

A METHODOLOGY FOR DETERMINING MINIMUM SEPARATION DISTANCE BETWEEN A STRUCTURE AND BUSHFIRE HAZARD

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Abstract

The ignition and subsequent destruction of a building in a bushfire event mainly result from one or more of the following three attack modes: embers, radiant heat and flame contact. To mitigate the effects of these bushfire attacks on a building, the provision of a separation distance together with the use of other bushfire protection measures has been proved to be an effective means and widely accepted by Fire Authorities in Australia. However, the existing separation distances prescribed within the majority of the Australian States were not derived from a sound and scientific bushfire assessment methodology which is able to quantify the levels of bushfire attack from radiant heat, flame contact and burning ember. In view of this, NSW RFS proposed a new methodology based on a more sophisticated bushfire attack model which reflects the most recent research findings in the field of bushfire behaviour modelling and radiant heat calculation. The proposed methodology consists of two sets of equations. The first sets of equations are used to model flame length which will be used for flame contact check and subsequent radiation modelling while the second sets of equations are used to model radiant heat flux. Compared with the existing methodologies, the proposed methodology has made a number of significant improvements. Firstly, it is based on a more scientifically sound bushfire attack model which reflects the latest research findings in bushfire behaviour and radiation modelling. Secondly, it provides a tool for determining the minimum separation distance for a site with specific conditions by using the parameter values, which are most appropriate to the local conditions. In addition, it is easy to be computerized into a computer-aided tool which can be used by layman. This paper will explain the methodology and its application in detail.

Introduction

To eliminate or minimize the risk of bushfires posed to property and life, one of the effective mitigation measures widely taken in Australia is the provision of a separation distance between a development site and its surrounding bushfire hazards. Depending on State or Territory, the term Separation Distance is usually exchangeable with Setback or Asset Protection Zone or Defendable Space or Fire Protection Zone. It is clear that the significant role which a separation distance may play has been well recognized by almost every State or Territory and consequently the provision of separation distance between a structure and the surrounding vegetation has been either enforced formally by using their planning instruments or recommended to the public by using the informal planning guidelines.

It is no doubt that the safety level of a development will be improved by the introduction of a separation distance. However, the level of protection rendered by the separation distance is to a large degree uncertain due to the shortcomings of the way in which they were determined. It is understood that the separation distances prescribed in the majority of States or Territories were not derived from a sound and scientific methodology, but simply were based on rules of thumb or an oversimplified model. Consequently, the resultant separation distances may be either inadequate or more than adequate.

In order for a safe and cost-effective separation distance to be prescribed, a methodology which is able to quantify the level of bushfire attack from the surrounding bushfire hazard is needed. However, a literature review on bushfire attack assessment methodologies suggests that there have been few methodologies available for this purpose in Australia. Maughan et al. discussed a methodology in the draft paper entitled "House Safety Zones: A Theoretical Model" (Maughan et al. 1999). The methodology comprises two types of models, that is, the bushfire behaviour model used to calculate flame length and radiation model used to predict the radiation level to which a building element at a given distance may be exposed. This methodology has taken vegetation, fire weather and slope into account and thus the accuracy and reliability of these prescribed separation distances derived from this methodology are higher than those simply determined by rules of thumb. However, the accuracy and reliability of the methodology are compromised due to the use of the empirical Leicester equation (Leicester 1988) for predicting radiant heat flux. Like any empirical models, the Leicester equation may not be applicable for a development sites with the situations which are different to

those from which it was derived. In addition, a maximum of radiant heat flux of 60 kW/m² is assumed in Leceiceter’s Equation and this is only believed to be appropriate for fires with thin flames (Vines 1981, Sullivan et al. 2003).

Ellis proposed a similar methodology (Ellis 2000). The principle of the methodology is that the minimum separation distance required for a development is the sum of the threshold distance determined by a view factor model and the flame length calculated by using the appropriate bushfire behaviour model for a given fuel type. It is assumed in the view factor model that a flame takes a width of 100m and radiates like a black body with an emissive power of 80kW/m². In addition, the slope between the flame and a structure assumed to be 0 degrees and 2m is used as the elevation of radiation receiver. Compared with Maughan et al.’s methodology, Ellis’s methodology has the potential to improve the accuracy and reliability of the resultant separation distances because of the use of a well established physical model i.e. view factor model for radiant heat flux prediction and the consideration of avoiding the potential flame contact by adding a flame length to the distance determined by using the view factor model. However, it also has a couple of shortcomings. Firstly, the accuracy and reliability of the predicted separation distances may be low because of the assumptions made about the flame and the topography between flame and a structure. Furthermore, the application scope of the methodology is narrow due to the fact that some input parameters used in the view factor model on which the derived separation distance equations are based on have been assigned to constant values.

In summary, although a few methodologies are currently available for prescribing separation distances between a development and its surrounding bushfire hazard, the levels of safety and cost-effectiveness of these prescribed distances are to some degree still uncertain because of the shortcomings associated with these methodologies. In order to prescribe more accurate and reliable separation distances and enable the minimum separation distances required by a development at a site with specific conditions to be determined, a new methodology for prescribing minimum separation distances is proposed in this paper. Compared with the existing methodologies, the proposed methodology made a number of refinements which includes the use of the latest bushfire behaviour models and a more generalised view factor model. This means that the proposed methodology is more accurate and more flexible. The following sections of this paper will expose the methodology in detail.

Methodology

Principle

The principle of the proposed methodology is to find a separation distance for a development located in bushfire prone land so that the development sited at this distance is able to avoid flame contact and withstand the potential radiant heat attack. As shown in Figure 1, the application of the methodology involves two sub-processes, that is, flame length modelling and radiant heat modelling. The details of these two sub-processes are dealt with below.

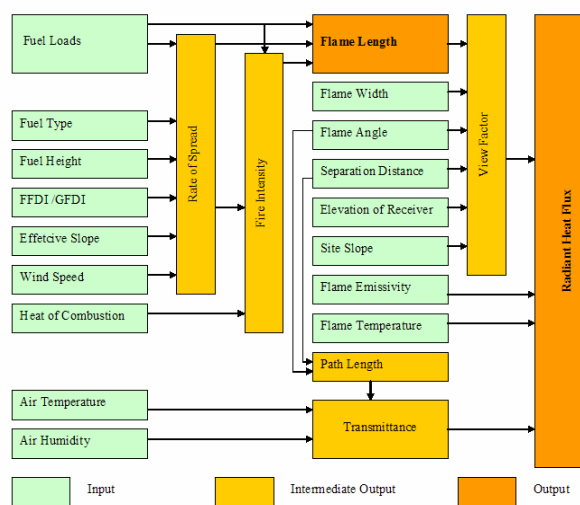


Figure 1. The process for flame length radiant heat flux modelling

Flame length modelling

The objective of flame length modelling is to estimate flame length required for flame contact check and the subsequent radiant heat modelling. Depending on the types of vegetation, flame length is modelled by using different empirical flame length equations derived from field fire trials for different vegetation types. As shown in Table 1, the modified Macarthur V equation is for forests and woodlands while Alexander's equation is for heath and shrub.

Table 1 Flame Length Equations

Vegetation Classification	Flame Length Lf (m)
Forest & Woodland (RFS PBP 2001)	$L_f = (13R + 0.24W)/2$
Shrub & Heath (Alexander 1982)	$L_f = 0.0775 * I^{0.46}$
Where Lf = flame length R = rate of spread, modelled by equations shown in Table 2 W = overall fuel load, specified in Table 3 I = fire intensity = $H * W * R / 36$ in kW/m (Byram 1959) H = heat of combustion, approximated as 18600 kJ/kg	

The use of these flame length equations requires the modelling rate of fire spread or fire intensity. Like flame length modelling, different rate of spread equations need to be used for different fuel types. As shown in Table 2, the McArthur forest V meter is used to model the rate of spread for forests and woodlands while the Catchpole's equation is used for shrub and heath. With respect fire intensity, Byram's equation is used for all vegetation types. As shown in Table 1, fire intensity is the function of heat combustion, fuel load and rate of spread.

Table 2 Rate of spread Equations

Vegetation	Rate of Spread (km/hr)
Forest & Woodland (Noble et al. 1980)	$R = 0.0012 * FDI * w * \exp(0.069 * \text{slope})$
Shrub & Heath (Catchpole et al. 1998)	$R = 0.023 * V^{1.21} * VH^{0.54} * \exp(0.069 * \text{slope})$
Note: FDI = forest fire index w = surface fuel load (t/ha), specified in Table 3 slope = effective slope (degrees) VH = average height of vegetation (m); specified in Table 3 V = average wind speed at 10m above ground, defaulted as 45 km/h	

Table 3 Vegetation Classifications and Fuel Load (PBP 2001 and DR05060 AS 3959)

Vegetation Class	Fuel Type	w (t/ha)	W (t/ha)	VH (m)
Forests	Forest	25	35	-
Woodlands	Woodlands	15	25	-
Closed Shrub	Shrub & heath	25	25	3
Open Shrub	Shrub & heath	15	15	1.5
Mallee/ Mulga	Shrub & Heath	8	8	3
Rainforest	Forest	10	12	-
Grassland	Grassland	6	6	-

Radiant Heat Flux modelling

The radiant heat modelling has been well researched in the field of fire safety engineering. The most widely used model for radiation calculation is the view factor model. When considering the effects of atmospheric attenuation, the view factor model can be mathematically expressed by:

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

Where

R_d = radiant heat flux (kW/m²)

ϕ = view factor

ε = flame emissivity, defaulted as 0.95.

σ = 5.67×10^{-11} kW/m² K⁴

T = flame temperature, defaulted as 1200K.

τ = transmittance factor

According to the radiant heat flux equation shown above, the radiant heat flux received by a point at a distance from bushfire flame is the function of flame temperature, flame emissivity, view factor and transmittance. 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 recommended flame temperature and flame emissivity for radiant heat flux modelling in the proposed methodology are 1200K and 0.95 which are considered to be conservative for determining separation distances.

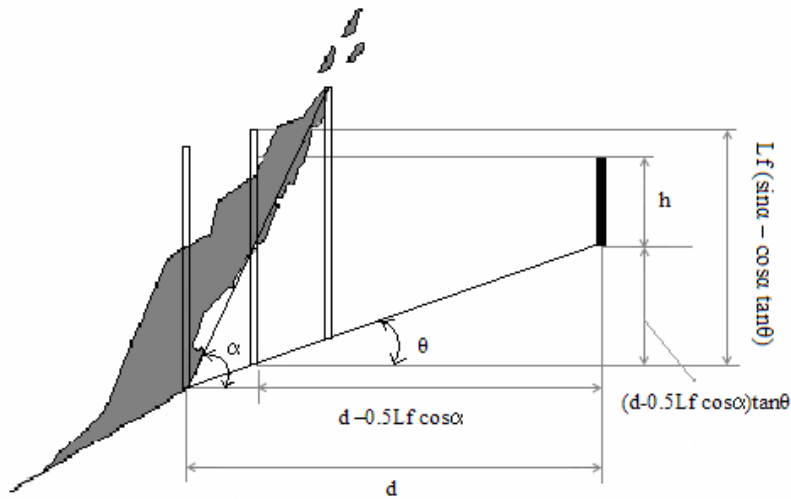


Figure 2 Diagram for Deriving View Factor of Inclined Flame

Flame temperature and flame emissivity have been considered to constant values. Therefore the determination of view factor becomes the key for radiant heat flux modelling with view factor model. In order to derive the view factor for the inclined flame show in Figure 2, 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 well 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 (Tan et al. 2005):

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

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

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

$$Y_1 = (0.5W_f) / (d - 0.5L_f \cos\alpha)$$

$$Y_2 = (0.5W_f) / (d - 0.5L_f \cos\alpha)$$

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 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 designed fire weather condition, flame length can be modelled through the flame length modelling process described previously. Flame width is defaulted as 100m in this application, which is considered to be a conservative value for bushfire applications (Ellis 2000). Site slope and elevation of receiver are site specific variables and can be determined in accordance with the conditions of a given site. Therefore, view factor becomes the function of flame angle only when flame length, flame width, site slope and elevation of receiver are known and there exists a flame angle which gives the maximum view. For instance, the maximum view factor and the corresponding flame angle are 0.289 and 66 degrees respectively for a point of at an elevation of 2m and 30 m away from a flame front with a length of 20m and a width of 100m (See Figure 3).

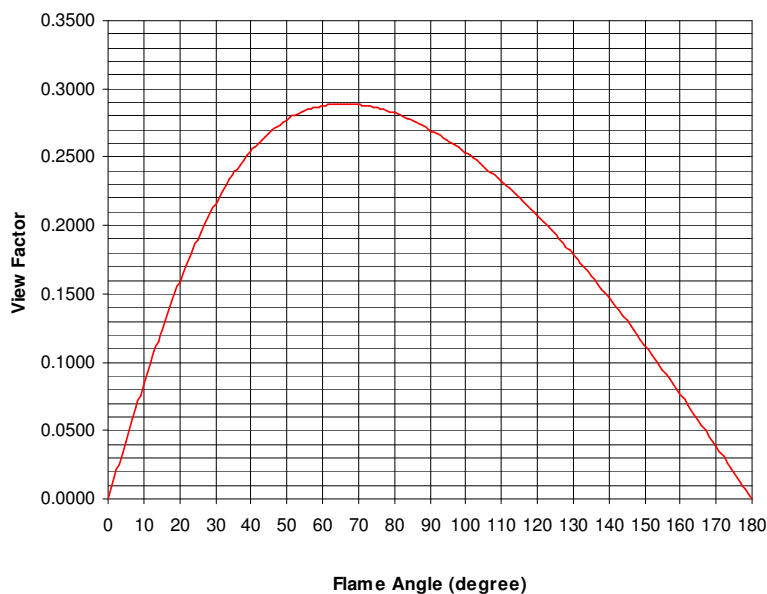


Figure 3 Effect of flame angle on view factor (based on $L_f=100m$, $W_f=100m$, $h=2m$ and $\theta =0$ degree)

In order to minimise the uncertainty resulting from the variability of flame angle, we assume that a flame always takes a flame angle giving the maximum view for a given elevation of receiver. Under this assumption, the maximum view factor and the associated flame angle can be determined by using either the graphic approach as shown in Figure 3 or the iterative approach shown in Figure 4.

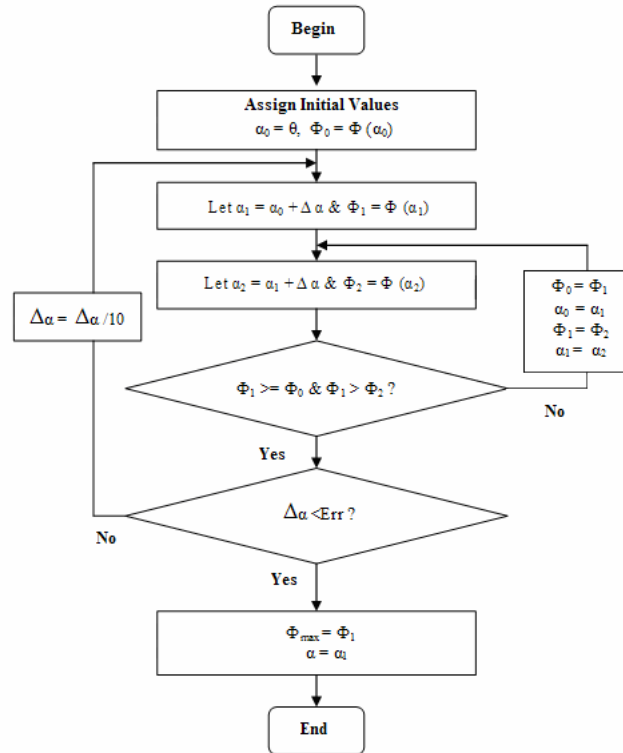


Figure 4 Algorithm for determining maximum view factor and the corresponding flame angle

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 remained 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 4

Table 4 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}

Verification

A systematic verification of the models constituting the methodology is not feasible because of the empirical nature of the bushfire behaviour equations used in the proposed methodology. As stated previously, the proposed methodology consists of two types of models. The first type of model is the bushfire behaviour model consisting of a number of empirical equations including Rate of Spread Equation, Fire Intensity Equation and Flame Length Equation. Because these equations were directly derived from field fire tests, they can not be verified or improved until more field fire tests are to be conducted in the future. Although it is not feasible to verify the methodology systematically, the core model, i.e. radiation model used in the methodology can be verified by specific examples. Below are three examples for the verification.

Example 1 Comparing With Verified Models

The computer program most widely used for radiant heat flux calculation by fire engineers in Australia is FireWind developed by Fire Modelling and Computing NSW Australia (2000). This program implements a view factor model for vertical flames. As mentioned before, the radiation model used in the proposed methodology is a generalized view factor model and therefore it should theoretically give the same results as those predicted by FireWind for a vertical flame. In order to verify this, the following hypothetical fire scenario is assumed:

Flame length=16 m
Flame width= 60 m
Flame angle=90°
Elevation of receiver= at the level of flame centre
Flame temperature =800 °C
Flame emissivity =1
No atmospheric attenuation correction

For the above assumed fire scenario, the radiant heat fluxes predicted by the two models at a distance of 5 m, 10m, 15m, 20m, 25m, 30m, 35m and 40m are tabled in Table 5 for comparison. As shown in Table 5, the predicted results from the two models are generally the same for the given fire scenario. This was anticipated because the generalized view factor model has, in this case, been adapted into the conventional view factor model for vertical flames.

Table 5 Comparing with FireWind Results

Distance from fire front (m)	Predicted by FireWind (kw/m ²)	Predicted by Proposed Model (kw/m ²)	Relative differences (%)
5	63.53	63.51	0.03
10	46.16	46.14	0.04
15	33.79	33.78	0.03
20	25.55	25.54	0.04
25	19.86	19.85	0.05
30	15.78	15.78	0.00
35	12.78	12.77	0.08
40	10.51	10.51	0.00

Example 2 Comparing With Laboratory Testing Results

Example 1 has verified the generality of the radiation model used in the proposed methodology. The following example is used to verify the appropriateness of the model in case of an inclined flame. The data used for the verification are those obtained from CSIRO's laboratory experiments (Sullivan et al. 2003). The major test equipment used in the experiments is a propane-fuelled flame front simulator. Radiant heat flux was measured at a height of 1m at a distance of 7.5m from fire front for a number of tests with different flame dimensions and flame temperatures. These measured radiant heat fluxes and those obtained from the radiation model for each given test condition are tabled in Table 6 for comparison. As shown in Table 6, the modelled data generally conform to the measured data from CSIRO. This suggests that the radiation model can provide reasonably good radiation prediction for an inclined flame under laboratory controlled experiments.

Table 6 Comparing with the CSIRO's experiment data (Sullivan et al. 2003)

Test	Flame Temperature (K)	Flame Length (m)	Flame Width (m)	Flame Angle (degree)	Radiation Measured (kw/m ²)	Radiation Modelled (kw/m ²)
5	1206	8.49	8	45	44	42.9
7a	1007	6.36	8	45	17	15.2
7c	1279	7.94	8	55	48	47.8
8	1217	6.36	4	45	22	19.7
16	1327	8.28	4	75	26	27

Example 3 Comparing With Field Test Results

Example 1 and Example 2 demonstrate that the radiation prediction by the proposed model predicated the radiation resulting from both vertical flames and inclined flames reasonably well on the condition that the required input parameters can be properly determined.

However, in real bushfire applications, some major input parameters such as flame length needs to be estimated by using the empirical bushfire behaviour models which are subject to large errors. In addition, some constant values used in the model such as flame temperature may vary within a certain range. Consequently the assessment results may be subject to a certain level of uncertainty due to the errors of these input parameters. In order to accommodate these uncertainties, it is necessary to set the parameters used in the model in a conservative way. This means that the radiation from a bushfire front may be over predicted for individual cases in which they have the circumstance which is different from the assumed one. However, the model should give pretty good prediction results when applying similar conditions to those that prevail in a real bushfire. The findings of the field studies conducted for the International Crown Fire Modelling Experiment project (Alexander et al. 1998 and Cohen 2000) can be used to verify the above statement.

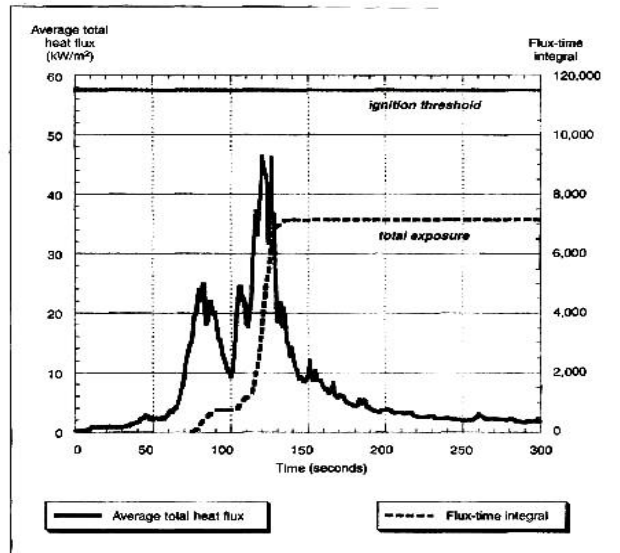


Figure 5. Measured Radiant Heat Flux

In the field studies for the International Crown Fire Modelling Experiment, total heat from heat transfer and ignition data were obtained from heat flux sensors placed in wooden wall sections. The wooden walls were located on flat, cleared terrain at 10m, 20m and 30m downwind from the edge of the forested plots. The forest was variably composed of an overstory of jack black spruce (*Picea mariana*). The spreading crown fire produced flames approximately 20m high and almost vertical. The heat flux sensors were placed at a height of 1.2m.

As shown in Figure 5, the peak heat flux measured at 10m is 46 kW/m² while the predicated radiation heat flux without atmospheric attenuation correction is 53.98 kW/m² when the major input parameter values used in the model reflect the

conditions of the field test (Flame length =20m, flame width=50 m, flame angle=90 degrees, elevation of receiver=1.2m). This indicates that the model without atmospheric attenuation correction will over predict radiant heat flux by 17.34% for the given example. Having considered the effects of atmospheric attenuation on radiant heat flux, the predicted radiant heat flux with the above test condition is 46.85 kW/m² which conforms favourably to the radiation heat flux level measured in the test. This means that by taking the effects of atmospheric attenuation on radiant heat flux into account, the radiation model will be able to predict radiant heat flux reasonably well in real bushfire situations on the condition that the values of the major input parameters used in the model reflect the conditions that prevail in these bushfires.

Application

The application of the proposed methodology for calculating minimum separation distance is not a one step process but a process involving multiple steps. To facilitate the use of this methodology, an example is given below. In this example, it is assumed:

- Vegetation type= forest.
- Effective slope=0 degree.
- Site slope =0 degree.
- FDI=80
- Other input parameters take the defaulted values

Under the above assumptions, the minimum separation distance for the specified radiant flux of 29kW/m² is then determined as follows:

Flame length modelling

(1) Rate of spread

$$R=0.0012 \times \text{FDI} \times w \times \exp(0.069 \times \text{slope}) = 0.0012 \times 80 \times 25 \times \exp(-0.069 \times 0) = 2.4 \text{ km/h}$$

(2) Flame length

$$L_f = (13R + 0.24W) / 2 = (13 \times 2.4 + 0.24 \times 35) / 2 = 19.8 \text{ m}$$

Radiant heat flux modelling

For a given separation distance, the radiant heat flux model under the above assumptions can be modelled. Therefore, the radiant heat flux – distance profile as shown in Figure 6 is then can be determined by calculating the radiant fluxes for a series of distances. Based on Figure 6, the separation distance for the radiant heat flux of 29 kW/m² is about 30m.

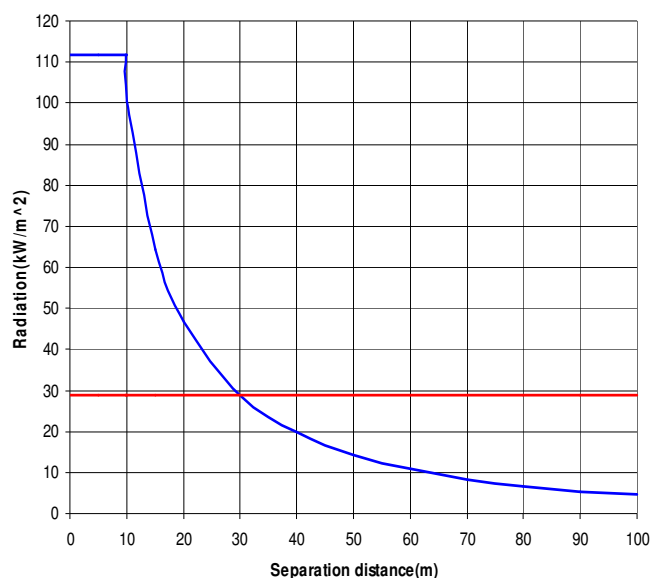


Figure 6 radiant heat flux –distance profile

Flame contact and upper limit check

In the majority of the cases, the separation distance determined by radiant heat flux modelling will be large enough to avoid flame contact and fall within the upper limit of separation distance. However, when radiant heat flux threshold used for determining separation distance is either very large or very small, then it is necessary to do flame contact check and upper limit check for the determined separation distance. For the purpose of flame contact check, it is assumed that flame follows the site slope. Therefore, to avoid flame contact, the condition $d > L_f \cos\theta$ need to be satisfied. The upper limit of separation is set to be 100m because it is the maximum separation distance specified in both AS 3959 -1999 and the Planning for Bush Fire Protection 2001. For the given example, the minimum separation distance is equal to the separation distance corresponding to the radiant heat threshold because it satisfies the flame contact and upper limit check.

Computerisation

As demonstrated in the application example, the application of the proposed methodology involves a large amount of computational effort. This means that the application of the methodology may be only limited to the well trained professionals. In view of this, a computer program implementing the methodology has been developed. Figure 7 and Figure 8 are the flowchart of the computer algorithm and the screen dump of the user interface. With the computer program, the minimum separation distance for a given radiant heat threshold can be quickly and easily determined based on the specified site conditions. For the application example given above, having specified the required inputs of vegetation type, effective slope, elevation of receiver, site slope and radiant heat threshold, the minimum separation distance will be calculated and displayed after clicking button **Calculate**. When necessary, the computer program can also be used to determine the minium separation distance for a site with specific conditions by adjusting the pre-set input parameter values.

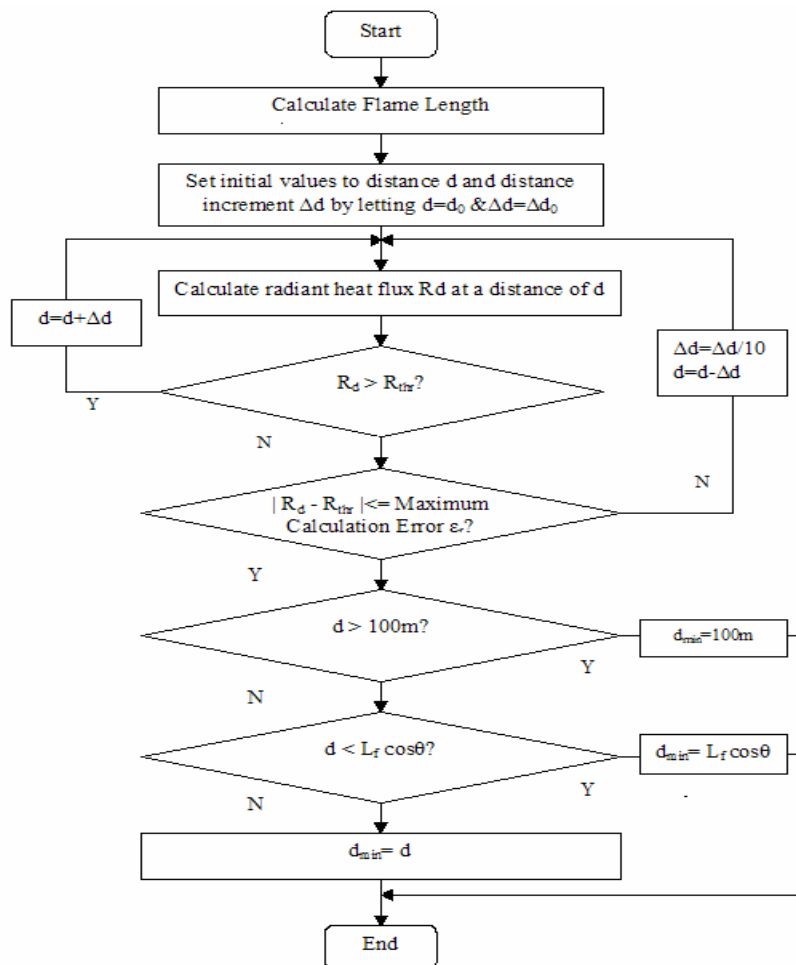


Figure 7 Algorithm for determining minimum separation distance

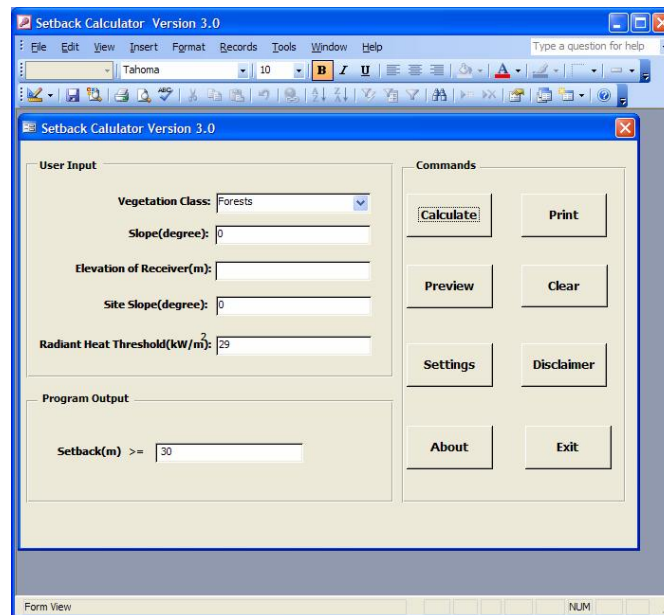


Figure 8 User interface of the computer program for calculating separation distance

Conclusions

To conclude, a methodology for determining minimum separation distance for a given radiant heat threshold has been proposed and verified with examples. Compared with the existing methodologies, the proposed methodology has the following features:

- (1) It is based on a generalised view factor model which is able to take the effect of flame inclination on radiant heat flux into account. In addition, it is more systematically constructed than other methodologies because it has articulated the bushfire behaviour model with the radiation heat flux prediction model in a systematic and logical way.
- (2) It enables safety factors to be built into the major input parameters required by the methodology. For instance, the values assigned to flame temperature, flame width, flame angle and elevation of receiver are selected either in a conservative way or by considering the worst-case scenarios.
- (3) It provides a tool for determining the minimum separation distance for a site with specific conditions by using the parameter values, which are most appropriate to the local conditions.
- (4) The core model i.e. the radiation prediction model has been verified by examples and the verification suggests that the radiation model provides reasonably good prediction for all the given examples.
- (5) It is easy for computerisation. The computerisation of the methodology makes the application of the methodology available not only to the trained professionals but also the people with little knowledge about the methodology.

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