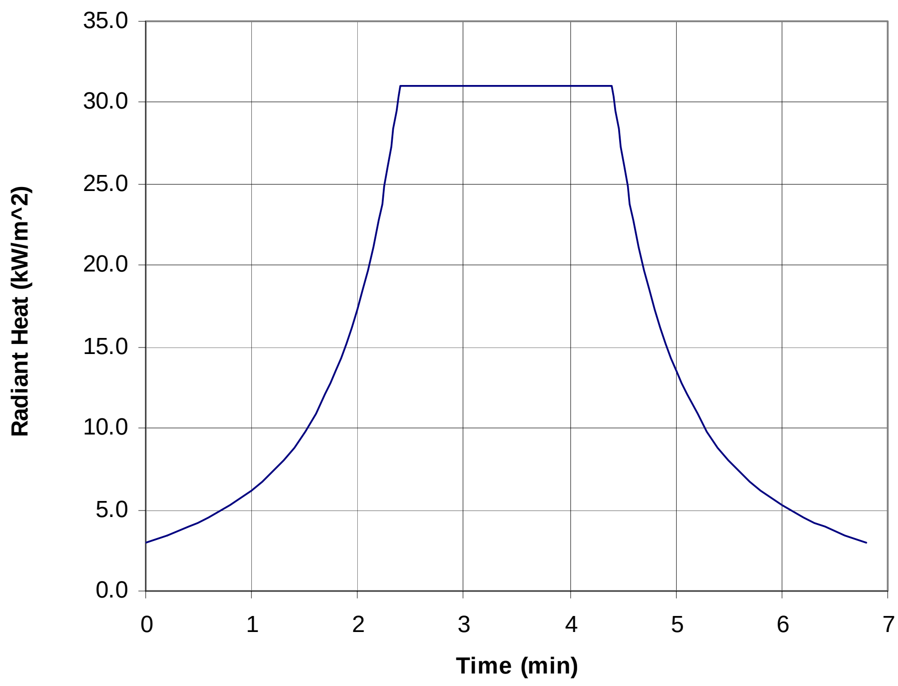

Figure 3. Sample Radiant Heat Exposure Profile

The radiant heat flux during the growing stage is modelled by conducting a repetitive radiant heat flux calculation for the fire front positions at a series of time points. The radiant heat flux prediction for the growing stage begins with an assumed initial fire front position at which time counting starts and ends with the final fire front position i.e. the edge of the bushfire hazard. The period which the establishing stage lasts depends on the flame residence time of a given vegetation fuel. The existing literature suggested that the flame residence times for all vegetation fuels without a continuous bed of large stem wood is within approximately 120s. Therefore, the use of 120s as the period of the stabilising stage is considered to be conservative. The decaying stage is dependant on the characteristics of the residual burning of large size vegetation fuels after a fire front passed. Due to lack of information, this stage is determined by assuming that the decaying process is the inverse process of the growing stage.

As stated above, the key for determining the radiant heat profile is to predict the radiant heat flux to which a development may be exposed for a given fire front position. The method used to calculate the radiant heat flux in this application is the well established view factor method which is expressed as (Drysdale 1985):

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

Where

R_d = radiant heat flux without atmospheric attenuation (kW/m^2)
ϕ = view factor
ε = flame emissivity
$\sigma = 5.67 \times 10^{-11}$ kW/m^2 K^4
T = flame temperature

When considering the effects of atmospheric attenuation, the above radiant heat equation can be mathematically expressed by:

$$R_d(\tau) = \phi \, \varepsilon \, \sigma \, T^4 \, \tau$$

Where

$R_d(\tau)$ = radiant heat flux with atmospheric attenuation (kW/m^2)
τ = transmittance factor

According to the radiant heat flux equation shown above, the radiant heat flux received by a point at a distance from fire front is the function of flame temperature, flame emissivity, view factor and transmittance factor. Flame temperature and flame emissivity are generally considered as constants. For bushfire applications, flame temperature is in a range of 1000K - 1300K (Vines 1981; Sullivan et al. 2003) while flame emissivity is a range of 0.91- 0.96. The suggested flame temperature and flame emissivity for radiant heat flux modelling in the proposed methodology are 1200K and 0.95 which is considered to be conservative for radiant heat modelling. These inputs can be refined with further information.

Flame temperature and flame emissivity have been considered to be constant values. Therefore the determination of view factor becomes the key for radiant heat flux modelling within the view factor model. In order to derive the view factor for an inclined flame shown in Figure 4, it is assumed that the view factor of an inclined flame is equivalent to that of a vertical flame with the same height located in the mid way of the flame. This assumption is justified by the CSIRO's research finding that the radiation at a distance from a tilted fire front can be modelled by the vertical flame with the same flame height located in the mid way of the flame (Sullivan et al. 2003). Based on the above assumption, the view factor of a point with a distance of d from the base of the flame at an elevation of h on the vertical plane crossing the vertical axis of the flame can be derived and expressed as (Douglas et al. 2005; Tan et al. 2005):

$$\phi = \frac{1}{\pi}\{\frac{X_1}{\sqrt{1+X_1^2}}\tan^{-1}[\frac{Y_1}{\sqrt{1+X_1^2}}] + \frac{Y_1}{\sqrt{1+Y_1^2}}\tan^{-1}[\frac{X_1}{\sqrt{1+Y_1^2}}] + \frac{X_2}{\sqrt{1+X_2^2}}\tan^{-1}[\frac{Y_2}{\sqrt{1+X_2^2}}] + \frac{Y_2}{\sqrt{1+Y_2^2}}\tan^{-1}[\frac{X_2}{\sqrt{1+Y_2^2}}]\}$$

$X_1 = (L_f \sin\alpha - 0.5 L_f \cos\alpha \tan\theta - d \tan\theta - h)/(d - 0.5 L_f \cos\alpha)$
$X_2 = [h + (d - 0.5 L_f \cos\alpha)\tan\theta]/(d - 0.5 L_f \cos\alpha)$

$Y_1 = (0.5Wf)/(d - 0.5Lf \cos\alpha)$
$Y_2 = (0.5Wf)/(d - 0.5Lf \cos\alpha)$

Where

L_f = flame length in meters,
W_f = flame width in meters, defaulted as 100m
h = elevation of receiver in meters, defaulted as the level opposite to flame centre
α = flame angle in degrees
θ = slope between vegetation and structure in degrees
d = separation distance in meters

The view factor formula above suggests that the calculation of view factor for an inclined flame requires the five inputs which are flame length, flame width, flame angle, elevation of receiver, and site slope. For a given vegetation type and a design fire weather condition, flame length can be modelled through the flame length modelling process described previously. Flame width is assumed to be 100m which is considered to be a conservative for bushfire applications (Ellis 2000). Site slope and elevation of receiver can be determined in accordance with the conditions of the given site. Therefore, when flame length, flame width, site slope and elevation of receiver are known, view factor becomes the function of flame angle only and reaches the maximum at a certain flame angle. For instance, the maximum view factor and the associated flame angle under the condition that elevation of receiver =2m, site slope = 0 degree, flame length = 20m, flame width = 100m and separation distance =30m can be determined to be 0.289 and 66 degrees respectively for the given condition. In order to minimise the uncertainly resulting from the variability of flame angle, it is assumed that a flame always takes a flame angle giving the maximum view. Under this assumption, the maximum view factor and the associated flame angle can be determined for the given condition by using an iterative approach (Douglas et al. 2005; Tan et al. 2005).

Research into radiant heat transfer through atmosphere identifies that radiant heat flux emitting from a radiant heat source is subject to a certain level of attenuation due to moisture and carbon dioxide in the atmosphere. The proportion of radiant heat flux remaining for a given path length is measured by transmittance factor τ which can be calculated by (Fuss and Hamins 2002):

$$\tau = a_0 + a_1L + a_2L^2 + a_3L^3 + a_4L^4$$

Where

L= path length, determined by $d - 0.5L_f \cos\alpha$
$a_n = C_{1n} + C_{2n}Ta + C_{3n}T + C_{4n}RH$
Ta= ambient temperature, defaulted as 308 K
T= flame temperature
RH= relative humidity, approximated as 0.25
C_{1n}, C_{2n}, C_{3n} and C_{4n} = Constants in Table 3

Table 3 Constants to calculate coefficient a_n

n	C_{1n}	C_{2n}	C_{3n}	C_{4n}
0	1.486	-2.003×10^{-3}	4.68×10^{-5}	-6.052×10^{-2}
1	1.225×10^{-2}	-5.900×10^{-5}	1.66×10^{-6}	-1.759×10^{-3}
2	-1.489×10^{-4}	6.893×10^{-7}	-1.922×10^{-8}	2.092×10^{-5}
3	8.381×10^{-7}	-3.283×10^{-9}	1.051×10^{-10}	-1.166×10^{-7}
4	-1.685×10^{-9}	7.637×10^{-12}	-2.085×10^{-13}	2.350×10^{-10}

Step 6 Determine Bushfire Attack Level and Construction Level

Once flame length and radiant heat profile are determined, the level of bushfire attack and the corresponding construction level can be determined according to the pre-defined exposure conditions for each level of bushfire attack as shown in Table 4. The deemed-to-satisfy provisions for the determined construction level can then be looked up from the Standard AS 3959-1999.

Table 4 Bushfire Attack Categories Defined in PBP 2001

Categories	Exposure Conditions	Construction
Low	Insignificant ember attack, radiation no greater than $14.5kW/m^2$ or is greater than 100 meters form all woody vegetation.	No requirements.
Medium	Significant ember attack, radiation heat greater than $14.5kW/m^2$ and no greater than $16kW/m^2$.	Level 1
High	Significant ember attack, possible flame contact, radiation heat greater than $16kW/m^2$ and no greater than $21kW/m^2$.	Level 2
Extreme	Significant ember attack, possible flame contact, radiation heat greater than $21kW/m^2$ and no greater than $31kW/m^2$.	Level 3
Flame Zone	Within the Flame Zone and/or greater than $31\ kW/m^2$.	Out of the scope of AS 3959.

Step 7 Formulate an alternative solution
If the building solutions to be used for a development are different from the DTS provisions, then these building solutions become alternative solutions and their acceptability should be evaluated in accordance with the principles stated in next step.

Step 8 Evaluate alternative solutions
In order to determine whether the alternative solution formulated in Step 7 is accepatable or not, the performance of the proposed alternative solution needs to be tested to the predicted exposure level as determined in Step 6 and pass the test which simulates the predicted bushfire exposure level. This means that the prosed alternative solution for Level 1, 2 and 3 constructions need to be subject to radiant heat test or ember test or the combination of the two. The specific types of tests to which the proposed alternative solution of a building component needs to be subject should be determined according to the orientation and position of the building component. A rule of thumb for this is that a building component is horizontally oriented or positioned at level less than 400mm or is intersected by a horizontal surface should be subject to both radiant heat test and ember test. Otherwise, only radiant heat test is required. In case of flame zone, any proposed building solutions need to be tested as per AS 1530.4. The conduction of radiant heat test and ember test should meet the general requirements listed in Table 5. In addition, the performance of the tested materia should be assessed against the failure criteria defined in FSE027 (WFRA 2005).

Table 5 Proposed general testing requirements

Test	General Requirements
Radiant heat test	• The proposed alternative solution for a given building component should be tested in full scale. • The simulated radiant heat profile should conform to the predicted radiant heat profile determined in Step 5 or an equitant radiant heat profile. • The test results should be assessed in accordance with the pre-defined failure criteria.
Ember/burning debris test	• The cribs chosen for ember/burning debris test should conform to the specifications specified in FSE027 (WFRA 2005). • The crib size should be determined in accordance with the risk of the building component retaining ember/burning debris. • The ember/burning debris test and radiant heat test should be conducted simultaneously if both tests are required. • The test results should be assessed in accordance with the pre-defined failure criteria.
Flame impingement test	• The proposed alternative solution for a given building component should be tested in full scale. • The test shall be conducted in accordance with AS1530.4. • The test results should be assessed in accordance with the pre-defined failure criteria.

It is understood that Standards Australia is currently working on the test standards specifically designed for evaluating the performance of alternative solutions for construction of buildings in bushfire prone areas. The testing requirements and the associated performance criteria proposed in this verification method shall be replaced by these standards once they become available. It should be also noted that testing is not an exclusive method for verifying the performance of an alternative solution. The use of any other methods should be considered to be acceptable if the performance of the proposed alternative solution can be verified by using these methods.

Application Example

Step 1 Obtain Site Specific Data
In this example it is assumed that a development is located 20m away from the surrounding bushfire hazard and the site has the following site specific conditions:

- Vegetation type= Closed shrub
- Vegetation height =3m
- Overall fuel load = 25 t/ha
- Effective slope=0 degree
- Site slope =0 degree
- Wind speed at 10m =45 km/h
- Other input parameters take the defaulted values

Step 2 Calculate Rate of Spread
$R= 0.023 \times V^{1.21} \times VH^{0.54} \times \exp(0.069 \times slope) =0.023 \times 45^{1.21} \times 3^{0.54} \times \exp(0.069 \times 0) =4.17$ km/h

Step3 Calculate Fire Intensity
$I = H*W*R/36 =18600 \times 25 \times 4.17/36 =53816$ k W/m

Step 4 Calculate Flame Length
$L_f = 0.0775*I^{0.46} = 0.0775 \times 53816^{0.46} = 11.63$ m

Step 5 Determine radiant heat profile
Based on the radiant heat profile determination procedure described in Step 5, the radiant heat profile for the given development is determined and illustrated in Figure 3.

Step 6 Determine Bushfire Attack Level and Construction Level
According to Table 1, the level of bushfire attack and the associated construction level are determined as Extreme and Level 3.

Step 7 Formulate an alternative solution
As per AS3959, the DTS provision for verandas and decks in a Level 3 construction in AS 3959 is:
"The requirements for windows in a Level 3 construction shall be as for Level 2 construction except that where the windows are not protected by non-combustible shutters, they shall be glazed with toughened glass". In this case, if the proposed window is glazed with non- toughened glass which is screened with stainless steel mesh, then an alternative solution for window in a Level 3 construction is formulated.

Step 8 Evaluate alternative solutions
If the position of window is 400mm above any horizontal surface connected with the window, then the level of ember attack is considered to be minimal. Therefore, the performance of the proposed alternative solution can be evaluated by simply conducting radiant heat test to the radiant heat profile determined in Step 5. If the test result is evaluated to be satisfactory against the pre-defined or standard failure criteria, then the proposed alternative solution is acceptable. Otherwise new alternative solutions need to be formulated and tested until an acceptable one is found.

Conclusions

- A step-wised verification method for formulating and evaluating alterative solutions for construction of buildings in bushfire prone area has been established and its applicability has been demonstrated with an example.
- The verification method enables alternative solutions for construction of buildings in bushfire prone areas to be easily formulated and evaluated and therefore allows new building design, new building materials and new building components to be used.
- The verification method provides councils, planners, fire authorities and home owners a tool for assessing the proposed building solutions for the developments being categorised into flame zone which current does not have deemed-to-satisfy provisions available.
- The verification method can be easily customised and adapted for a worst case scenario across a range of vegetation types into a standard test method in the future.

Acknowledgements:

The authors wish to acknowledge the assistance and feedback provided by Dr Noreen Krusel of the Victorian Country Fire Authority, Mark Chladil of the Tasmanian Fire Service, Dr Paul England of Warrington Research and Dr Peter Ellis of the CSIRO, Forest and Forest Products Division.

References

Alexander, M.E. (1982). Calculating and interpreting forest fire intensities. *Can.J.Bot. 60:349-357*.

Alexander, M.E.; Stocks, B.J.; Wotton, B.M.; Flannigan, M.D.;Todd, J.B.; Butler, B.W.; Lanoville, R.A. (1998). The international crown fire modelling experiment: an overview and progress report**.** In "Fire and Forest Meteorology", *Proc. of the second symposium on fire and forest meteorology*. p20-23. American Meteorological Society, Phoenix, MA.

Byram GM (1959). Forest fire behaviour. Forest fire control and use (Ed. KP Davis), McGraw – Hill, New York.

Catchpole,W.R.,Bradstock,R.A, Choate,J., Fogarty.L.G., Gellie,N., McCarthy,G.J, McCaw,W.L., Marsden-Smedley,J.B. and Pearce,G. (1998). Co-operative development of equations for heathland fire behaviour, Proc. 3rd Int. Conf. Forest Fire Research and 14th Conf. on Fire and Forest Meteorology. (Ed. Viegas,D.X.) Luso, Coimbra, Portugal, pp631-645.

Douglas G and Tan Z. (2005). Integrating site assessment and performance planning outcomes for bushfire prone areas. Paper presented at the symposium of planning for natural hazards, Wollongong.

Drysdale D (1985). An introduction to fire dynamics. John Wiley and Sons, 424 pp.

Ellis, P. (2000). Review of current methodology of assessment of bushfire hazard and the prescription standards. The development of a robust model to achieve this for different vegetation types. Client Report 901, CSIRO Forestry & and Forest Products, Bushfire Behaviour and Management Team, ACT.

Fuss S.P. and Hamins A. (2002). An estimate of the correction applied to radiant flame measurements due to attenuation by atmospheric CO_2 and H_2O. *Fire Safety Journal* **37**, 181-190.

Noble, I.R., Bary, G.A.V, & Gill, A.M. (1980). McArthur Fire Danger Meters Expressed As Equations. *Aust. J. Ecol.* **5**, 201-203.

NSW Rural Fire Service (2001). Planning for bushfire protection – a guide for councils, planners, fire authorities, developers and home owners, NSW RFS, Sydney.

Standards Australia (2005). DR 05060 Construction of buildings in bushfire-prone areas, Public Comment Draft.

Sullivan AL, Ellis PF and Knight IK (2003). A review of radiant heat flux models used in bushfire applications. *International Journal of Wildland Fire* **12**, 101-110.

Tan Z., Midgley S. and Douglas G. (2005). A computerized model for bushfire attack assessment. Paper presented at the symposium of planning for natural hazards, Wollongong.

Vines RG (1981). Fire and the Australian biota. (Eds AM Gill, RH Groves and IR Noble), Australian Academy of Science, Canberra, pp.129-150.

Warrington Fire Research Australia (2005). Test procedure FSE 027 Part 1 Version 1.3 - Performance of external construction elements subjected to simultaneous radiant heat and burning brand exposure. Prepared by Warrington Fire Research Australia, Feb 2005