House Ignition Likelihood Index - An Hazard Assessment Method for Land Managers in the Wildland-Urban Interface

K.G. Tolhurst and K A. Howlett
University of Melbourne, Creswick VIC, Australia

It has been well established now that the primary method of house ignition from bushfires is via ember attack. However, direct flame contact, radiation, and convective heating can also cause house ignition. The House Ignition Likelihood Index has been developed to indicate the relative importance of each of the four mechanisms at a particular house. The index was developed using all the available information on house ignition and was tested in an area which had been subjected to a severe bushfire on Ash Wednesday 1983, in Victoria, Australia.

A lot has been learnt about the method of house ignition in bushfire prone environments. Building design, fire prevention works and suppression strategies can all be undertaken by the house owner to improve the likelihood of a house surviving a bushfire. However, often the fuels adjoining the house are managed by a public authority such as a Forest Service or National Park Service and public pressure is put on these land managers to reduce the fuel hazards. The House Ignition Likelihood Index provides an objective way of assessing the effectiveness of hazard reduction works on this public land.

The House Ignition Likelihood Index assesses the individual and combined effect of the surface, elevated and bark fuels on the ember attack, radiation load, convective load and potential flame contact for the local topographic conditions. The Index is calculated for a 1 in 50 year fire event, that is the worst likely fire weather expected to occur in a 50 year period.

Results of this research indicate that ember ignition poses the greatest threat to house ignition under a wide range of conditions for up to 600 metres from a fire edge. The threat from flame contact and radiation is only significant when forest fuels are within about 30 metres of the house, but the threat increases when houses are on steeper slopes. The threat from convective heating is generally only important on slopes steeper than 30 degrees.

The House Ignition Likelihood Index provides fire managers with a tool to assess the nature and extent of fuel hazard reduction, at a give site, to achieve an acceptable level of house ignition risk. The Index also provides a model which can be used in Bushfire Risk Management models where the appropriate level of prevention and suppression resources need to be determined.

Introduction

About 6,500 houses have been destroyed by bushfires in Australia between 1939 and 1997 (Leonard & McArthur 1999). A further 500 house have been destroyed in the most recent fire season. The increasing trend for people to live in the wildland/urban interface (WUI) increases the chances for further house destruction. This destruction of houses not only represents an economic loss, but often it also causes great human trauma and social dysfunction.

Houses do not burn as part of the fire front, they catch alight and then burn independently of the bushfire. Therefore it is important to know two things about houses in fire prone environments if the risk of their burning is to be reduced. The first is to understand the factors which lead to the ignition of the house and the second is to understand the factors which result in the house continuing to burn once it is ignited.

Much of the wildland areas in Australia are publicly owned land and the majority of this land is managed by the local National Park and State Forest agencies. Jasper (1999) recognizes the responsibility of these land management agencies in limiting the fire hazards on the public bushland, but also makes the point that the private house owners must also contribute to reducing the potential fire impact. However, given the litigious nature of our society, a large proportion of the fire management onus will always remain with the public land managers. Therefore, it is important that these land managers have a clear objective for managing fuel hazards in these parks and forests which interface urban, semi-urban and rural developments.

One of the first documented studies of house loss due to bushfires, was conducted by Barrow (1945) following the loss of houses in Beaumaris, Victoria. Barrow inspected about 100 house, 58 of which had been destroyed by the fire in 1944, and concluded that it was not the nature of the building materials used to build the house that determined its survival as much as the nature of its surroundings and the design of the house. Barrow found that all except two of the houses burnt, were ignited internally i.e. burnt from the inside out as a result of embers entering the house. Subsequent work by Wilson and Ferguson (1986) and Ramsay *et al.* (1986) following the 1983 Ash Wednesday Fires and Ramsay and McArthur (1995) following the 1994 Sydney bushfires drew some similar conclusions about the importance of ember ignition.

Ember ignition appears to be more important to house ignition in Australia than elsewhere in the world and this is probably due to the ubiquitous nature of eucalypts which produce prolific embers due to their bark (McCarthy *et al.* 1999). Cohen and Butler (1998) attribute the principal cause of house ignition to radiant heat flux. This is also the assumption made by Gettle and Rice (2002) in their model which determines the "safe" distance between houses and the fuel, although they do flag the potential importance of embers in assisting radiative ignition and acknowledge the need for further study. However, in Australia, houses up to 684 m from the nearest bushfire have been ignited (Ahern & Chladil 1999) and it has been widely accepted that the effect of radiative heat flux is not likely to be important much more than 40 m from the fire front.

There are four potential sources of house ignition: embers, radiation, flame contact and convection. In many cases it is likely that a combination of these factors are involved. The relative importance of each of these ignition mechanisms has not been incorporated into a single model, and not particularly well related to the nature of the fuel and its proximity to houses. The House Ignition Likelihood Index presented here, attempts to bring together the fuel, weather, and topographic factors that affect the likelihood of house ignition. This paper does not give any attention to house design, maintenance, suppression resources or other factors that may prevent a house from being destroyed, these factors have been dealt with elsewhere (e.g. Wilson 1988). The aim of this paper is to present a simple model that will assist land managers manage the fuel hazards in the wildland/urban interface to reduce the risk of house ignition.

Model Outline

A “design fire danger” situation is taken to be the worst possible fire weather likely in a 1 in 50 year event. The fires of Ash Wednesday in 1983 and Black Friday in 1939 represent such conditions. For the purpose of the example given here, the McArthur Forest Fire Danger Index under these conditions is 103 or Extreme. The likelihood of house ignition will be less, under less severe weather conditions.

Four methods of ignition have been recognised. These are: ignition by convective heating, direct flame contact, ember attack and radiant heating. Of these four, ember attack is known to be the most common source of ignition in house surrounded by eucalypt forests and woodlands. However, the other three mechanisms cannot be ignored since they will all play a role in different circumstances. For example, convective heating will be important to houses in steep terrain and at the top of hills or ridges, and direct flame contact and radiation will be important where there are fuels close to the house.

Five types of fine fuel are recognised, but only four are used in this model. Coarse fuels are important, but not to the same extent as the fine fuels. It is the fine fuels that largely determine the rate of spread of the fire, the flame height and the amount of embers produced. Coarse fuels add to the total heat load from the fire, but will only cause house ignition if they are within a few meters of the house, such as a firewood stack on the verandah of a house or in an adjacent wood shed. The four types of fine fuel used in this model are: surface fine fuel (predominantly leaf, twig and bark litter and grasses), near-surface fine fuels (swards of fine grasses and sedges up to 30 cm high with associated suspended litter), elevated fine fuels (shrubs, ferns, twiners and grass thickets), and tree bark fine fuels (dead, loose bark predominantly on eucalypts) as described in McCarthy *et al.* (1999). Tree canopies also have a significant amount of fine fuel, but most of this fuel is above the fire zone which affects houses on the ground. There would certainly be circumstances where canopy fuels will play and important role, but they have not been included in this model for the sake of simplicity.

The basic inputs needed to operate this model are:

- Slope of the ground below the house.
- Height of the house above the slope.
- Fine fuel hazard assessment in up to four easily recognised fuel suites.
- Distances from the house to the beginning and end of each fuel suite.
- Wind mitigation factor due to the presence of trees, walls, cliffs, etc.

Fuels are presented in this model as combinations or suites. Each suite extends for a given distance from the house before it changes to another set of conditions. This is important because it may not be the fuels closest to the house that represent the greatest threat and it may not be the same suite of fuels which pose the greatest hazard for each of the different ignition processes. For example, embers may be coming from a forest 50 m away but flame contact may be coming from elevated fuels much closer to the house.

Ignition Processes

Convective Heating

Around 80% of all the heat given out by a bushfire is in the form of convection – hot gases generally rising above the fire (Knight & Dando 1989, Tolhurst & Cheney 1999). This is therefore a potentially significant source of heating and hence ignition.

The hot gases generated from a fire tend to be buoyant and hence rise. The rate at which they rise depends on the relative temperature of the plume and the ambient air. The hotter the gases, the quicker they rise. Under very hot and dry conditions at the Berringa fire in Victoria in 1995, the smoke plume was observed to be rising at about 700 m per minute and rose to a height of about 11,000 m (Tolhurst & Chatto 1997). This rate has been used as an estimate of the vertical rise of convective heat under the extreme conditions used in this model.

Horizontally, the plume will travel at a speed dependent on the surface windspeed. The surface windspeed may be moderated by the presence of trees, rock walls, cliffs or other obstructions. In open eucalypt forest, the windspeed under the canopy near the ground is about one third that of its speed at 10m in the open (Sneeuwjagt & Peet 1985). A wind mitigation factor has therefore been used to account for the degree of exposure of the house to the wind. Houses on the top of ridges or hills have no wind reduction factor applied and those surrounded by forest have a wind reduction factor of 0.3. Other factors can be applied as appropriate.

The angle of the plume generated by a bushfire can then be calculated from the resultant vector of the horizontal and vertical velocities. Where the plume angle is less than the angle from the base of the fire to the top of the house, it is assumed that the house will receive significant convective heating. In practice, convective heating is only a likely ignition factor in very steep terrain, where the surface winds are very strong or the house is very high in the terrain.

A convective heat index of 1 is assigned when convective heat impinging on the house is coming from a fire of greater than 3000 kW/m but less than 10,000 kW/m and it is given an index of 2 when the fireline intensity exceeds 10,000 kW/m.

Flame Zone Contact

Direct flame contact can be a very effective way of igniting a house if it is applied for enough time. In this model, it has been assumed that if the conditions are suitable for the flaming zone to contact the house, then there is a high probability of ignition. It is recognised that flames may contact the house for short periods of time when volatiles are blown towards the house, but this is not considered to be of sufficient duration to ignite the structure. The house must be in the flaming zone of the fine fuels for the two or so minutes it takes for these fuels to burn out for flame contact to be a primary ignition source.

The flame length of the fire is estimated from the fireline intensity. It is based on the generalised relationship in eucalypt forest:

$$I = 300\, F_L^{\;1.2}$$

Where I is Byram's fireline intensity (kW/m), and F_L is the estimated flame length (m). Parameters for this equation are consistent with Burrows (1994) and Cheney (1981) but differ significantly from those given by Byram (1959) who developed his parameters in Ponderosa pine forest fuels. The fireline intensity has been limited to a maximum of 120,000 kW/m and the maximum forward rate of spread has been limited to 14,000 m/h since these are the maximum ever recorded under extreme weather conditions. Extrapolation of the fire behaviour models (Noble *et al*. 1980) produces unrealistically high rates of spread and flame lengths once the limits of the original model are exceeded. This estimate of flame size is less than McArthur's estimate of flame height, particularly at lower fire intensities and seems to better reflect the size of the flames observed in bushfires.

The flaming zone has a leading edge beyond the fuel if the fire is wind driven (Welker *et al*. 1965). In forests under moderate to high wind speeds, this leading edge has been assumed to be about 20% of the flame height, beyond the fuel bed. Unless the fine fuels are hard up against the house, it is assumed that this leading edge is where flame contact will be of sufficient duration to cause ignition. Periodically, the flames will skim along the ground so the horizontal extent of the flame is greater than the distance between the fire (fuel) and the house, but this flame contact is assumed to be of too short a duration to ignite a structure. When the flaming zone impinges on a house, the Flame Contact Index is given a value of 1 and where there is no contact it is given a value of zero.

Ember Attack

Thousands of embers are produced from all bushfires, but especially from those in eucalypt forests. Embers may originate from burning leaves, bark, twigs, grass or any other dislodged fine fuel, but the bark from eucalypts produces the greatest amount of ember material.

The Overall Fuel Hazard Guide (McCarthy *et al.* 1999) specifically assesses the bark hazard in eucalypt forests. The Bark Hazard rating has been converted into an effective fine fuel load. This effective fine fuel load has been used to rate the amount of ember material being produced. With an Extreme bark hazard rating, the equivalent fine fuel load is taken to be 7 t/ha and 5, 2, 0.5 and 0 t/ha for Very High, High, Moderate and Low hazards respectively. This means that the model assumes that there is about 14 times as many embers being produced from extreme bark fuels as there is from moderate bark fuels.

The ember density decreases exponentially with the distance from the fire front. It has been assumed in this model that most of the embers falling at a house will come from a distance closer than 700 m down wind. The ember density ahead of the fire is therefore described by the formula:

$$ED = \exp^{(-0.007 * D)}$$

Where *ED* is the proportion of the maximum ember density for the prevailing fuel conditions at a distance *D* from the fire front (MacAulay 2002).

The ember distribution pattern and the pattern of house damage with distance from the fire edge are compared in Fig. 1. The house damage distribution information was derived from Fig.2 of Ramsay & McArthur (1995) and shows a clear reduction with distance from the fire. The ember distribution used by MacAulay (2002) comes from measurements in a Messmate stringybark forest in Victoria. There is a remarkable similarity between the two relationships indicating a strong correlation between ember density and the probability of house damage.

It is not only the amount of ember material being produced that is important, but also the period of time over which it is being produced. The distances for each suite of fuels are used in conjunction with the estimated rate of fire spread to determine how long the embers can be expected to be landing at the house being assessed. This period of ember showers is taken to be the sum the individual release times for each fuel suite.

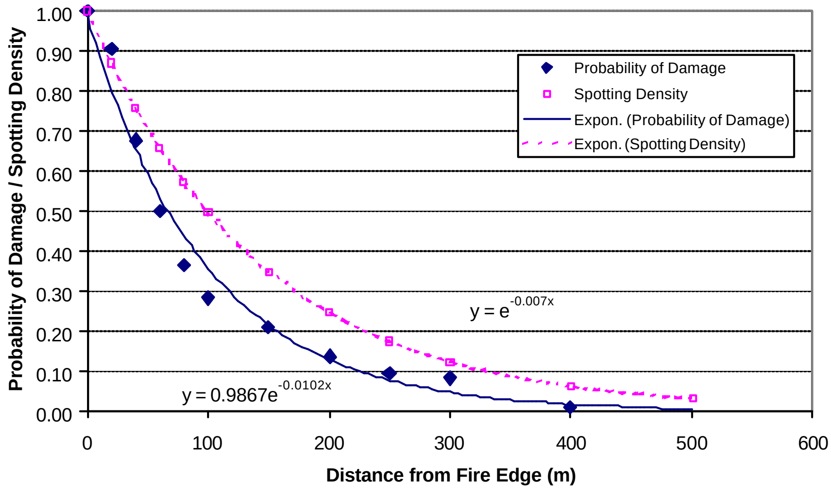

Figure 1. House damage distribution at Como/Jannali, NSW 1994 using data from Ramsay & McArthur (1995) and ember distribution used by MacAulay (2002).

The ember load is then calculated from the relative amount of ember material being released and the duration over which it is being released. This gives an "ember attack value" in tonne-minutes. This value is compared with what has been set as a maximum value when the yield distance is 700 m and the bark hazard is extreme. The ember attack index is the ratio of the ember attack value over the arbitrarily defined maximum value and then weighted by multiplying the ratio by a factor of two. For convenience, these indices have been divided into four classes (Table 1).

Table 1. Classification of Ember Attack Index into classes of ignition risk.

Ember Attack Index	**Ember Attack Class**
0 – 0.40	Low
0.41 – 0.80	Medium
0.81 – 1.20	High
> 1.20	Extreme

Radiant Heating

Radiant heat is electromagnetic radiation and hence is travels through space in straight lines. Its intensity is dependent on the size of its source (the flames) and its distance from the house and represents about 20% of the total heat output of a bushfire (Tolhurst & Cheney 1999). The intensity of radiation reduces as the square of the distance from the source.

From experiments, it has been found that when the radiant heat flux exceeds 29 kW/m^2, combustible materials, such as wood, ignite (Cohen & Wilson 1994, Gettle & Rice 2002). The radiant heat flux (Q_o) was calculated using a formula described by Leicester (1987):

$$Q_o = 60(1\text{-exp}(-I/(3000 \text{ x } D_o)))$$

Where I is the fireline intensity (kW/m), D_o is the distance of the main face of the house from the flame front (m) and Q_o is the radiant heat flux at the house (kW/m^2).

Where the radiant heat flux exceeded 20 kW/m^2, the Radiant Heat Ignition Index was given a value 1 unless it also exceeded 29 kW/m^2 in which case it was given a value of 2.

House Ignition Likelihood Index

The House Ignition Likelihood Index was then calculated as the sum of the four individual indices, i.e. the Convective Heat Load Index, the Flame Contact Index, the Radiant Heat Load Index and the Ember Attack Index. To make the interpretation of this index easier, it was divided into four classes (Table 2.).

Table 2. Classification of the House Ignition Likelihood Index in to an Ignition Likelihood Rating

House Ignition Likelihood Index	Ignition Likelihood Rating
≤ 0.5	Low
0.51 – 1.80	Medium
1.81 – 2.80	High
> 2.80	Extreme

The House Ignition Likelihood Index represents the likelihood of house ignition in unmitigated circumstances. If, for example, a radiation screen such as a rock wall is in place, the effect of radiation can be largely discounted, or if a hedge of low flammability trees surrounds the house, the effects of ember showers and radiation will be reduced. Alternatively, firefighting appliances may be in place at the time of the fire that will reduce the likelihood of the house igniting. There is a range of mitigating options that could be put in place.

A worked example is shown in Fig.2. When combined with the House Survival Meter (Wilson 1988), the House Ignition Likelihood Index can be used to explore the various options of mitigating the risk of losing a house during a bushfire.

Performance

A study was undertaken by one of the authors (KH) in the Mt Macedon area, the area studied by Wilson and Ferguson (1986) after the Ash Wednesday fire. This study assessed the fuel and topography around 38 houses, 10 of which had survived the 1983 fire and 28 of which had been either rebuilt on the site of a destroyed house or on a new site. Whilst there probably has been some vegetation modification since the 1983 fire, the area still provided a guide to the performance of the House Ignition Likelihood Index.

The results in Fig.3 show that about 70% of the houses which survived the 1983 Ash Wednesday fires had a House Ignition Likelihood Rating of Low or Moderate and only 10% were assessed to be Extreme. Of the houses built since Ash Wednesday, about 50% of them have a House Ignition Likelihood rating of High or Extreme. Since many of these houses have been built on sites where previous houses were destroyed, the House Ignition Likelihood Index seems to give a reasonable separation between potential survivors and potential losses. It should be remembered that house design and suppression activities during the fires have not been taken into account as was done soon after the fire by Wilson and Ferguson (1986). It should also be noted that there has been vegetation modification around some of these houses since Ash Wednesday to reduce the fuel hazard levels.

House Ignition Likelihood Index

Tolhurst and Howlett (2001) *DRAFT*

Legend	
	Default input
	Input
	Results

House Ignition Likelihood Index	2.35
Ignition Likelihood Rating	High

Inputs

1 in 45 year bushfire weather	
Air Temperature (oC)	40
Relative Humidity (%)	15
Wind @ 10m in open (km/h)	55
KBDI	150
Time since rain (days)	28
Last rainfall (mm)	10
Unstable atmosphere	
Drought Factor	10
Forest Fire Danger Index	103

Local Topography	
Slope below house (degrees)	10
Height of house above slope (m)	4

Local Fuels	Rating (L,M,H,VH,E)	Equivalent Fuel Load (t/ha)	Distance (m) Start - Stop
Suite 1 (adjacent to house)			
Surface FF	L	2	10
Near-surface FF		FALSE	40
Elevated FF	L	0	
Bark FF	L	0	
Overall FF		2	
Suite 2 (away from house)			
Surface FF	M	6	40
Near-surface FF	X	4	100
Elevated FF	L	0	
Bark FF	VH	5	
Overall FF		15	
Suite 3 (further away)			
Surface FF	L	2	100
Near-surface FF		FALSE	500
Elevated FF	L	0	
Bark FF	H	2	
Overall FF		4	
Suite 4 (surrounding vegetation)			
Surface FF		FALSE	
Near-surface FF		FALSE	
Elevated FF		FALSE	
Bark FF		FALSE	
Overall FF		0	

Wind Mitigation Factor	
Forest within 1 tree height	0.3
Forest within 1 to 3 tree heights	0.5
Clear view to horizon or >75m cle	0.8
Hill top, ridge top	1
Factor here =	0.5

Outputs

Fire Behaviour	Suite 1	Suite 2	Suite 3	Suite 4
Forward Rate of Spread (m/h)	494	3706	988	0
Flame Height (m)	4.9	49.8	11.8	0.0
Spotting Distance (m)	1668	13259	3630	0
Fireline Intensity (kW/m)	511	28722	2042	0
Flame Length (m)	1.6	44.8	4.9	0.0

Convective Heat Load			
Assumed rate of plume rise (m/min)	700		
	3,000 kW/m	10,000 kW/m	Default
Distance to convective heat (m)	40	40	100 m
Slope to house top (degrees)	15.4	15.4	
Plume slope (degrees)	37.4	37.4	
Convective Heat Index (0,1,2)	0		

Direct Flame Contact	
Flame conctact Suite 1?	No
Flame conctact Suite 2?	Yes
Flame conctact Suite 3?	No
Flame conctact Suite 4?	No
Flame Contact Index (0,1)	1

Ember Attack Load	
Max duration of ember attack (min)	203
Max ember attack value (t*min)	79.3
Local ember attack value (t*min)	53.4
Ember Attack Index	1.35
Ember Attack Class	Extreme

Ember A.I.	Rating
0 - 0.40	*Low*
0.41 - 0.80	*Medium*
0.81 - 1.20	*High*
> 1.20	*Extreme*

Radiant Heat Load	
Radiation Suite 1	1.0
Radiation Suite 2	12.8
Radiation Suite 3	0.4
Radiation Suite 4	0.0
Radiant Heat Flux (kW/m2)	12.8
Radiant Heat Ignition Index (0,1,2)	0

House Ignition Likelihood Index	2.35
Ignition Rating	High

House I.L.I.	Rating
0 - 0.5	*Low*
0.51 - 1.80	*Medium*
1.81 - 2.80	*High*
>2.80	*Extreme*

Figure 2. An example of the worksheet used to calculate the House Ignition Likelihood Index. In this case, the probability of ignition is High due to embers attack and flame contact.

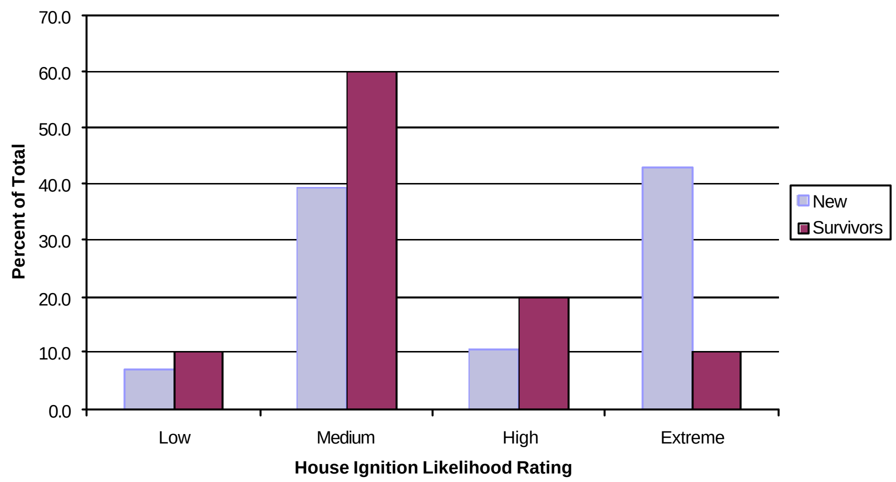

Figure 3. House Ignition Likelihood rating of 10 surviving houses and 28 new houses in the Mt Macedon area burnt in 1983 (data from Howlett 2000).

The model can also be used by land managers to help decide on how to best manage the fuel hazards on their land. Setback distances of 20 to 30 m are sufficient to reduce the risk of house ignition from radiation and flame contact in most situations. The more problematic issue is reducing the bark hazard levels to reduce the likelihood of ember ignition. Table 3 provides a guide for the depth of the necessary fuel management zones to achieve an acceptable level of risk. For example, if a Medium level of house ignition risk is considered acceptable, then houses need to be 100 to 180 m away from Very High bark hazards, but if the bark hazard is only High, then this distance is reduced to 25 to 80 m for the same level of house ignition risk.

Table 3. A guide to the distance between areas with bark hazards of different levels and a house to achieve a particular level of House Ignition Likelihood.

Bark FF	**Low Risk (m)**	**Medium Risk (m)**	**High Risk (m)**	**Extreme Risk (m)**
Extreme	>220	140 - 220	95 - 140	<95
Very High	>180	100 - 180	65 - 100	<65
High	>80	25 - 80	7 - 25	<7
Moderate	>1	0 - 1	N.A.	N.A.

Conclusions

There is a sufficient body of knowledge to construct a simple model of House Ignition Likelihood. Ignition by convective heating is likely to only occur where houses are built in exposed situations in very steep terrain, and although these houses may represent a small proportion of the total lost, convection should not be dismissed as a source of combustion, especially if assisted by embers. Ignition by radiation and flame contact only occurs where fuels are quite close to a house, and this is the most visibly obvious source of ignition, but most of this occurs from fuels 30 m or closer to the house. Probably the most important source of house ignition is ember attack. Because of the aerodynamics of embers, they can travel significant distances, igniting houses up to 600 m away from the fire edge.

The House Ignition Likelihood Index is a spreadsheet based model requiring readily available inputs. It provides landowners and land managers with a relatively simple tool that will reduce the risk of house ignition. If used in conjunction with appropriate building design, fire prevention and fire suppression, the number of houses lost in bushfires at the wildland/urban interface (WUI) could be significantly reduced.

References:

Ahern, A. and Chladil, M. (1999) How far do bushfires penetrate urban areas? Paper presented to the Australian Bushfire Conference, "*Bushfire '99*" 7-9th July 1999, Albury, Australia. Pp. 9-18.

Barrow, G.J. (1945) A survey of houses affected in the Beaumaris fire, January 14, 1944. *Journal of the Commomwealth Scientific and Industrial Research* **18**(11), 27.

Burrows, N.D. (1994) Experimental development of a fire management model for Jarrah (*Eucalyptus marginata* Donn ex Sm.) forest. PhD thesis, Dept Forestry, Australian National University (p.164).

Byram, G.M. (1959) Combustionof forest fuels. **In:** K.P. Davis, G.M. Byrma, and W.R. Krumm (eds.), *Forest Fire – Control and Use*. McGraw-Hill Book Co., New York, Chapt. 3.

Cheney, N.P. (1981) Fire Behaviour. **In:** Gill, A.M., Groves, R.H. and Noble, I.R. (eds.) *Fire and the Australian Biota.* Australian Academy of Science, Canberra, Australia. Chapt. 7.

Cohen, J.D. and Butler, B.W. (1998) Modeling potential structure ignitions from flame radiation exposure with implications for wildland/urban interface fire management. 13th Fire and Forest Meteorology Conference, Lorne, Australia, 1996. Pp.81-86.

Cohen, J.D. and Wilson, P. (1994) Current results from Structure Ignition Assessment Model (SIAM) research. Poster presented at Fire Management in the Wildland/Urban interface: Sharing Solutions Symposium. Kananaskis, Canada, October 2-5, 1994, pp.120-131.

Gettle, G. and Rice, C.L. (2002) Criteria for determining the safe separation between structures and wildlands. 4th International Forest Fire Research and Wildland Fire Safety Conference, Luso, Coimbra, Portugal, 18-23 November 2002. 9pp.

Howlett, K.A. (2000) A critical review of the Bushfire Attack Assessment Methodology used for sites deemed to be situated within a Bushfire-prone Area by Standards Australia in AS 3959-1999. 86pp. Honours project, B.For.Sc., University of Melbourne.

Jasper, R.G. (1999) The changing direction of land managers in reducing the threat from major bushfires on the urban interface of Sydney. Paper presented to the Australian Bushfire Conference, "*Bushfire '99*" 7-9th July 1999, Albury, Australia. Pp.175-184.

Knight, I. and Dando, M. (1989) Radiation above bushfires. National Bushfire Research Unit, Report, CSIRO, Canberra.

Leicester, R.H. (1987) Building technology to resist fire, flood and drought. *The Fireman*.

Leonard, J.E. and McArthur, N.A. (1999) A history of research into building performance in Australian bushfires. Paper presented to the Australian Bushfire Conference, "*Bushfire '99*" 7-9th July 1999, Albury, Australia. Pp. 219-225.

MacAulay, A.S. (2002) An investigation of the impacts of massive short distance spotting on the forward rate of spread of forest fires. M.For.Sc. thesis, Institute of Land and Food Resources, University of Melbourne. 194pp. (under examination).

McCarthy, G.C., Tolhurst, K.G. and Chatto, K. (1999) *Overall Fuel Hazard Guide* (3 edn). Fire Management, Dept. Natural Resources and Environment, Victoria. 28pp.

Noble, I.R., Bary, G.A.V. and Gill, A.M. (1980) McArthur's fire danger meters expressed as equations. *Australian Journal of Ecology* **5**: 201-203.

Ramsay, G.C. and McArthur, N.A. (1995) Building in the urban interface; lessons from the January 1994 Sydney bushfires. Australian Bushfire Conference, 27-30 September 1995, Hobart, Tasmania. 13pp.

Ramsay, G.C., McArthur, N.A. and Dowling, V.P. (1986) Building survival in bushfires. Fire Science '86, 4th Australian National Biennial Conference, 21-24 October, The Institute of Fire Engineers.

Sneeuwjagt, R.J. and Peet, G.B. (1985) *Forest Fire Behaviour Tables for Western Australia* (3 edn). For. Dept. Western Australia.

Tolhurst, K.G. and Chatto, K. (1997) Behaviour and threat of a plume driven bushfire in west-central Victoria, Australia. Proc. 13th Conference on Fire and Forest Meteorology, Lorne, Victoria, Australia, 28 - 31 October 1996. 15pp.

Tolhurst, K.G. and Cheney, N.P. (1999) *Synopsis of the knowledge used in prescribed burning in Victoria*. Dept. Natural Resources and Environment, Victoria. 97pp.

Welker, J.R. and Sliepcevich, C.M. (1966) Bending of wind-blown flames from liquid pools. *Fire Technology* **2**, 127-135.

Welker, J.R., Pipkin, O.A. and Sliepcevich, C.M. (1965) The effect of wind on flames. *Fire Technology* **1**,122-129.

Wilson, A.A.G. (1988) A simple device for calculation the probability of a house surviving a bushfire. *Australian Forestry* **51**(2), 119-123.

Wilson, A.A.G. and Ferguson, I.S. (1986) Predicting the probability of house survival during bushfires. *Journal of Environmental Management* **23**, 259-270.

Wotton, B.M., Martin, T.L. and Engel, K. (1998) Vertical flame intensity profile from a surface fire. 13th Fire and Forest Meteorology Conference, Lorne, Australia, 1996. Pp. 175-182.