Predicting the radiant heat flux from burning logs in a forest following a fire

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Summary

The radiant heat flux resulting from burning logs on the forest floor determines how soon after the passage of a bushfire people can survive on the burnt-out ground. A method to predict this flux was developed from the burn-out time of logs expressed as a function of initial log diameter and a given size-class distribution of logs and branches. This gives an estimate of the fraction of total power emitted per unit area, and an estimate of the radiant heat flux. In jarrah (*Eucalyptus marginata*) forest, 7 years after the last prescribed burn and carrying 36.5 t ha^{-1} of log and branch material, it takes 15 min before the radiant heat flux drops below the threshold for near-instantaneous pain and 31 min before it drops below the threshold value for long-term survival. Examples of minimum times to thresholds for other forest type groups are given, along with field observations that support the estimates.

Keywords: forest fires; fire fighters; occupational hazards; safety; heat; thermal radiation; burning; logs; Australia

Introduction

Common Australian bush lore is that it is possible to seek refuge from a bushfire by running through the fire edge onto burnt ground. This may have originated from early settlers' experience with grassfires, and with a basic understanding of grassfire behaviour it is quite possible to await a lull in the fire before stepping over short flames onto burnt ground (Cheney and Sullivan 1997). This opportunity does not readily present itself in forest fires because the flames in forest fuel persist longer than in grass fuel. Early advice (King 1961) suggested that one could pass through flames 1.5 m high and 10 m deep, although later advice (Luke and McArthur 1978; Anon. 1991) stated that running through flames should not be attempted unless one can see clearly behind the flames and they are less than 1.5–3 m deep.

Safe operating procedures for fire suppression (Luke and McArthur 1978) in forests recommend direct attack from an anchor point with planned egress back onto recently burnt ground. However, specific advice about location of anchor points, rate of line construction, and the time required for egress back to burnt ground, is either unclear or lacking (see AFAC Ltd 1996). We have been unable to find any reference that indicates how long one must wait before recently burnt ground is survivable. In the minutes immediately following the passage of the fire front it is obviously too hot to enter safely, and time is needed for the burned ground to cool sufficiently for safe access.

Firefighters caught in a burn-over situation need to shelter from the peak intensity of the fire front as well as from the residual radiation from burning material behind the fire front. Vehicles are yet to be built which can provide a safe haven indefinitely. Tyres and plastic fittings catch fire and eventually force occupants to evacuate the cabin due to toxic emissions (Cheney 1972; Mangan 1997).

In the flaming zone of a fire front, fine fuel (<6 mm) is consumed and contributes to the flame characteristics and rate of spread of the fire (McArthur 1967). Immediately behind the fire front, larger material (>6 mm), ignited by the fire, takes some time to be consumed and transfers heat by both radiation and convection.

There remain a variety of hazards on the burnt area that will be discussed later. The key factor that determines whether the burnt ground is habitable is the radiation from residual burning material. The length of time for this radiation to reduce to a survivable threshold value is dependent on the intensity of the fire front, the amount and size of the material burning behind the front, the rate of burning, and the burning characteristics of that material.

Pain has been found to occur when skin temperature reaches between 42°C and 45°C (Buettner 1950; Stoll and Greene 1959). This occurs when the peripheral blood flow in the skin is unable to remove heat arriving on the surface of the skin and damage to cells begins. The value of the thermal radiation energy required to cause pain is dependent upon the incident radiant energy and the period of exposure. Arnold *et al*. (1973) as cited by Backer *et al.* (1976) note that burn damage to human skin is caused by thermal input rates in excess of approximately 0.05 cal cm^{-2} s^{-1} (2 kW m^{-2}) and that it takes about 2.0 cal cm^{-2} (84 kJ m^{-2}) of accumulated heat with exposure in excess of this rate to cause a partial thickness blistering (second degree) burn. At these general threshold values, blistering will occur in approximately 42 s. This compares to the findings of King (1962) of about 32 s before pain is unbearable. Budd *et al.* (1997a) use the value of 2 kW m^{-2} to define the thermal radiation pain threshold.

Butler (1969) chose 1.25 kW m^{-2} as the long-term (greater than 1 h) radiant heat survival threshold for studies of life safety in mass fires. While this value is much lower than that required to cause burns, if radiation in excess of this value, but less than the pain threshold, is received for extended periods (e.g. 1 h) in a situation where heat-loss capability is marginal, the skin will eventually not be able to rid itself of the excess energy and will rise in temperature causing pain and eventually incapacitation and possibly death.

The recommended standard for wildland firefighter clothing is light, well-ventilated garments, to protect from sparks and low levels of radiant heat and allow the escape of metabolic heat from physical exertion. Firefighters regulate their work environment by wearing very little beneath their overalls (Budd *et al.* 1997b), working with bare skin exposed (e.g. no gloves, sleeves rolled up, etc.), and retreating from the fire when conditions become uncomfortable (Budd *et al.* 1997c; Budd 2001). In retreating onto burnt-out ground, the clothing will heat up during prolonged exposure to radiant heat, well above the pain threshold temperature, and give pain when the cloth eventually, through movement, comes in contact with the bare skin beneath.

For the purposes of setting threshold radiant energy levels, those thresholds based on bare skin have been chosen. Despite the ability of clothing to increase the radiant energy threshold, exposed skin such as that of the hands, face and neck will limit the amount of radiant energy a firefighter can safely tolerate.

By using information on the burning rate of logs and the distribution of appropriate log attributes within the forest, we propose a method to determine the expected rate of release of energy from the logs which we have called the power output of the logs. An approximation of the total amount of radiant heat flux as a percentage of the total power output enables us to estimate the radiant heat flux expected from the burning logs. While the burning relationships and log size distributions used in this paper are for specific cases, these are for example only. The method could be applied to any forest fuel type.

Log burning characteristics

Log flame residence time

Cheney *et al.* (1990) developed an equation to predict the flame residence time of silvertop ash (*Eucalyptus sieberi)* logs from experiments conducted in a hearth using pilot ignition. Log diameters ranged from 0.6 cm to 25 cm; each log was 70 cm in length. Moisture content of the logs ranged from 12% to 64% oven-dry weight. The relationship they found for logs <12.5 cm was independent of moisture content:

$$t_r = 1.7 d^{1.686}\,, \tag{1}$$

where t_r is residence time of flames (min) and d is diameter of log (cm). This is similar in form to that found by others (e.g. Clements and Alkidas 1973; Burrows 2001). Burrows (2001), using dead oven-dried round wood (twigs and branches) of jarrah (*E. marginata)* up to 16 mm in diameter burnt on a metal gauze platform suspended over methanol flames, found:

$$t_r \propto d^{1.875}\,. \tag{2}$$

Cheney *et al.* (1990) found that logs >12.5 cm diameter had higher moisture contents and did not maintain continuous flaming combustion and also observed that both flaming and glowing combustion were maintained longer when there was a forced air flow over the fuel. Under a Keetch–Byram Drought Index (Keetch and Byram 1968) of 106 (just into the top fuel consumption class in McArthur's Mk 5 Forest Fire Danger Meter), O'Loughlin *et al.* (1982) reported 100% consumption of litter and twigs, 74% of 5–10 cm diameter branches, and up to 56% of logs up to 20 cm diameter. Under conditions of extended drought, extreme fire danger and strong winds, we have assumed that Equation 1 can be used to define the burning rate of logs of up to 15 cm radius.

In SI units, Equation 1 becomes:

$$t = 7.729 \times 10^5 r^{1.686}\,, \tag{3}$$

where t is in seconds, and r is the radius of a log in metres.

Log burning rate

If we assume that instantaneous burning rate is dependent only on current diameter and not burning history (i.e. it does not depend on time since ignition, initial diameter, charcoal/ash buildup, etc.), then Equation 3 can be re-interpreted as an equation describing the change in radius with time as it burns. To do this we must differentiate Equation 3 with respect to r, invert and negate to ensure that the radius of the log decreases with increasing time:

$$\frac{dr}{dt} = -7.674 \times 10^{-7} r^{-0.686}\,. \tag{4}$$

We now need a relationship from which we can determine r as a function of the time t and the initial log radius r_0. By inverting Equation 4 and integrating over the range of r: $r_0 \rightarrow r$ we obtain:

$$t = -1.303 \times 10^6 \int_{r_0}^{r} r^{0.686}\,dr\,. \tag{5}$$

The solution of this equation is:

$$t = -7.729 \times 10^5 (r^{1.686} - r_0^{1.686})\,. \tag{6}$$

Rearranging to solve for r, we obtain a relationship for the radius of the log as a function of r_0 and the time the log has been burning:

$$r = \sqrt[1.686]{r_0^{1.686} - \frac{t}{7.729 \times 10^5}}\,. \tag{7}$$

Log power output per metre

The total energy contained in a unit length of log is:

$$E_L = H\rho\pi r^2\,, \tag{8}$$

where E_L is the total energy of the log (kJ) per unit length, H is the heat yield of the log (kJ kg^{-1}) and ρ is the density of the log (kg m^{-3}). The time rate of energy released from the log is the power output (kW), i.e. $P = -dE/dt$. Thus:

$$P_L = -\frac{1}{dt}(H\rho\pi r^2)\,. \tag{9}$$

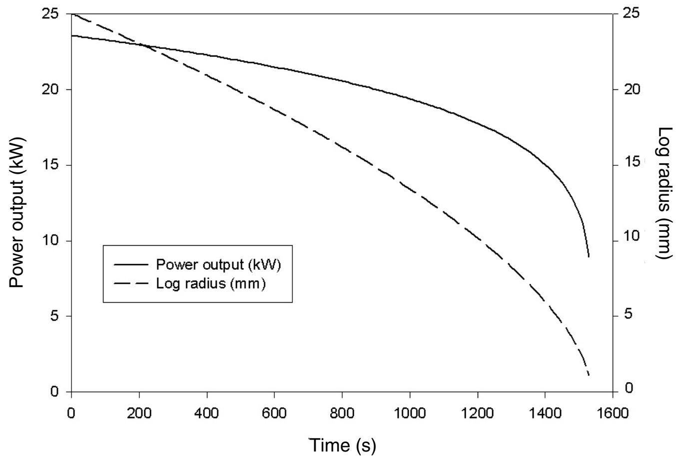

Figure 1. An example of the power produced by a log 1 m long, 25 mm in radius, over time (solid line). The reduction in radius of this log as it burns is also shown (dashed line). Heat yield H = 18 700 kJ kg^{-1} and density ρ = 830 kg m^{-3}. The steep drop-off of the power towards the end of the life of the log is a property of the burning rate relationship on which the power function is based. The resolution of the time step also affects the appearance of the relationship. The estimated total energy under the solid line is 30 629 kJ. The potential total energy for this log is 30 475 kJ.

Using the chain rule, this becomes:

$$P_L = -2H\rho\pi r\frac{dr}{dt} . \quad (10)$$

By substituting Equation 4 into Equation 10 we get:

$$P_L = 1.535 \times 10^{-6} H\rho\pi r^{0.314} . \quad (11)$$

If we substitute Equation 7 into Equation 11, we get a relationship for P per unit length of log as a function of initial log radius r_0 and t:

$$P_L = 1.535 \times 10^{-6} H\rho\pi \left(r_0^{1.686} - \frac{t}{7.729 \times 10^5}\right)^{0.186} . \quad (12)$$

Therefore, knowing the initial radius of a log, we can determine the power output per metre of log as a function of time as it burns. For a given heat yield, density and initial log radius, the power produced by the log can be tracked over time. Figure 1 shows the power produced per metre length by a log 0.025 m in radius, H of 18 700 kJ kg^{-1}, and ρ of 830 kg m^{-3}. Figure 1 also shows the reduction in log radius with time. The estimated total energy output from the log, calculated as the sum of the energy for each time step, is 30 629 kJ. The potential total energy for this log (Equation 8) is 30 475 kJ, so the approach is valid. The slight difference in the two values is due to the resolution of the time step used when processing Equation 12.

While Equation 12 and Figure 1 are based on the flame residence time equation of Cheney *et al.* (1990) for *E. sieberi*, substitution of Equation 2 (Burrows 2001) gives similar results. In order to devise a power relationship applicable to a broad range of fuel sizes, we retain Equation 1 because it is based on a larger range of log sizes than Equation 2.

Log size distribution

In order to apply Equation 12 to a forest, we need to know something about the distribution of branch and log material. A number of techniques exist to assess and quantify the amount and distribution of log fuel on the floor of the forest (Warren and Olsen 1964; Van Wagner 1968, 1982; Brown 1971, 1974) using a line intersect method of sampling. Recent work by Arcos *et al.* (1996) discusses estimating woody debris volume from stereoscopic images. For the purposes of this paper we will use, as an example, a data set obtained by Burrows (1994) for a commercial jarrah (*E. marginata*) forest using the line intersect method of Van Wagner (1968). These data are reproduced in Figure 2. A total of 36.5 t ha^{-1} was measured by Burrows.

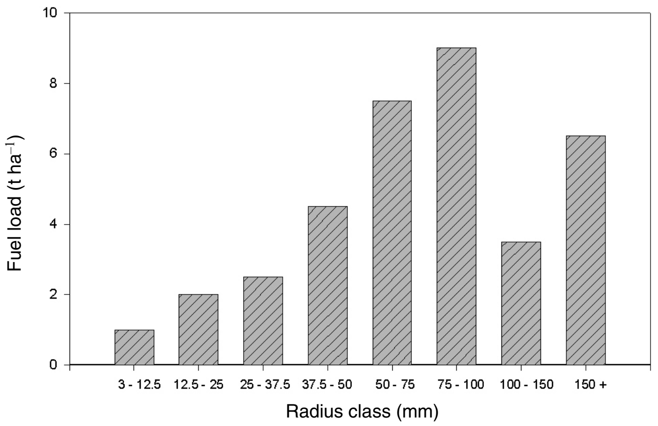

Figure 2. Mean quantity of coarse woody fuel on the floor of a typical jarrah forest burnt 7 years previously. The quantity of coarse fuel depends on the silvicultural and fire history of the forest. Reproduced from Burrows (1994).

Burrows found that the quantity and distribution of the large material was highly variable and reflected past silvicultural operations on the site (i.e. harvesting procedures and prescribed burning practices) and natural processes of limb cast and tree fall.

By knowing the distribution (kg m^{-2}) of each radius class and assuming a linear distribution within each size class, we can apply a simple geometric relation to convert these data to a distribution of radius class in total lengths. That is:

$$L_A = \frac{w}{\rho\pi r^2} , \quad (13)$$

where L_A is the total length per unit area for that radius class, w is the fuel load per unit area for that radius class (kg m^{-2}), and r is the median of the radius class. Figure 3 shows the values of Figure 2 for each radius class median converted to total length per unit area. The largest radius class (150+ mm) has been dropped as the open-ended nature of this class makes determining the median difficult. The total length of this radius class would be negligible when compared to that of the other classes.

Total power output

If we apply Equation 12 for each radius class median and multiply by the total length of log per square metre (Equation 14), the result is the total power per unit area (kW m^{-2}) for that radius class:

$$P_A = P_L \times L_A . \quad (14)$$

As all radius classes co-exist, the total power released by all

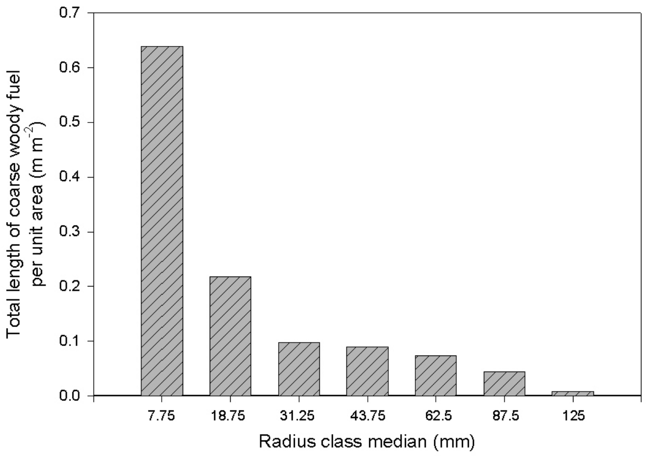

Figure 3. Total length of coarse woody fuel for each radius class median based on the fuel load measurements of Burrows (1994). Fuel loads have been converted to total length per unit area using Equation 13.

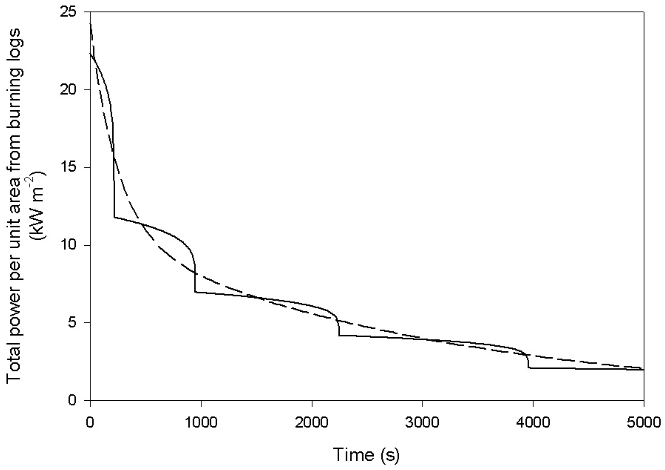

Figure 4. Total power per unit area (kW m^{-2}) estimated for a typical commercial jarrah forest based on fuel load measurements by Burrows (1994). The contribution of each radius class via the median can be clearly seen in the stepwise nature of the graph. The smallest radius class provides most power but is quickly consumed because of its dimensions. Larger material releases less power, but over a longer time. The step-wise nature of the curve is due to the discrete radius-size data set used. It can be approximated by an exponential decay curve (dashed line).

burning logs is simply the sum of the power output of each log class. However, the conditions under which the forest is burnt (e.g. drought, soil moisture deficiency and fire weather) will determine which of the log radius classes actually ignite and burn.

For the purposes of this paper we will assume that all log material is contributing to the power output following the passage of the fire. Figure 4 shows the total power per unit area output from Burrows' data.

Radiant heat flux

Estimation of the radiant heat flux from the total power per hectare depends on the fraction of fuel consumed by different modes of combustion (e.g. flaming, glowing or smouldering), and the fraction of the total power released by a fire emitted as radiant energy (total power being the sum of radiation, convection and conduction).

Burrows (2001) found that the proportion of fuel consumed by flaming combustion decreased with increasing fuel diameter. At fuel diameters 65–75 mm, 45% of oven-dried jarrah was consumed by flaming combustion and 45% by glowing combustion. Cheney (1990) found that in a large pile of brigalow fuel, mostly 25–75 mm in diameter, continuous flaming accounted for 60% of fuel consumption.

Provided the whole of the log is involved, the rate of mass loss during combustion is constant (Cheney *et al.* 1990). Because both flaming and glowing combustion continue simultaneously, we have assumed that the fraction of energy released as radiation is independent of the mode of combustion.

Anderson (1969) states that the radiation component will not be more than 40% of total energy output. Packham (1971) found a ratio of convection to radiation of 3:1, suggesting 25% radiation. Knight and Dando (1989) measured 17% above a grass fire. For most purposes, a value of 20% of total power will be suitable for the radiation component.

The actual spatial distribution of the coarse woody material will be difficult to know without detailed sampling of the site prior to the fire. On a compartment scale, we can assume that the distribution of all radii is uniform across the area in question. On the scale that radiation will impact on a firefighter, namely the size of a person and the area contributing significant radiation flux, we must treat larger radius material differently to smaller radius material.

The separation of these two components will occur when spacing of the components is such that gains can be made by selecting an optimal travel path through the material. In our example data set, we would argue that this threshold would occur at a radius class median of 18.75 mm where total length of material larger than this radius is less than 0.2 m m^{-2}, but any value can be selected.

Branch material (e.g. radius class median 7.75–18.75 mm)

The total amount of this branch material will be quite high when compared to larger log material. In the case of our example, there is over 0.8 m m^{-2} of total length for these classes (Fig. 3) and, for the most part, the bulk of the radiant heat flux comes from this source. If we assume a uniform distribution of this material then it is essentially omnipresent and it can be argued that the radiant heat flux from the combustion of these smaller radius fuels will be diffuse. That is, there is no one particular source for the radiant energy.

Thus for small logs, the radiant heat flux, I_{RHF} (kW m^{-2}), will be:

$$I_{RHF} = 0.2 \times P_A \,, \tag{15}$$

where P_A is the total power per unit area (kW m^{-2}), and 0.2 converts total power per unit area (or total heat flux) to radiant heat flux (kW m^{-2}).

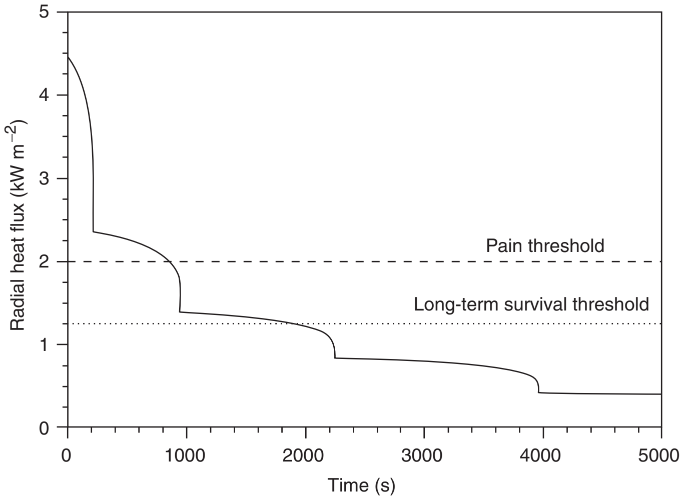

Figure 5. Total radiant heat flux (kW m^{-2}) estimated for a typical commercial jarrah forest 7 years after last being prescribed burnt, based on the fuel load measurements by Burrows (1994), where soil moisture deficiency is such that all log material (radius 3–150 mm) is contributing to the radiant heat. The dashed line at 2 kW m^{-2} shows the threshold of pain on unprotected skin. The dotted line at 1.25 kW m^{-2} shows the long-term (>1 hour) survival threshold. In this fuel load, the time to pain threshold is 15 min and the time to long-term threshold is 31 min.

Larger log material (e.g. radius class median ≥ 31.25 mm)

In contrast to branches, there is much less total length of each larger radius class (<0.1 m m^{-2}). In addition, due to the larger nature of the logs, they cannot be considered omnipresent and their radiant heat flux is not diffuse. That is, when walking through a forest, one will be able to pick a path between larger logs but necessarily step on the many smaller branches. As a result, the radiant heat flux from larger logs must be treated as line sources.

One way to do this is to assume that the logs are uniformly distributed across the area and the resultant intensity is that felt following an optimal path between evenly separated logs. Given the semi-circular emission of the logs and assuming that the average distance between the logs, D, is less than the average length of each log, the radiant intensity (20% of the total power per unit length, P_L) must be distributed evenly on a hypothetical half-cylinder of diameter D. The radiant intensity is thus:

$$I_{RHF} = \frac{0.2P_L}{\pi(0.5D)}, \tag{16}$$

and D, the average distance (m) between uniformly separated logs, is given by

$$D = \sqrt{\frac{h}{L_A}}, \tag{17}$$

where L_A is the total length of log of a radius class per unit area and h is the average length of log (m). The average length of logs of each radius class can be ascertained by biomass sampling methods, determined from various taper functions or estimated. In our example, an estimate of the ratio of log length to median radius of 100:1 was chosen for simplicity.

Results

The calculated total radiant heat flux following a fire in a jarrah forest 7 years after the last prescribed burn, where all log material is contributing to the radiation, is shown in Figure 5. This figure combines (using simple addition) the diffuse radiant heat flux from branch material with the line source radiant heat flux from larger log material.

Figure 5 shows that at least 15 min must pass before one can safely venture into the jarrah forest without suffering near instantaneous pain from the radiant heat from the burning log material. At or above this threshold, 40 s exposure will result in partial thickness blistering (which used to be called second-degree) burns. More than 31 min must pass before the thermal radiation has dropped to below the long-term (>1 h) threshold. In practice, however, fuel is never uniformly distributed, and optimum travel paths or relative refuges can be found in the forest where fuel density is less than other areas.

Making the assumptions that other species have the same burning characteristics as *E. sieberi,* and that the distribution of log material is the same as measured by Burrows (1994), we can examine the minimum time needed for the thermal radiation from coarse fuels to reduce to the pain threshold (2 kW m^{-2}) and long-term threshold (1.25 kW m^{-2}) for different forest type groups (Table 1).

Indicative fuel (>6 mm) volumes are used as an illustration, based on the log fuel loads measured by Burrows: 44 m^3 ha^{-1} (36 t ha^{-1} in jarrah forest) represents a dry eucalypt forest subject to regular prescribed burning (Burrows 1994); 84 m^3 ha^{-1} (70 t ha^{-1} in jarrah) represents a long-unburnt dry/transitional eucalypt (O'Loughlin *et al.* 1982); 120 m^3 ha^{-1} (100 t ha^{-1} in jarrah) might represent tall wet eucalypt forest. In some forest types or following particular silvicultural practices, log fuel volumes can be much higher than these examples (Cheney *et al.* 1992).

There are not a lot of data about the amount and distribution of coarse fuel (>6 mm) in forests. Not all forest types will have the same distribution as the example or be capable of achieving the coarse fuel loads listed in Table 1. The shaded cells highlight peculiarities of some threshold times due to the step-wise nature of the radiant heat flux curve (a result of the discrete nature of the radius class data) as seen in Figure 5. In these cases we would expect the difference between the two threshold times to be greater than calculated.

Discussion

The extent of combustion of large woody material during forest fires is variable, depending on fuel dryness, wind speed and the intensity of the fire in the litter fuel (Burrows 2001). Under conditions of moderate drought (KBDI = 106) and High Fire Danger (FFDI = 24), O'Loughlin *et al.* (1982) noted that 56.5% of branches (0.05–0.1 m radius) and 26% of logs (>0.1 m radius) were consumed. We have observed high consumption of log material under extreme fire weather conditions, particularly when strong winds maintain glowing combustion. Even if the largest logs are not completely consumed, we consider that it is reasonable to expect log material up to 0.15 m radius to remain

Table 1. Minimum time to threshold values for different forest types[a]

Forest type group	Average air-dried wood density (kg m^{-3})[b]	Average air-dried wood heat yield (MJ kg^{-1})[c]	Large fuel (> 6 mm) volume per hectare								
			44 m^3 ha^{-1}			88 m^3 ha^{-1}			120 m^3 ha^{-1}		
			Equivalent fuel load (t ha^{-1})	Minimum time to pain threshold (min)	Minimum time to long-term threshold (min)	Equivalent fuel load (t ha^{-1})	Minimum time to pain threshold (min)	Minimum time to long-term threshold (min)	Equivalent fuel load (t ha^{-1})	Minimum time to pain threshold (min)	Minimum time to long-term threshold (min)
Box-ironbark (e.g. *E. melanophloia*, *E. crebra*, *E. paniculata,* *E. fibrosa*, *E. sideroxylon*, *E. microcarpa*, *E. microtheca*)	1100	17.2	48.4	16	37	92.4	65	91	132.0	102	120
Darwin stringybark (e.g. *E. tetrodonta*, *E. miniata*)	1000	17.2	44.0	16	36	84.0	63	66	120.0	83	120
Bluegum (e.g. *E. nitens*, *E. globulus*, *E. cypellocarpa*)	900	16.8	39.6	14	28	75.6	54	66	108.0	66	118
Stringybark (e.g. *E. obliqua*, *E. muellerana*, *E. baxteri*, *E. macrorhyncha,* *E. marginata*)	860	17.5	37.8	14	27	72.2	53	66	103.2	66	118
Peppermint/ash (e.g. *E. sieberi*, *E. fastigata*, *E. amygdalina*, *E. nitida*, *E. radiata*, *E. dives*)	800	17.1	35.2	7	16	67.2	38	66	96.0	66	115
Radiata pine (*Pinus radiata*)	510	17.9	22.4	4	12	42.8	30	48	61.2	57	66

[a] Data given in this table provide only relative indications of time to threshold for each forest type. Shaded cells illustrate the peculiarities of the step-wise nature of the discrete radius classes used to determine the threshold times, which must be taken into account. In these cases we would expect the difference between the two threshold times to be greater than calculated.

[b] Taken from Boland *et al.* (1984) and Wallis (1956).

[c] Taken from Groves (1983) and Todd (1983).

burning at least while the thinner branches and logs are burning and contributing to the radiant heat flux above the survival threshold value.

The time listed in Table 1 is the minimum time required for the radiant heat flux from burning branch and log material to reduce below the given pain and long-term threshold values (i.e. minimum time to threshold). Validation of Table 1 is understandably difficult. Nevertheless, observations made by the authors during experimental burning tend to support the calculated threshold values.

Specific measurements of the time for the radiation to drop below the pain threshold value were not undertaken during the Project Vesta (Cheney *et al.* 1996) experiments, but some general observations of the time required before access was considered safe were noted. Scientists charged with recovery of equipment considered they would have to wait longer than 15 min in an 8-year-old jarrah forest (carrying in the order of 10–12 t ha^{-1} fine fuel) before radiation reduced below the pain threshold (Gould[1] *pers. comm.* 2001). One of the authors (Cheney) found that the minimum time which elapsed before he could traverse a 3-m-wide cleared track between burning 20-year-old and 2-year-old residual fuels was 12 min. He is confident that the radiation within the 20-year-old fuel at this time would have exceeded his pain threshold.

The tall open forests of the Northern Territory (*E. tetradonta, E. miniata*) that were subjected to annual burning have little branch material and scientists conducting grass fire experiments in annual grasses walked as close as 20 m to the end of the flaming zone of the fire (in the order of 30 s behind the flame front). In the dry season after Cyclone Tracy, further fire experiments were carried out in a 2-year-old fuel containing uncharacteristic branch fall as a result of the cyclone. Scientists stepping through the flames close to the head fire found unexpected thermal radiation loads from burning branch material and had to immediately seek egress to a cooler part of the burn, which was 180 m upwind of the head fire and had been burnt about 7 min previously. Radiation caused burns to parts of the body orientated horizontally (e.g. forearms when holding objects, earlobes, etc.). By working backwards and assuming Burrows' fuel distribution, this time equates to a total fuel load of about 25 t ha^{-1}. However, as the branch and log fuel had a maximum radius size of only around 50 mm, this time suggests an equivalent branch fuel load of about 7 t ha^{-1}, which is not unreasonable.

The high density of the wood of Darwin stringybark and box-ironbark species significantly extends the minimum time to threshold. Firefighters need to exercise caution in box-ironbark forests with a grassy understorey due to the much longer time to pain threshold than adjacent grasslands.

The figures given in Table 1 may underestimate the time taken for radiation from burning logs to reach a given threshold value because the combustion of the logs could well be slower than calculated using Equation 1, e.g. logs burning on the top surface rather than uniformly all round, logs burning in segments rather than all at once, etc. If this occurs, the peak radiation will in fact be below the calculated peak, but could remain above the long-term threshold, which is really a very low radiation flux value, for some considerable time. Under extreme drought conditions, when there is high consumption of branch and log material, there have been anecdotal reports of minimum time to pain threshold as long as 1 hour in dry stringybark forests, which equates to a coarse fuel load of 70–100 t ha^{-1}.

In practice, there could be considerable variation in the minimum time to threshold depending on the dryness of the coarse material and its combustibility. Some species, e.g. *E. marginata*, tend to char but not maintain combustion, whereas other species in the same community, e.g. *Corymbia calophylla*, will burn away to a white ash.

The low volume of *Pinus radiata* in Table 1 appears to have extremely short minimum times to threshold values when compared to eucalypt forest type groups. This is due to the low equivalent fuel load for a given volume of fuel because of the low density of the wood. Anecdotally, softwoods have shorter minimum times to thresholds. Again, the lower density of these woods means that there is much less weight of wood for a given volume than is found in higher-density hardwood species. In addition, there may be some differences in the wood composition and resultant combustion characteristics of softwoods that make them burn differently to hardwoods (Crane 1983).

The minimum time to threshold should be taken into consideration when planning fire suppression. Where it is necessary to establish a refuge area by burning (e.g. at the anchor point of a burning-out operation), there will be a considerable delay before the area is cool enough to be used. When undertaking direct attack on the flank, it is possible to find a suitable area by progressing some depth into the burned area where, due to the slow spread of the flank fire, the area has burnt out some time before. In the same vein, experience with egress onto burnt area during prescribed burning operations may lead to a false sense of security when it comes to wildfire suppression. A distance of 20 m from the fire edge in a prescribed fire may have been burnt 20 min previously, whereas a distance of 20 m from the fire edge in a wildfire may have been burnt only a few minutes previously.

Differences in rates of spread and in fuel consumption mean that the minimum time to threshold after any wildfire is much more a temporal entity than a spatial one. This means there can be no simple rules of thumb when it comes to determining how far one should proceed into the burnt area to reach relatively safe ground. Additionally, not only is the surface material ignited during a wildfire, but bark and dead material aloft may remain burning and contribute to the residual heat load. Generally, bark is consumed within the fire front, but the bark of long-unburnt stringybark-type species may have significant but unquantifiable thermal output long after the fire front has passed.

Even after the surface material has stopped burning and radiant heat loads have reduced, considerable dangers remain on the recently burnt ground. Old stumps and organic terrain can remain burning underground; at one stage this was the major source of

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injury to firefighters in Victoria (P. Billings[2] *pers. comm.* 2001). In addition, there is the high risk of falling limbs and trees, particularly in long-unburnt old-growth forests. Firefighters creating a safe refuge by burning must also take these factors into consideration and select a safe spot within the burnt area.

Conclusion

A method for determining the radiant heat flux from logs burning behind the fire front has been proposed and illustrated using an example flame residence equation and fuel distribution data set. The minimum time required before the radiant heat flux in the forest dropped below the threshold values for pain and long-term survival is determined for a number of forest types. While difficult to validate, the method is shown to provide reasonable estimates of these times and is supported by field observations.

While the practice of burning out refuge areas is common in grass fuels, the results of this paper show that time in the order of tens of minutes must be allowed before similar burnt refuges in forest fuels are safe. This knowledge should be included in firefighter safety training.

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