Symbol	Types of wood	Diameter (mm)	Fuelbed width (cm)
+	Bamboo	2.3	55
⧖	Birch	3.3	55
□	White pine	1.3	55
△	White pine	1.3	100
•	White pine	1.9	55
○	Birch/White pine	3.3/1.3	55

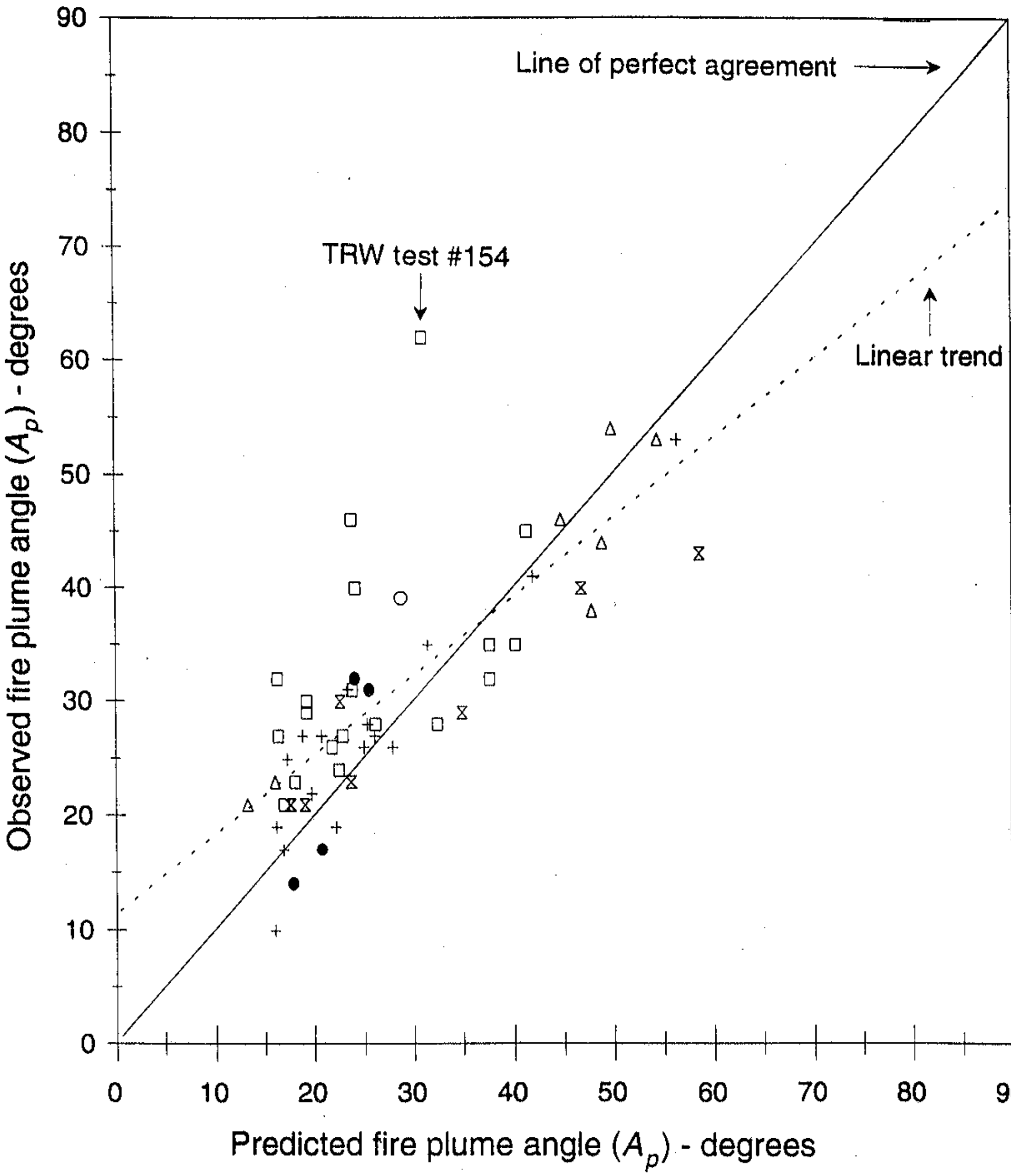

Figure 3.11: Fire plume angle predictions by Equation 3.15a versus actual observed fire plume angles based on experimental fires conducted in a wind tunnel as reported on by Fendell et al. (1990).

individual wind tunnels, the range of environmental conditions tested, and the ensuing fire characteristics. The maximum $\boldsymbol{u}$ examined by Nelson and Adkins (1986) was 2.29 m/sec compared to 4.6 m/sec (Table 3.2) in the Fendell et al. (1990) study and although the computed I_B values were comparable between studies, A in turn averaged 58±8° and ranged from 44-72° in contrast to the more acute angles encountered in the Fendell et al. (1990) study (Table 3.2). However, the differences could be due to the fact that turbulent flames simply have greater rigidity than heated air with respect to the bending by wind. In other words, for a given I_B and u, A will always be a steeper incline than A_p except under calm conditions, in which case they will both be equal to 90°.

3.2.3.4 Practical Significance

Admittedly, Equation 3.15a still remains to be validated in an outdoor setting. In this regard, note that for the conditions described previously by Cheney et al. (1992) in Section 3.2.3.1, that Equation 3.15a would predict an A_p = 43° and thus a crown scorch height of 8.6 m (i.e., *sin* 43° = 0.682 x 12.6 = 8.6) versus an observed height of 9 m. However, Equation 3.15a intuitively makes sense and matches the general impression obtained from observing forest fires (Fig. 3.12). In other words, as the fire intensities and the flame size in turn increases, the flaming front and the fire plume or convection column becomes increasing more difficult to tilt with respect to the prevailing wind. Thus, for a given intensity and height above ground, a surface fire burning under near calm conditions would result in a larger A_p (and thus a higher ΔT and/or higher crown scorch height) than would be the case with stronger winds. Of course, fuel moisture would obviously have to be greater in the latter situation, and in turn available fuel loads thereby less, in order to compensate for the faster spread rates that would be required to produce the same fire intensity as in the former case with lower wind speeds and drier fuel conditions (Van Wagner 1973b). Some authors have had difficulty fully comphrending the various inter-relationships involved. For example, Engle and Stritzke (1995) made the following comments in regards to the graphs produced by Albini (1976a) from Van Wagner's (1973b) equations relating height of crown scorch to Byram's (1959a) fire intensity and (*i*) air temperature or (*ii*) air temperature and wind speed:

> *The graphs demonstrate that height of crown scorch increases with increasing air temperature. In contrast, higher wind speeds sharply decrease scorch height, which is somewhat counter intuitive since Byram's fireline intensity usually increases rapidly with wind speed.*

In any event, the principle of dissipating the heat or limiting its vertical height to tree crowns is a basic tenet of prescribed underburning in order to reduce the level of crown scorching of forest overstory canopies (Dixon 1965; Mobely et al. 1978; Wade 1983; de Ronde 1988; Wade and Lunsford 1989; de Ronde et al. 1990; Cheney et al. 1992). As Byram (1948) noted, "... scorching is severe when a fire burns in calm air ... the lack of turbulence permits the hot gases to pass straight upward in a more or less streamline flow" (*see* also Mann and Whitaker 1955). Sackett (1972) made the following observations in connection with the results obtained from the 1966 treatments associated with an interval burning (every 2, 4 or 6 years) study initiated in the late 50s within a natural stand of longleaf pine (*Pinus palustris*) in the Coastal Plain of northern Florida, U.S.A., involving different ages of "rough" (i.e., the time in years since the forest floor was last reduced by fire) or fuel accumulation:

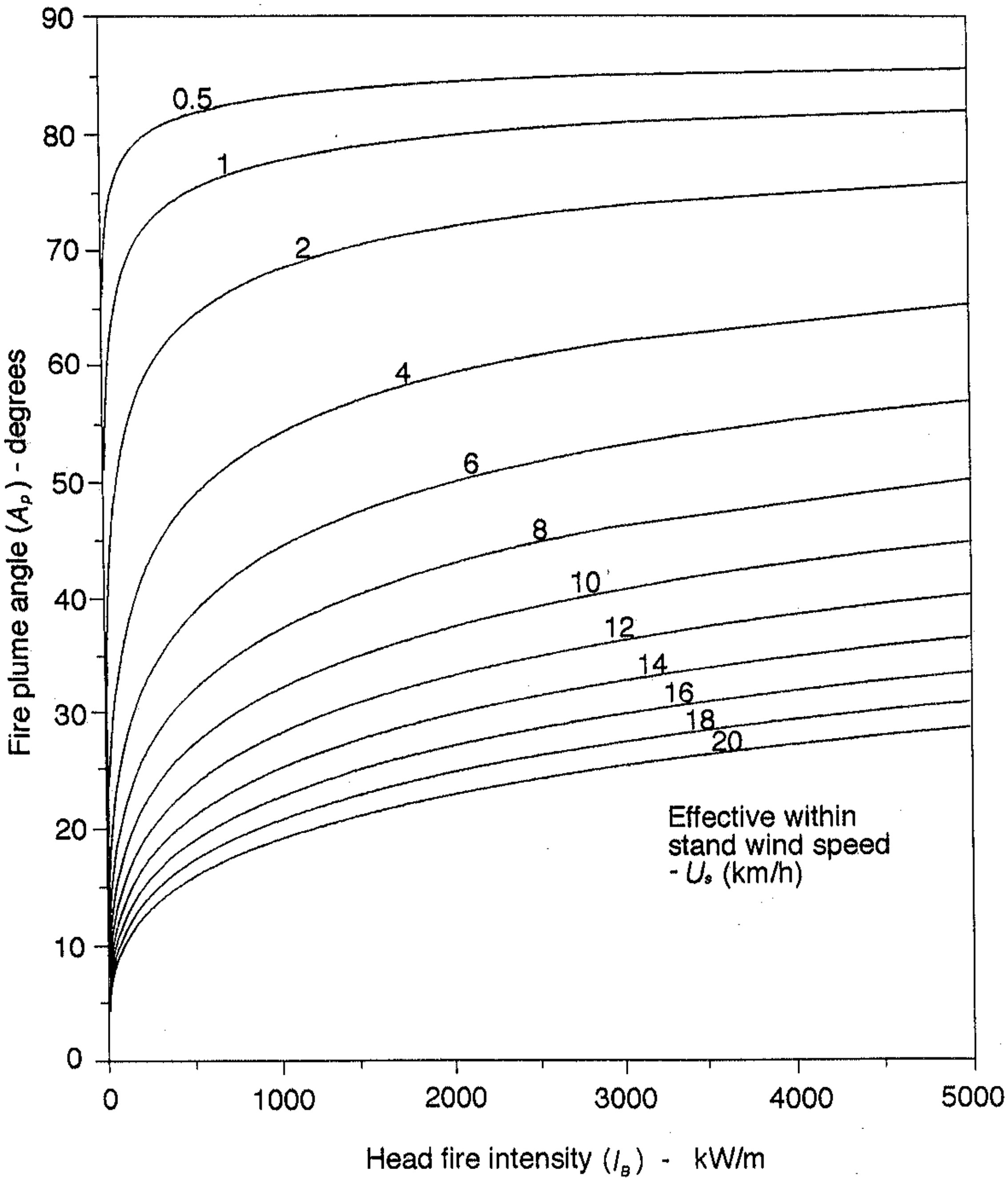

Figure 3.12: Fire plume angle as a function of Byram's fire intensity and wind speed according to Equation 3.15a.

Intensities were greatest in the heavier roughs and the highest kill was found on plots that achieved intensities above 700 B.t.u.'s/sec./foot [2421 kW/m] *of fire front. Light scorch was found generally in plots with intensities less than 300 B.t.u.'s/sec/foot* [1030 kW/m]*; moderate scorch on plots with 300-700 B.t.u.'s* [1038-2421 kW/m] *and severe crown scorch was associated with plots that developed more than 1,000 B.t.u.'s/sec./foot of fire front* [3459 kW/m]. *This was generally the case except for one instance on a 4-year rough ... The scorch on this plot developed from the lack of wind. All the heat energy output went straight up into the crowns.*

Wind is also important in cooling crowns heated by radiation from the fire as well (Byram 1948; Tibbals et al. 1964; Gates et al. 1965).

Strictly speaking, Equation 3.15a is valid only for surface head fires on level terrain and its applicability or relevance to backing fires is unknown at present. Four sets of simultaneous measurements of A_T for head fires and backfires at low wind speeds (< 4 km/h) by Weise (1993) indicates inclination differences of about 10° with a range of 3-17°. Considering the inherit variability in the dynamics of buoyant plumes above the flame front of spreading surface fires and the difficulty of measuring A_p, it's felt that Equation 3.15a represents a digest of currently available knowledge concerning the effect of wind on fire plume angles near the ground surface under forest canopies. A better relation is unlikely to come from a field study because of the spatial and temporal variation in wind velocity as demonstrated, for example, in Anon. (1970, p. 35), Anderson et al. (1982, p. 463, Fig. 11), McAlpine (1988, p. 20, Fig. 7) and Cheney et al. (1993, p. 36, Fig. 6)[2]. This is certainly an excellent example of where a laboratory approach constitutes the most fruitful means of deriving a desired relationship.

3.2.4 Initiation of Crown Combustion

Equation 3.4 constitutes a theoretical relation for the temperature profile above a line heat source. Empirical calibration of Equation 3.4 in terms of forest fires would permit one to predict the temperature at any given height above a fire depending on its frontal intensity or energy output rate per unit length of front. For present purposes Equation 3.4 can be rewritten as follows:

$$\Delta T = \frac{k I_B^{2/3}}{z} \tag{3.16}$$

[2]During the course of reviewing the draft manuscript of Johansen (1987) dealing with various ignition patterns and fire spread based on six experimental fire in a slash pine plantation, Johansen (1986) communicated the following to the author:

We took a continuous measure of wind speed (and direction) during the course of the first three burn replications with the hope we could correlate our record 1-minute line headfire movements with changes in wind speed. Plotting of these data, even with deferred time intervals to allow for the wind to travel from the anemometer to the fire front, could have been easily mimicked with No. 8 shot discharged from an improved cylinder shot gun barrel.

The difficulty of correlating fire behaviour characteristics in relation to wind speed for short periods of time stems from the local variations in wind strength and direction (Alexander and Quintilio 1990).

where ΔT is the temperature rise above ambient conditions at height z within the convection column of a surface fire (°C), k is a proportionality constant, I_B is Byram's (1959a) fireline intensity (kW/m), and z is the crown base height on level ground (m). If Equation 3.15a is taken into account (i.e., the influence of wind is considered), the equation for calculating ΔT then becomes:

$$\Delta T = \frac{k_l I_B^{2/3} \sin A_p}{z} \tag{3.17}$$

where k_l is a proportionality constant. Otherwise if Equation 3.15b is used, then Equation 3.16 is used to calculate ΔT (Fig. 3.13). The following equation would be used to calculate an effective z when terrain slope is involved:

$$z_{\theta} = z \sin (90 - \theta) \tag{3.18}$$

where z_{θ} is the effective crown base height (m) for a given slope and θ is the slope steepness (°). Equation 3.18 would be evoked when stand structure-z relationships developed from level terrain data (e.g., Muraro 1971; Alexander 1979, 1988; McAlpine and Hobbs 1994) or for constant z values where it's assumed they reflect level terrain conditions (e.g., Forestry Canada Fire Danger Group 1992). Equation 3.18 captures the worst case scenario because the lowest z will be the crucial distance in determining the onset of crowning. It also avoids the problem of dealing with the variation in crown base width (Lawson 1995).

For ignition of pine needle foliage to initiate combustion of the entire crown fuel layer, the T_c at height z, as determined by the sum of ($\Delta T + T_a$), where T_a is the ambient air temperature (°C), must meet or exceed the critical threshold value of ≈ 400°C as previously established. This temperature level must then be maintained for a specified minimum period of time. In the present context, the duration of heating received at the crown base during the active flaming stage of combustion at the ground surface would be inferred from the fire's flame front residence time t_r as defined by Equation 3.1 (i.e., t_i and t_r are assumed to be equal here as discussed previously in Section 3.1). Thus, for the onset of crowning to occur, t_r must be greater than or equal to t_i. The sum of ($T_a + \Delta T$) is substituted for T_c in Equation 3.3 in order to determine t_i.

3.2.5 Nature and Derivation of the Proportionality Constant(s)

The proportionality constants (k and k_l in Equations 3.16 and 3.17 are empirical in nature and must be determined from field measurements and observations. A value for k_l could be derived from some of the same information that Van Wagner (1977a) used in deriving the needed empirical constant C in his equation for predicting crown fire initiation as discussed in Section 2.4.1, if one is willing to accept the concepts that have been set out in this chapter, particularly Equation 3.3. First of all, it becomes necessary to transpose Equation 3.3 thereby giving the following result:

$$T_c = \frac{\ln t_i - 0.00729\, m - \ln 291.917}{-0.00664} \tag{3.19}$$

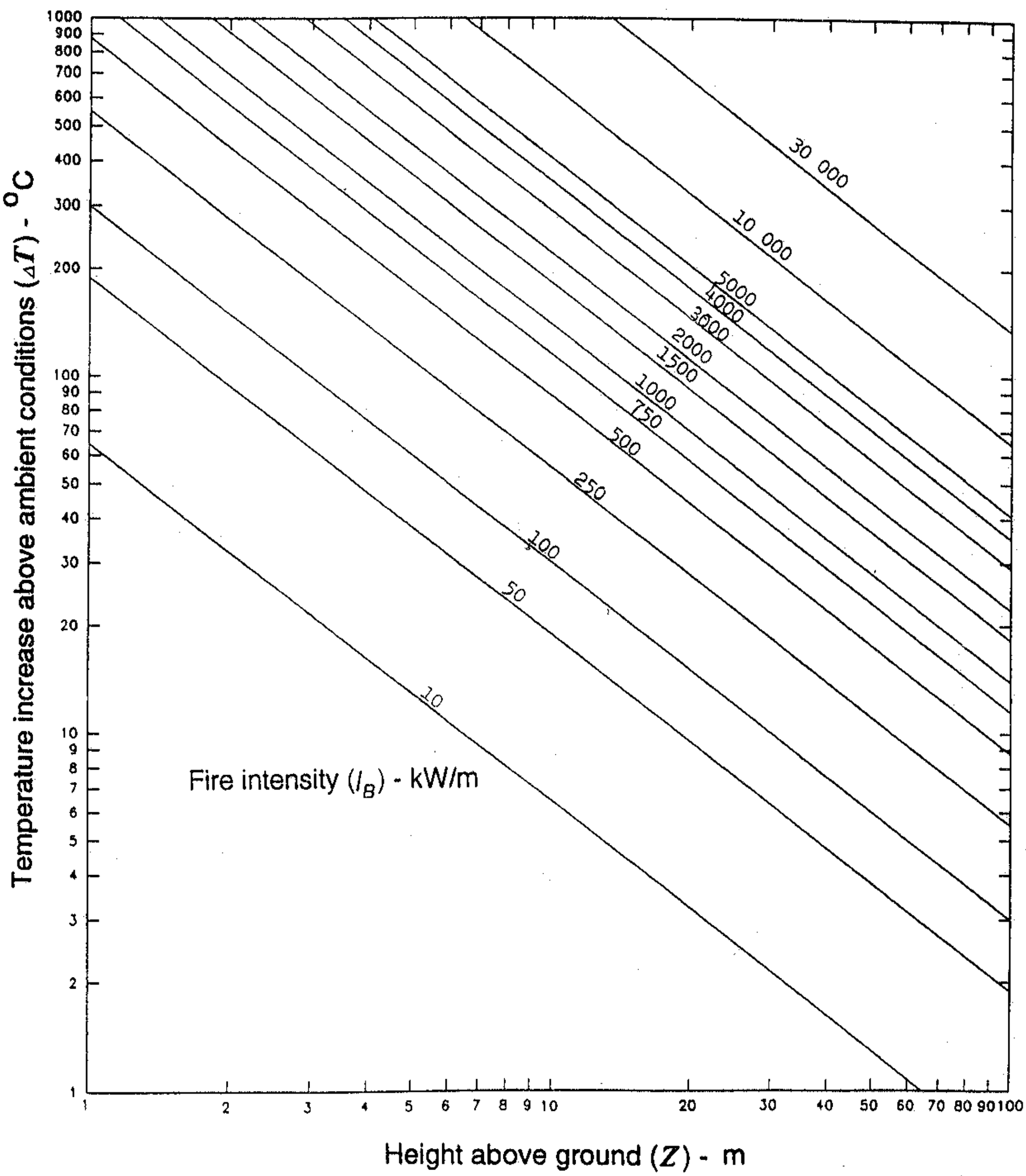

Figure 3.13: Temperature rise above ambient conditions in the convection column above a flame front of a given fire intensity for a "calm" wind situation according to Equation 3.16 where $k = 13.9$ (after Alexander 1991d).

The nominal values for the variables associated with the three experimental crown fires in a red pine plantation mentioned earlier on in Section 3.1 as taken directly from Van Wagner (1977a) or inferred from Van Wagner (1968) and other sources[3] are as follows: $T_a \approx 22°C$, $U_s \approx 5.5$ km/h, $m = 100\%$, $z \approx 6$ m, $I_B \approx 2500$ kW/m, and $t_r \approx 47$ sec (Table 2.1). Substituting $t_r = 47$ sec in place of t_i in Equation 3.19, with $m = 100\%$, gives $T_c = 385°C$ which is very close to the minimum T_c of 400°C presumed to be necessary for ignition of pine foliage. In fact, if $t_r = 42.5$ sec, then T_c would equal 400°C. Given the relatively rough nature of determining D in Equation 3.1 by ocular estimation because of the inherit lack of a clear demarcation in the trailing edge of the flame front (Rothermel and Deeming 1980; Wilson 1982), it therefore seems reasonable to accept that T_c was in fact equal to at least 400°C and therefore $\Delta T \approx 378°C$. $A_p = 54°$ by Equation 3.15a and *sin* 54° = 0.809. Thus, using a transposition of Equation 3.17, (*see* Equation 3.21 in Section 3.2.5.1), $k_l = 15.2$ when $z = 6$ m. In the text of his paper, Van Wagner (1977a) may have mistakenly had set $z = 6$ m in discussing his derivation of C rather than having $z = 7$ m as given in Table 1 of his paper i.e., there's likely a typographical error (*cf.* Van Wagner 1968, p. 21). If this is in fact true (i.e., $z = 7$ m), then $k_l = 17.8$ rather than 15.2.

3.2.5.1 Direct Inference from Thermocouple Studies

Van Wagner (1975) has in fact suggested that k is a universal constant $\approx$ 3.9, as presented by Alexander (1982) and confirmed by Van Wagner (1981), without any regard to the type of fuel complex involved (Table 3.3); Johnson and Gutsell (1993) have recently reported this value to be 2.39 in their transformation from the old metric unit system (m-sec-kg-kcal-°C) employed by Van Wagner (1975) to the present one used here (m-kW/m-°C unit system), but this is definitely in error (*cf.* Alexander 1996). As Van Wagner (1975) put it, "... if the ambient temperature is known and the line fire intensity can be estimated, the expected temperature at any height can be calculated ..." by simply inserting a k of 3.9 in Equation 3.16. Others have simply indicated that k was a proportionality constant without any discussion of the possible universality of a constant value or the significance, if any, of differences in fuel type characteristics (e.g., Weber, Gill, Lyons and Mercer 1995; Weber, Gill, Lyons, Moore, Bradstock and Mercer 1995). The results presented by Williamson and Black (1981) showing T_c variation with Z above the litter fuel beds of longleaf pine, turkey oak (*Quercus laevis*) and sand live oak (*Q. geminata*) support the view that k is in fact fuel complex specific or at least for structurally similar fuel types. Weber (1991) has suggested that k could possibly be regarded as a universal constant given a sufficiently large sample size.

Van Wagner's (1975) determination of $k \approx 3.9$ was based on the "rough average" of k_l obtained from two separate field studies; this is of course a considerably smaller value that the k_l value derived from Van Wagner's (1977a) empirical constant C. The first determination, $k \approx 4.4$ (in the unit system m-kW/m-°C), was made indirectly by inference from crown scorch heights (Van Wagner 1973b) observed on many small-scale experimental surface fires, which will be discussed in Section 3.2.5.2. The second determination was based on direct temperature

[3] For example, T_a was obtained from the unpublished database used in the development of the Canadian Forest Fire Behavior Prediction System as assembled by the Forestry Canada Fire Danger Group (1992) of which the author was a "core" member of from 1981 until the termination of the group in 1995 as a result of restructuring by the Government of Canada.

Table 3.3: Evaluation of the proportionality constant *k* in Equation 3.14 for six experimental fires carried out in four distinct fuel complexes at the Petawawa Forest Experiment Station, Ontario, Canada, arranged in order of decreasing fire intensity (adapted from Van Wagner 1975).

Fuel type (and experimental fire number)	"Average" I_B (kW/m)	Slope[a] b ($\Delta T,Z$)	Constant k ($b/I_B^{2/3}$)
Jack pine slash #1[b]	6221	1300	3.84
Jack pine slash #2[c]	2418	383	2.13
Trembling aspen forest (leafless)	469	120	1.99
Red-white pine forest #1[d]	364	273	5.36
Red pine plantation[e]	318	126	2.70
Red-white pine forest #2	88	86	4.35

[a]Van Wagner's (1975) determination of slope **b** might be a bit confusing to some readers. He indicates in a footnote to Table 1 of his paper that the **b** slope values are "From Figure 1". However, this is strictly speaking not the case since the numbers on the x-axis have been scaled to $1/\Delta T$ x 1000 in order to give nice whole numbers. So when x = 10, this actually represents a $1/\Delta T$ value of 0.01 or in other words, 100 °C. Van Wagner (1975) should have simply scaled the x-axis of Figure 1 to $1/\Delta T$ instead of $1000/\Delta T$ (Wotton 1995). In this way slope **b** could have been determined directly from his graph. As it stands now, slope **b** as determined from Figure 1 of Van Wagner (1975) must be multiplied by 1000 in order to match the values given in Table 1 of his paper.

[b]Plot no. 1 in Van Wagner (1966) were $U_{1.2}$ = 9.7 km/h. Thus, A_p = 47° by Equation 3.15a and therefore $\sin A_p$ = 0.731. This results in k_1 = 5.26 (i.e., 3.84 ÷ 0.731).

[c]Plot no. 2 in Van Wagner (1966) were $U_{1.2}$ = 7.7 km/h. Thus, A_p = 45° by Equation 3.15a and therefore $\sin A_p$ = 0.707. This results in k_1 = 3.0 (i.e., 2.13 ÷ 0.707). Note that Johnson (1992, Fig. 4.8, p. 55) has incorrectly converted 578 kcal/sec-m to 2422 kW/m instead of 2418 kW/m according to the standard conversion factor (*cf.* Van Wagner 1978).

[d]Note that Johnson (1992, Fig. 4.8, p. 55) has incorrectly converted 87 kcal/sec-m to 365 kW/m instead of 364 kW/m according to the standard conversion factor (*cf.* Van Wagner 1978).

[e]Fire no. C1 in Van Wagner (1968) were $U_{1.2}$ = 2.1 km/h. Thus, A_p = 60° by Equation 3.15a and therefore $\sin A_p$ = 0.866. This results in k_1 = 3.12 (i.e., 2.70 ÷ 0.866).

Table 3.4: Temperatures recorded within and above the flame zone along with selected environmental conditions and fire characteristics for two experimental fires carried out in a red pine plantation at the Petawawa Forest Experiment Station, Ontario, Canada (adapted from Van Wagner 1968).

Exp. fire no.	Type of surface fire	T_a (°C)	$U_{1.2}$ (km/h)	I_B (kW/m)	L (m)	D (m)	Maximum recorded temperatures above ground (°C) 0.1m	0.3m	5m	10m
C2	Back	22.2[a]	2.1	109	0.3	0.15	600	240	50	25
C1	Head	24.4[a]	2.1	318	0.6	0.50	760	650	60	40

[a]From the unpublished database used in the development of the Canadian Forest Fire Behavior Prediction System assembled by the Forestry Canada Fire Danger Group (1992) of which the author was a "core" member of from 1981 until the termination of the group in 1995 as a result of restructuring by the Government of Canada.. Experimental fire C1 is suspected as being the "red pine plantation experimental fire" reported on in Van Wagner (1975); *see* Table 3.3.

measurements made with 20-gauge (0.8 mm diameter), non-aspirated and non-shielded thermocouples involving six experimental fires in four different fuel types, namely jack pine (*Pinus banksiana*) slash, trembling aspen (*Populus tremuloides*) forest presumably burnt in the spring, red and eastern white pine (*Pinus strobus*) forest, and a red pine plantation (Van Wagner 1975). Two of the six experimental fires were common to the set analyzed in the crown scorch study (i.e., either red-white pine #1 or #2 and/or red pine plantation as given in Table 3.3). On the basis of six instrumented experimental fires in four quite distinctly different fuel complexes where $\boldsymbol{I_B}$ ranged from 88 to 6221 kW/m, Van Wagner (1975) found that $\boldsymbol{k}$ varied from 1.99 to 5.36 and averaged ≈ 3.4 (Table 3.3); he purposely made no allowance for the influence of wind in tilting the plume or convection column which would have resulted in $\boldsymbol{k_I}$ values 16-41% larger than $\boldsymbol{k}$ alone according to Equation 3.15a for the three experimental fires for which wind speed data were readily available (*see* footnotes b, c and d in Table 3.3). He attributed this variation was due solely to the procedures employed in determining fire intensities; Johnson (1992, Fig. 4.8, p. 55) considered the slopes of the lines in Figure 1 of Van Wagner (1975) to simply reflect differences in fire intensities rather than the influence of fuel type composition and structure. As Van Wagner (1975) noted (where $k = \boldsymbol{k}$ in the notation used here):

> *...some of the variation in k ... is no doubt due to the difficulty of specifying the exact intensity while each fire was passing under the thermocouple station. The best that could be done was to calculate average intensities for the whole fire.*

While acknowledging that extrapolation is always dubious, Van Wagner (1975) felt that on the basis of his thermocouple study that the temperature-height relationship given by Equation 3.16 should be valid for a considerably greater height than actually measured (i.e., perhaps greater than 10 m). However, the absolute validity of his temperature measurements he made and in turn their corresponding affect on the magnitude of $\boldsymbol{k}$ or $\boldsymbol{k_I}$ has to be seriously questioned, especially in light of the type (non-shielded and non-aspirated) and size (20 gauge) of thermocouples used. Earlier on, Van Wagner (1968) acknowledged that thermocouples in hot gas are subject to error by radiation loss to cooler surroundings and therefore the temperature readings recorded within the flame zone for low-intensity fires (e.g., the red pine plantation fire in Table 3.3) were probably below their true value. He felt that the maximum temperatures in the flame zone of "... all fires were of the same order, namely, about 1000°C". Examination of the thermocouple readings for two of Van Wagner's (1968) low-intensity experimental fires indicated that temperatures well below 1000°C were recorded (Table 3.4). Stocks and Walker (1968) have shown that errors of 150-330°C can occur when using 20-gauge thermocouples to measure flame temperatures. In a laboratory setting, Martin et al. (1969) found that shielded-aspirated thermocouples recorded peak flame temperatures greater than 1100°C whereas values for non-shield, non-aspirated thermocouples were some 230°C lower. Differences of ≈ 50°C have been recorded in the plume or convection column above surface fires in an outdoor setting based on a similar comparison (Anon. 1990a). One thing is certain, the exact difference is often variable (Jones 1995). Even when adjustments are made to the thermocouple data, a substantial degree of uncertainty exists (Byram et al. 1966).

Martin et al. (1969) have duly noted that most time-temperature traces produced from thermocouple measurements reported on in the literature are generally considered to be the true "fire temperatures" when in reality they are the temperatures attained by the thermocouple sensor inspite of the care that might be taken to calibrate to a known temperature (e.g., ice bath or muffle furnace) prior to their use and/or to the attention paid to the thermocouple wire diameter used. This is because shielded-aspirated thermocouples are typically not utilized in the measurement of flame and gas temperatures (Philpot 1965; Palmer 1970; Newman and Croce 1979; Jones 1993). Some authors like Van Wagner (1968) have acknowledged that their readings may not be fully representative of ambient air temperatures because of the radiated energy intercepted by the bare thermocouples (e.g., Beaufait 1961). Furthermore, many studies have reported values that are well below what would commonly be accepted as maximum temperatures in forest fires (e.g., Kayll 1966; Hobbs and Gimingham 1984; Engle et al. 1989), thereby indicating that the sensors and recording instrumentation used were "... too coarse ..." for the highly transient nature of temperatures associated with free-burning wildland fires (Van Wagner and Methven 1978).

Obviously there's a great deal of uncertainty associated with the temperature measurements made by Van Wagner (1975) and thus the relative magnitude of the value of $\boldsymbol{k}$ or $\boldsymbol{k_1}$. One direct estimate of $\boldsymbol{k}$ and $\boldsymbol{k_1}$ with immediate relevancy is that offered by the measurements made by Packham (1970) on an experimental fire in a maritime pine (*Pinus pinaster*) plantation at Gnangara, Western Australia; stand height (**SH**) averaged ≈ 11 m. Particular attention was paid to documenting the characteristics of the fire in the immediate vicinity of the thermocouple station; the fire was lit as a continuous source upwind of this location (Packham 1995). The fire consumed 7.5 t/ha of needle litter ($\boldsymbol{w}$ = 0.75 kg/m^2) that exhibited a moisture content of 10%. The head fire rate of spread ($\boldsymbol{r}$) was 0.0076 m/sec (27.4 ± 0.2 m/h). The average height, depth and tilt angle (from the horizontal) of the flame front were 1.1 m, 0.9 m and 60°, respectively. The $\boldsymbol{t_r}$ was thus 120 sec or 2 min according to Equation 3.1. $\boldsymbol{I_B}$ was recalculated in SI units to be 106 kW/m based on a fuel low of combustion value of 18 700 kJ/kg subsequently reduced by 24 kJ/kg per moisture content percentage point (Van Wagner 1972b; Alexander 1982). $\boldsymbol{T_a}$ was 20°C, relative humidity (**RH**) was 67%, and the wind speed measured at 1.8 m above ground was 5 km/h although the exposure was not noted so there is no way of knowing whether this was a within stand measurement or from a more open exposure. $\boldsymbol{A_p}$ = 31° by Equation 3.15a (assuming that $\boldsymbol{U_s}$ = 5 km/h), which when compared to the observed $\boldsymbol{A}$ of 60° appears logical but perhaps more acute than expected. Given the uncertainty of the wind speed it was therefore decided to assume $\boldsymbol{U_s}$ = 3 km/h (i.e., midpoint of 1-5 km/h). Thus, $\boldsymbol{A_p}$ = 43° and *sin* 43°= 0.682. At a $\boldsymbol{Z}$ ≈ 3.65 m, a maximum air temperature or $\boldsymbol{T_c}$ of 100°C was recorded with a shielded-aspirated thermocouple. In order to determine $\boldsymbol{k}$ and $\boldsymbol{k_1}$, it becomes necessary to transpose Equations 3.16 and 3.17. Solving for $\boldsymbol{k}$ and $\boldsymbol{k_1}$ gives the following results:

$$k = \frac{\Delta T\, z}{I_B^{2/3}} \tag{3.20}$$

$$k_1 = \frac{\Delta T\, z}{I_B^{2/3}\, \sin A_p} \tag{3.21}$$

Thus, according to Equations 3.20 and 3.21, for $\Delta \boldsymbol{T}$ = 80°C and substituting $\boldsymbol{Z}$ for *z*, the derived values for $\boldsymbol{k}$ and $\boldsymbol{k_1}$ (i.e., without and with the effect of wind considered) are 13.0 and 19.1, respectively.

3.2.5.2 Insights from Crown Scorch Studies

An excellent example of the significance of vertical fuel arrangement in this connection is afforded by the experiment undertaken by Just (1969, 1974) within a 11-year-old slash pine (*Pinus elliottii*) plantation in southeastern Queensland designed to examine the effect of pruning on fire behaviour under mild burning conditions as a possible prerequisite for prescribed underburning (Table 3.5); the compartment was unthinned and the planted spacing was 2.4 x 2.4 m or 1736 stems/ha. The pruned "treated" area had the dead suspended needles and branches in the lower bole region of the trees pruned off up to a height of ≈ 3.2 m just prior to burning negating the possibility that the trees in the pruned plot were unduly stressed at the time the fire treatment took place. This pruned material tends to be trampled down during the pruning operation, gradually settling further with time (*cf.* Fahnestock and Dieterich 1962; Carlton and Pickford 1982; Christiansen and Pickford 1991). The two areas within the same plantation compartment were burned within 15 minutes of each other rather than simultaneously which unfortunately prevented a true comparison. There was a slight decrease in the T_a and a corresponding increase in **RH**. More importantly, however the effective within stand wind speed during the fire in the unpruned area was less than half that experienced during the burning of the pruned area, no doubt reflecting to a certain extent the greater surface roughness associated with the branches and dead suspended needles below the green crown layer; unfortunately, U_{10} was not measured during the two experimental fires so there is no way of knowing for certain whether this was indeed the case. Had the T_a, **RH** and U_{10} been exactly the same during the burning of the unpruned stand, the combined result would simply have contributed to a higher overall crown scorch height. Just's (1974) conclusion was that:

> *The most significant difference in fire behaviour was the amount of flaring (up to 12-15'* [≈ 3.7 - 4.6 m]) *which occurred in the unpruned stand,* [and virtually absent in the pruned stand (Just 1969)] *and it was this flaring which accounts for the big difference in scorch heights on the two areas.*

He was also to note that "One can only assume from this that crowning is much more likely ... in an unpruned stand compared with a pruned stand" (Just 1969), a sentiment shared by others (e.g., McArthur 1965; Cheney 1973; McCaw et al. 1988). This is borned out by various crown scorch height (h_s) -I_B relationships (Fig. 3.14)[4] which to a large extent is a reflection of surface and ladder fuel characteristics alluded to in Section 2.1; *see* also the tabulation in van Wagtendonk (1972, 1974). Billing (1990), for example, found that the observed h_s in radiata pine thinning slash in southwestern Victoria, Australia, was higher (even for cooler T_a conditions) than would be predicted by Van Wagner's (1973b, Equation 8) basic h_s-I_B model and attributed this to the elevated fuel structure. For this reason, the wisdom of using a relation such as Van Wagner's (1973b) to predict h_s (e.g., Jakala 1995) or in turn to estimate I_B (e.g., Norum 1975, 1976; Cain 1984; Tozzini and Soares 1987; McCaw et al. 1997) has some serious limitations if applied to a distinctly different fuel complex. In considering the existing h_s-I_B relationships, it's worth bearing in mind that the differences evident in Figure 3.14 could be due to a number of factors in addition to differences in surface fuelbed characteristics, such as:

- The manner in which fire intensity was determined, in other words whether Equation 2.1 is used to compute I_B or it's inferred from flame size by using an existing L-I_B

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4 Burrows (1990) confirmed that the h_s-I_B equation given on p. 48 of in Burrows et al. (1989) was correctly presented but the y-axis of Figure 4 is incorrectly scaled.

Table 3.5: Summary associated with two experimental point-source ignition fires conducted in a 12-year-old slash pine plantation in southeastern Queensland, Australia, designed to examine the effect of pruning on fire behaviour (adapted from Just 1969, 1974).[a]

Item	Pruned area	Unpruned area
Stand height, SH (m)	7.6	8.5
Live crown base height, z (m)	3.2	3.7
Start of ignition (p.m. local time)	2:00	2:45
Duration of fire (min)	30	26
Final area burnt (m²)	39.0	39.2
Ambient air temperature, T_a (°C)	20.0	18.3
Relative humidity, RH (%)	54	56
Effective within stand wind speed, U_s (km/h)[b]	3.0±1.0	1.5±0.7
Head fire rate of spread, R (m/h)[c]	33.8±10.1	31.1±13.4
Head fire flame height, h_F (m)	1.0	1.3
Head fire flame depth, D (m)	0.40	0.46
Head fire residence time, t_r (sec)[d]	42	53
Head fire intensity, I_B (kW/m)[e]	170	157
Crown scorch height, h_s (m)[f]	4.5±0.9	7.1±3.4

[a]The understory fuel complex "... in both areas was devoid of any grass or shrub cover, and consisted entirely of pine needles" (Just 1969) and averaged 11.3 t/ha over the two areas based on sampling at four representative sites. The sampled surface and profile moisture contents of the forest floor layer were 22% and 24%, respectively. The moisture content of the dead suspended needles in the lower bole region of the unpruned trees was 16%. The Keetch-Byram Drought Index (**KBDI**) (Keetch and Byram 1968) on the day of the burning, 3 June 1969, was 11 (units: mm); the last previous rain event occurred 5 days earlier when a total of 81 mm fell between May 27-29.

[b]Mean and standard deviation based on 2-minute averages (range: 1.6 - 4.3 and 0.8 - 2.7, respectively).

[c]Mean and standard deviation based on 2-minute averages (range: 16.5 - 60.4 and 11.0 - 53.0, respectively).

[d]Computed from Equation 3.1.

[e]Calculated from Equation 2.1 by: (*i*) using a low heat of combustion (H) value of 18 700 kJ/kg subsequently reduced for the presence of moisture (Alexander 1982); (*ii*) the observed fuel consumption for both areas (i.e., w = 1.0 kg/m²; and (*iii*) the observed mean head fire rate of spread.

[f]Mean as reported by Just (1969, 1974) with standard deviation added; although a 100% sample of each area was undertaken (64 and 76 trees, respectively) only those trees that experienced some degree of crown scorching were included in these determinations (in the pruned area, 50% of the trees received some scorching whereas in the unpruned area, 63% of the trees experienced some scorching of their crowns). The maximum h_s in each area was 6.1 m and 8.5 m, respectively.

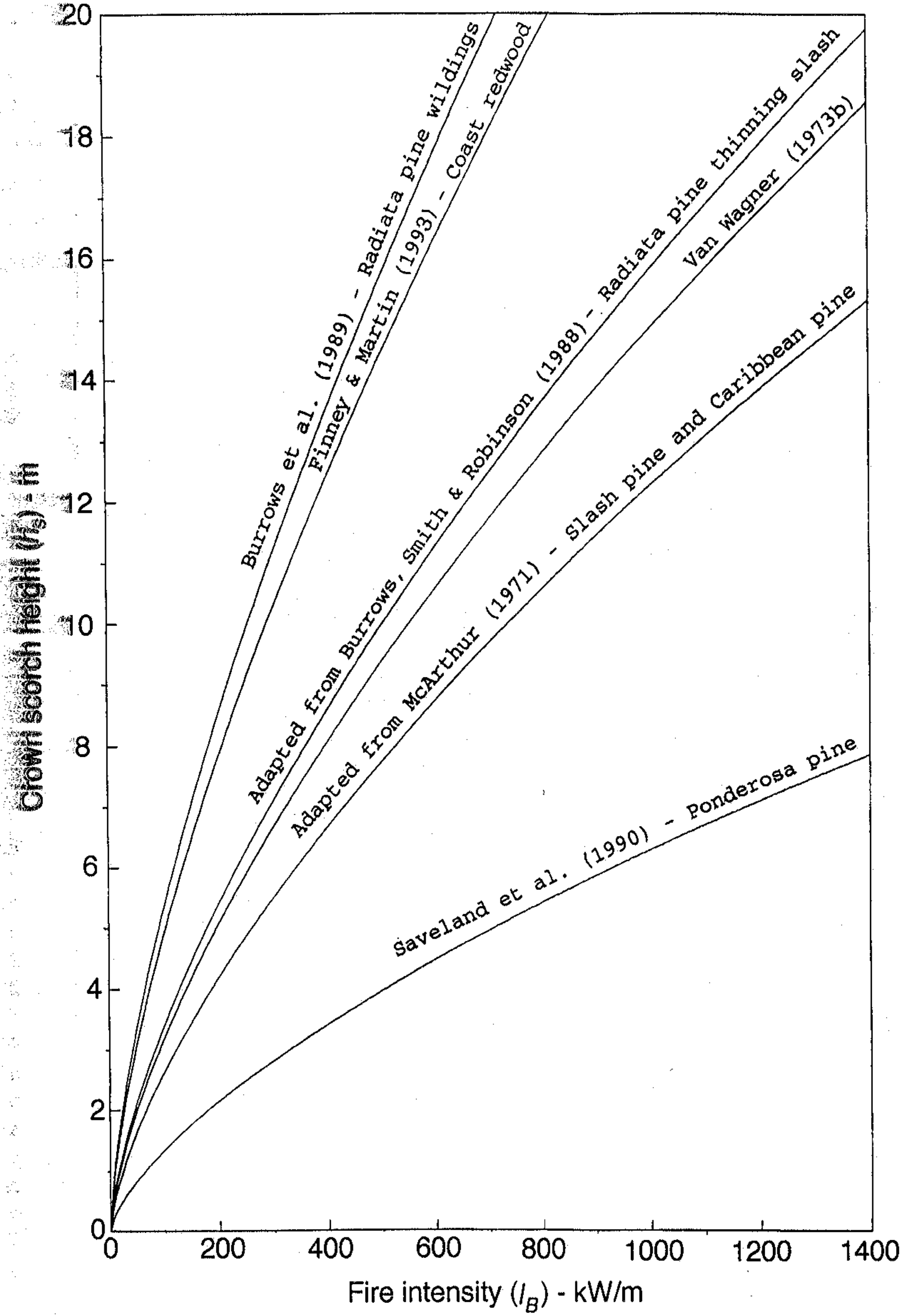


Figure 3.14a: Summary of existing fire intensity-crown scorch height relationships reported on in the literature.

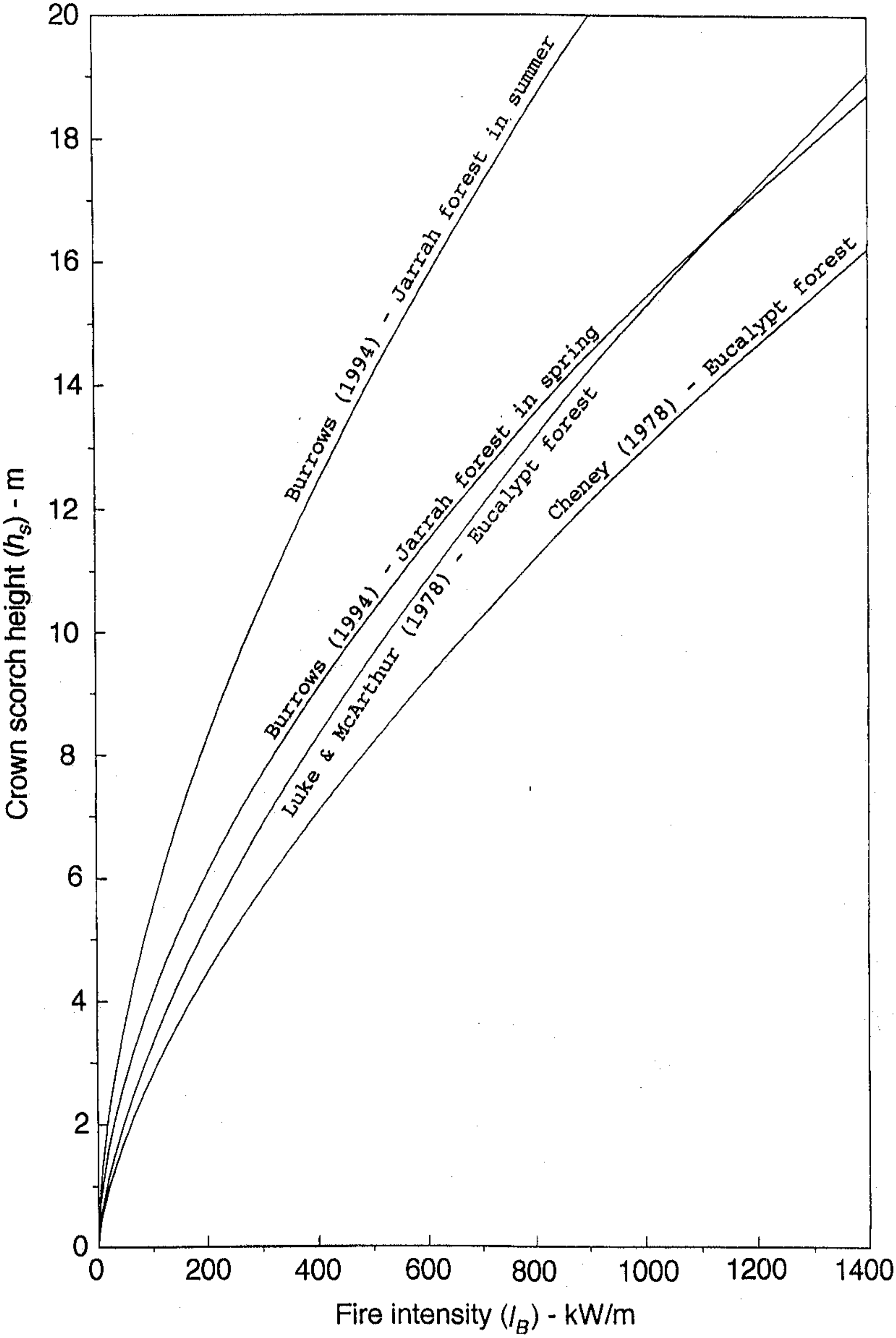


Figure 3.14b: concluded.

relation, because quite different I_B values are certainly possible as shown by McArthur (1980) and Smith et al. (1993), for example, and the evidence presented here -- Finney and Martin (1993), for example, estimated I_B from Byram's (1959a) L-I_B relation (*see* Equation 3.24) using estimates of L based on measurements of h_F and A (Finney 1991) as per Ryan (1981) rather than relating h_s directly to L or h_F and U_s;

- The ignition or firing pattern -- the Saveland et al. (1990) relation, for example, is based on a combination of backfires, strip head fires and single head fires whereas the one for Van Wagner (1973b) is presumably based on single head fires;
- Season or time of year that the burning took place -- for example, the dormant period or growing season? (Jameson 1961; Robbins and Myers 1992); vulnerability could possibly be related to seasonal changes in foliar moisture content (Van Wagner 1973b);
- The environmental conditions under which the fires took place, especially with respect to T_a and U_s, and the species specific lethal time-temperature thresholds (this subject is covered in greater detail in Section 3.2.5.4.1); and
- To a lesser extent, the H value used in computing I_B (e.g., Van Wagner 1973b, 1975 used 18 828 kJ/kg) although this is very often left unstated by investigators even though such documentation is considered essential (Alexander 1982).

Furthermore, in the derivation of k_1 (or for that matter k_2 and k_3), the quality of the instrumentation used to measure wind speed and the averaging periods should be kept in mind. For example, in the Saveland et al. (1990) study, wind speed was measured only at the time of ignition (Bakken 1981, 1995) with a Dwyer hand-held wind speed indicator (Finklin and Fischer 1990) which gives instantaneous readings rather than integrated averages. As well, rate of fire spread was observed for just three 1-min periods during the duration of each fire rather than on a continuous basis or determining a plot average (i.e., plot width divided by total elapsed time since ignition).

Finney and Martin (1993) have attributed the differences between the Saveland et al. (1990) h_s-I_B relation and that of others, including their own, to the fact that they felt that Saveland et al. (1990) had correlated I_B against the height of bud kill rather than foliage scorching or death; buds of course would be far more resistant to scorching then needle foliage, depending on the time of the year (Sucoff and Allison 1968), because of their mass and thermal insulation (Byram 1948). This interpretation was no doubt due to the comment in Saveland (1982) and Saveland et al. (1990) that tree damage data (e.g., h_s) was acquired after budbreak in the spring following the late fall fires the previous year. However, Bakken (1981) indicates that the h_s data were collected at the "... onset of budbreak" and felt confident that the previous year's crown scorch line was still very discernable several months after the fires (Bakken 1995). In actual fact, the differences may be due to the mix of ignition patterns coupled with the manner in which the r value used in Equation 2.1 was arrived at as mentioned above.

In light of the findings from Packham's (1970) study, the validity of Van Wagner's (1973b) derivation of k from his crown scorch study has to be questioned. Van Wagner's (1973b) 13 experimental fires included eight in a red and white pine stand, two jack pine stands, one northern red oak (*Quercus rubra*) stand, and two in a red pine plantation. The plots varied from 0.07-0.10 ha in size. A single strip head fire ignition was presumably used, but there is no way of knowing for sure (*cf.* Van Wagner 1963b). The calculated I_B values (based on measured rate of spread and fuel consumption) ranged from 67 to 1255 kW/m. The average crown scorch heights, determined on the basis of 3-10 measurements per plot (no statistics such as the standard deviation or range were given), varied from 2 to 17 m, although it's unknown which fuel complexes were associated with which measurements since no basic data is tabulated in the paper other that what's contained in the text and graphs. The fires were conducted with light to moderate winds ($U_{1.2} \simeq$ 2.3-4.7 km/h) but under moderate to high temperatures ($T_a \simeq$ 23-31.5°C) according to the information presented in Figures 2 and 3 of his paper and presumably all were carried out on level ground. In contrast to Van Wagner's (1975) thermocouple study in which the average fire intensity for the plot as a whole was related to a single sample point, the inference of k from his crown scorch study (which also used a simple mean rate of spread and fuel consumption values for the entire plot) was based on 3-10 "sensor trees" or sample points per plot. Inspite of this, exactly matching the h_s with I_B could still be a potential source of error in deriving k. The basic model of Van Wagner (1973b, Equation 8) relating h_s to I_B is as follows (from Alexander 1982):

$$h_s = 0.1483\, I_B^{2/3} \tag{3.22}$$

The equation derived by Van Wagner (1973b, Equation 9) for predicting the height of lethal crown scorching as a function of I_B expressed in kW/m instead of kcal/sec-m (as in his original paper) and T_a is as follows[5]:

$$h_s = \frac{4.4713\, I_B^{2/3}}{60 - T_a} \tag{3.23}$$

In the present case, the term (60 - T_a) would be substituted for ΔT. As Van Wagner (1973b) notes, "A single lethal foliage temperature of 60°C was chosen for the present analysis. Actually, as is well known, time and temperature work together. Conifer foliage stands 60°C for about a minute according to Kayll (1968) ...". Some authors have interpreted Van Wagner's (1973b) use of a constant 60°C as the assumed instantaneous lethal temperature for conifer foliage (e.g., Ryan 1982; Andrews and Bradshaw 1990; Gill and Bradstock 1994; Moore et al. 1995) or independently assumed this (e.g., Vines 1968; van Wagtendonk 1972, 1974; Wade 1993) while others have assumed that the 60°C is the accepted lethal temperature for conifer foliage subject to a heat exposure of one minute (e.g., Albini 1976a; McArthur 1980; Robbins and Myers 1992). Probably a far more reasonable interpretation is that the 60°C is the appropriate lethal temperature for conifer foliage where the effective heating time by the passing surface fire matches the relevant duration of exposure for death to occur. The value of t_r for wind-driven surface fires in pine plantations with a moderately compacted organic layer would typically vary from $\simeq$ 30-60 sec (McArthur and Cheney 1966; Van Wagner 1968); Van Wagner (1972a) assumed that t_r was a constant 60 sec in his modelling of duff consumption by fire.

[5]Note that the conversion of Van Wagner's (1973b) original equations from old metric to SI units has been incorrectly done and/or presented by several authors in the past (e.g., Chandler et al. 1983; Barney et al. 1984; Johnson 1992; Johnson and Gutsell 1993; Johnson and Miyanishi 1995).

It would appear that Van Wagner (1973b) made no allowance for the effect of wind in limiting h_s with respect to his derivation of the constant in Equation 3.23. As mentioned in Section 3.2.5.1, this was explicitly stated in his thermocouple paper (Van Wagner 1975) but this is not discernible from the text of his crown scorch paper (Van Wagner 1973b).

With respect to the influence of the variation of T_a on h_s, Van Wagner (1973b) came to the following conclusion (where $h_s = h_s$, $I = I_B$, $T = T_a$ and $U = U_{1.2}$ in the notation used here):

> *Since scorch height for the present set of fires is so well correlated with fire intensity alone, there is not much room for improvement by adding the effects of air temperature. However, even if the fit of h_s and with $I^{2/3}$ had been poorer, it is possible that consideration would still not have improved the picture very much.* ***The reason is seen in Figs. 2 and 3, which show that the ranges of T and U in the present data are too small to effectively test the theory of their effects.*** [bolding for emphasis by author]

Some authors have misinterpreted Van Wagner's (1973b) conclusion about air temperature (e.g., Albini 1976a, 1976b; Andrews and Bradshaw 1990; de Ronde et al. 1990) or gone ahead and unknownly applied the relationship given by Equation 3.23 (e.g., Albini et al. 1977; Norum 1977; McRae et al. 1994; Taylor and Armitage 1996) or a derivative of it (e.g., van Wagtendonk and Botti 1984; de Ronde 1988; de Ronde et al. 1990; Reinhardt et al. 1996).

Forest fire researchers in the southeastern U.S.A. have contended for years that the variation in T_a can have a profound effect on h_s (Byram 1948, 1958; Byram and Nelson 1952; Nelson 1951, 1952; Storey and Merkel 1960; Dixon 1965; Mobely et al. 1978; Wade 1983; Wade and Johansen 1986; Wade and Lunsford 1989) as evident by the following tabulation for initial crown temperature T_{ic} at a constant I_B for a loblolly pine (*Pinus taeda*) stand as reported on in the 1949-50 biennial report of the USDA Forest Service's Southeastern Forest Experiment Station (adapted from Anon. 1951):

T_{ic} (°C):	-1.1	4.4	10.0	15.6	21.1	26.7	32.2	37.8	43.3
h_s (m):	1.7	1.9	2.1	2.5	3.0	3.6	4.5	5.9	8.2

Thus, the range in h_s for nearly a 45°C range in T_{ic} is 6.5 m (i.e., 8.2 - 1.7 = 6.5), *ceteris paribus* of course. The above tabulation "... shows that the rate of increase is small at the lower temperature but becomes large at the higher temperatures" (Anon. 1951). In contrast to the importance of T_{ic} in relation to h_s, the role of moisture in the convective gases produced by combustion are not so precisely known. For example, King (1973) felt that the well known effect of fuel moisture in reducing a fire's rate of spread was due, in large part at least, to the water vapour produced as a result of the combustion process in reducing the emissivity of the flames. With respect to Australian forestry and fire management, King (1973) was to note that:

> *There may also be a practical application of this effect in the timing of prescribed fires in commercial forests. Provided conditions are so chosen that similar flame heights are produced, prescribed fires are less likely to scorch the tree crowns in spring than in autumn; for, in autumn, fuels are usually drier, and radiation from the flames will therefore be more pronounced.*

Martin et al. (1969) on the other hand have speculated that higher crown scorch heights were more probable with moist surface fuels than drier ones due to an increase in dew-point temperature as a result of the additional water vapour produced by the combustion process.

More direct evidence for the significant of T_a or T_{lc} on h_s can be found in the pioneering work of the late George M. Byram in a study carried out in the pine forests of the southeastern U.S.A. during the late 40s and early 50s Byram (1958). For 17 experimental fires Byram (1958) documented a range in h_s ranged from ≈1.2 to 8.5 m where T_{lc} (or T_a) in turn varied from ≈ 2.6 to 42.2°C (Fig. 3.15a). The plotted data extracted from Figure 1 of Byram's (1958) paper (*see* Fig. 3.15a), originally presented in English units (i.e., °F and ft), is given below in SI units:

T_{lc} (°C):	2.64	7.08	13.06	15.56	18.89	18.89	19.72	21.11	22.36
h_s (m):	1.37	1.19	3.41	4.72	3.47	3.11	2.07	1.92	2.50

T_{lc} (°C):	23.89	27.36	28.89	30.00	32.22	32.22	42.22	42.78
h_s (m):	2.80	5.61	3.96	3.44	3.60	5.36	8.53	5.70

Robbins and Myers (1992) have pointed out that Byram (1958) provided no details as to the whether the I_B levels amongst the experimental fires differed or not. However, judging by the flame lengths (0.3-0.46 m or 1-1.5 ft) observed and reported by Bryam (1958), I_B was essentially constant for practical purposes, thereby permitting the opportunity to isolate the effects of T_a on h_s. Unfortunately, no mention is made of the associated wind speeds. Although it's difficult to be specific since no tabulated data is given in Byram (1958), the data scatter evident in Figures 3.15a and 3.15b is likely due to several factors, namely the slight range in I_B, as reflected in the observed flame lengths, variation in cloud cover or solar radiation and wind speed, type of fire (head or back) and the inherent spatial variability associated with I_B. I_B according to Byram's (1959a) fire intensity - flame length relationship, which is probably very valid since some of the experimental fires reported on in his 1958 study were undoubtedly used (*cf.* Lindenmuth and Davis 1973) in deriving Equation 2.2, the transposition of which is as follows (from Alexander 1982):

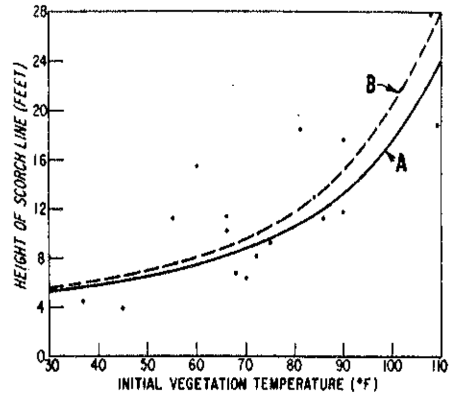
$$I_B = 259.833\ (L)^{2.174} \qquad (3.24)$$

where L is the flame length (m). The range in L reported by Byram (1958) was used to calculate the range in I_B (20-47 kW/m) by this relation that was in turn used in Equation 3.23 to calculate the variation in h_s depicted in Figure 3.15b that was predicted by Van Wagner (1973b); T_a was assumed to be equal to T_{lc} as discussed in Section 3.1. It's obvious that Van Wagner's (1973b) model consistently underpredicts h_s. For a nominal value of I_B = 32 kW/m, based on Equation 3.24 and assuming L = 0.38 m (15 in or 1.25 ft), h_s by Van Wagner's (1973b) would have varied from 0.75-3.0 m over the range in T_a from 0-45°C.

Van Wagner's (1973b, Equation 10) equation for predicting h_s which incorporates $U_{1.2}$ in addition to I_B and T_a is as follows (from Alexander 1985b)[6]:

[6]Note that the conversion of Van Wagner's (1973b) original equation from old metric to SI units has been incorrectly done by several authors in the past (e.g., Chandler et al. 1983; Keane et al. 1989).

(a)



(original size)

(b)

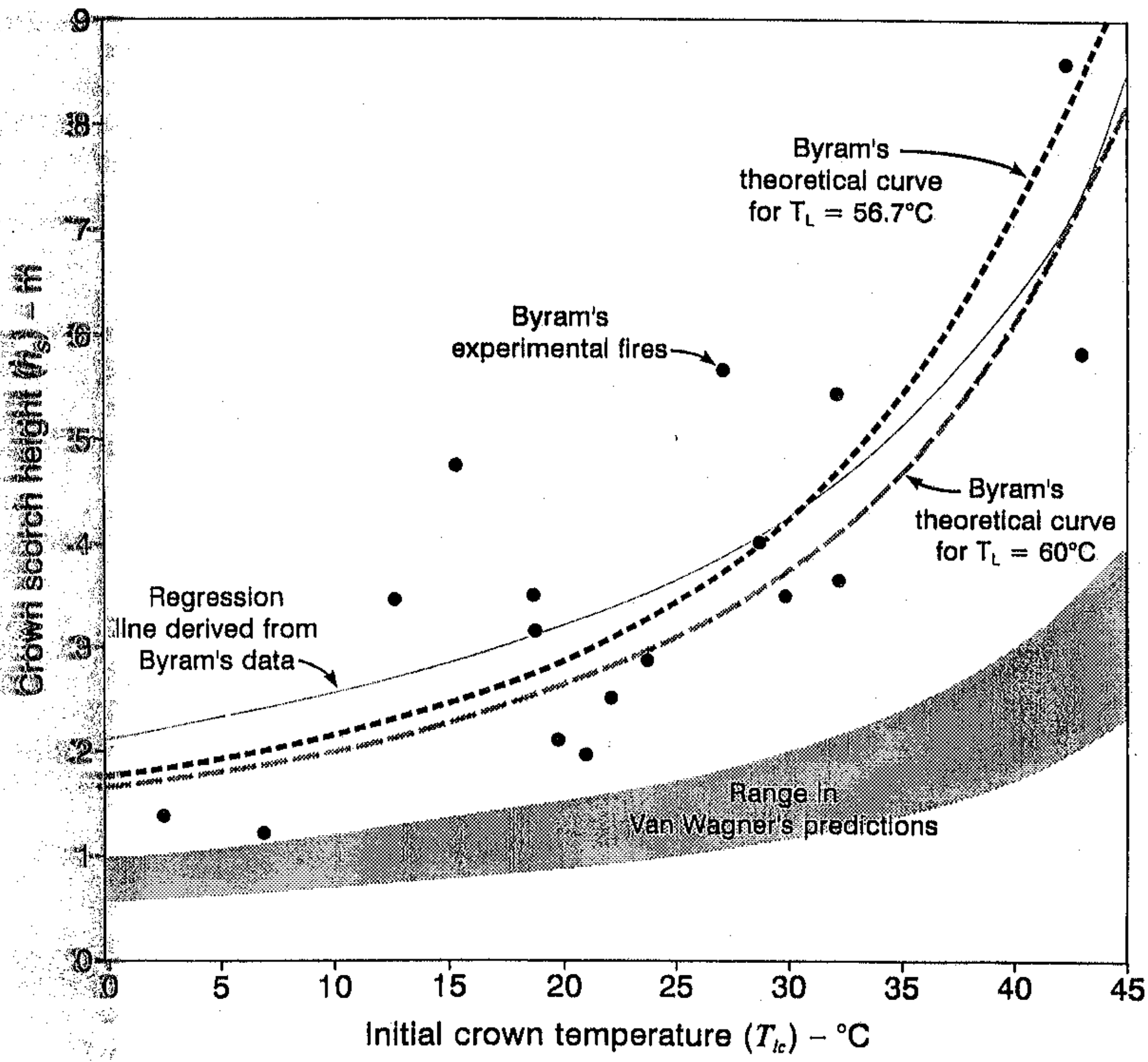


Figure 3.15: Byram's (1958) original presentation of crown scorch height in relation to initial crown temperature at essentially a constant fire intensity of ≈ 32 kW/m (a) and (b) an adapation including a comparison to predictions by Van Wagner's (1973b) relation represented by Equation 3.23 were fire intensity was varied from 20-47 kW/m.

$$h_s = \frac{0.74183\ I_B^{7/6}}{(0.025574\ I_B + 0.021433\ U_{1.2}^{3.0})^{0.5}\ (60 - T_a)} \tag{3.25}$$

If it was assumed during the Byram (1958) experimental fires that $U_{1.2}$ (or U_s) varied from ≈ 1.5-5 km/h, as would be typical for prescribed underburning in the southeastern U.S.A. (Wade and Lunsford 1989), then according to the Equation 3.25, h_s would have varied, at $U_{1.2}$ = 1.5 km/h, from 0.7-3.0 m over a T_a range of 0-45°C and at $U_{1.2}$ = 5 km/h, h_s would have varied from 0.4-1.5 m over the same range in T_a.

Byram (1958) included two theoretical curves on his graph of h_s versus T_a, one for a lethal temperature of pine foliage (T_L) of 60°C (140°F) which he presumed, in light of Nelson's (1952) findings of lethal temperatures in relation to time for southern pines (to be discussed in Section 3.2.5.4) was "... probably about right for headfires" and the other for T_L = 56.7°C (135°F) which he viewed "... would be more realistic for the slower spreading backfires because of the longer exposure time". Unfortunately, Byram (1958) gave no details of the mathematical computations used in plotting these curves. However, assuming that I_B = 32 kW/m, k or k_l without the influence of wind considered (i.e., A_p = 90° or in other words *sin* 90° = 1.0) derived from the following equation:

$$k_l = \frac{(T_L - T_a)h_s}{I_B^{2/3}\ sin\ A_p} \tag{3.26}$$

where in this case T_L is assumed to equal 60°C which is felt to be quite reasonable (*cf.* Byram and Nelson 1952). In the absence of wind (i.e., U_s = 0 and thus $sin\ A_p$ = 1.0), this would give the following result from Byram's (1958) T_L = 60°C (i.e., for head fires) curve for T_{lc} levels ranging from 30 to 110°F in 10°F increments:

T_{lc} (°C):	-1.11	4.44	10.0	15.56	21.11	26.67	32.22	37.78	43.33
h_s (m):	1.58	1.74	1.95	2.23	2.65	3.23	4.02	5.33	7.32
k:	9.6	9.6	9.7	9.8	10.2	10.7	11.1	11.8	12.1

For U_s = 1.5 km/h, A_p would range from 23-59° according to Equation 3.15a, assuming I_B = 32 kW/m. Therefore, *sin* 23° = 0.391 (at U_s = 5 km/h) and *sin* 59° = 0.857 (at U_s = 1.5 km/h). This would result in k_l varying from 11.2-24.6 (i.e., 9.6 ÷ 0.857 or 9.6 ÷ 0.390) at T_a ≈ 4.4°C to 14.1-31.0 (i.e., 12.1 ÷ 0.857 or 12.1 ÷ 0.390) at T_a ≈ 43.3°C.

Based on a regression fit of the data points extracted for the 17 experimental fires from Byram's (1958) graph, a k value of 12.4 was derived using Equation 3.20 in lieu of Van Wagner's (1973b) coefficient of 4.4713 as given in Equation 3.23 (r^2 = 0.96), a result remarkably similar to that derived for the Packham (1970) study for the no-wind case. If a wind was considered (i.e., U_s = 1.5-5 km/h), then k_l would in turn vary from 14.5 (i.e., 12.4 ÷ 0.857) to 31.7 (i.e., 12.4 ÷ 0.391), respectively.

Wade (1983, 1987) has stated that Van Wagner's (1973b) models will overpredict crown scorch heights associated with prescribed underburning in pine forests of the southeastern U.S.A. For example, Wade (1983) has recommended that the optimum range for I_B in slash pine stands is about 71-250 kW/m (T_a and U_s were not explicitly stated), in which case crown scorch heights should not exceed about 4.5 m (*see* also de Ronde et al. 1990, p. 235, Table 3). According to Equation 3.22, h_s = 5.9 m for a I_B = 250 kW/m. One possible explanation is that Equation 3.22 has been derived from 13 experimental fires where T_a ranged from ≈ 23 - 31.5°C. In the southeastern U.S.A., prescribed burning would normally take place under considerably cooler ambient temperatures if the objective were fuel hazard reduction -- perhaps typically 10°C or slightly less up to around 20°C (Wade and Lunsford 1989).

From the preceding discussion it follows that a more or less complete generalized crown scorch model would, in contrast to Van Wagner's (1973b) relationship represented by Equation 3.25, take the following form based on a transposition of Equation 3.26:

$$h_s = \frac{k_1 I_B^{2/3} \sin A_p}{T_L - T_a} \qquad (3.27)$$

where in turn T_L would be determined using the following commonly accepted logarithmic equation form for lethal temperatures in relation to time (Martin 1963a, 1963b; Martin et al. 1969):

$$T_L = \mathbf{A} + \mathbf{B} \ln t_d \qquad (3.28)$$

where **A** and **B** are regression coefficients and t_d is the duration of exposure which can be expressed in either minutes or seconds, although the latter quantity is preferred here. For practical purposes, t_d could be approximated from t_r as discussed in Section 3.1. Furthermore, the effects of solar radiation on leaf temperature (Tibbals et al. 1964; Gates et al. 1965) should also be considered in any model for predicting h_s when applied to situations where U_{10} or U_s are ≈ 5 km/h and 1 km/h or less, respectively (i.e., near calm conditions), in which case T_{lc} be increased by ≈ 10°C according to the calculations undertaken by Gates et al. (1965, p. 70, Fig. 5) for ponderosa pine needles.

3.2.5.3 Flame Size Characteristics in Lieu of Byram's Fire Intensity

The difficulty of applying Equation 3.17 to the prediction of crown fire initiation is that k_1 presumably cannot be considered as a universal value as long as Byram's (1959a) fire intensity is used in place of some more fundamental property or characteristic of surface fire behaviour incorporating both flame size and geometry reflecting both convective and radiant heating for the very reasons mentioned in Section 2.1. Because I_B is directly related to flame size, it is quite conceivable that h_F could be used in place of $I_B^{2/3}$ in Equation 3.26. In other words:

$$k_2 = \frac{(T_L - T_a) h_s}{h_F \sin A_p} \qquad (3.29)$$

In these instances, rather than using Equation 3.15a to predict A_p, in the absence of a relationship between A_p and h_F or L (and u), A might be used to loosely approximate A_p. In this regard, at least two possibilities exist (after Nelson and Adkins 1986 and Albini 1981a, respectively):

$$A = tan^{-1}\,(1.12\,(g\,h_F/u^2)^{0.29} \tag{3.30}$$

$$A = tan^{-1}\,(0.820\,(g\,h_F/u^2)^{0.5} \tag{3.31}$$

Similarly, L could also possibly be used in place of $I_B^{2/3}$ in Equation 3.26 as follows:

$$k_3 = \frac{(T_L - T_a)h_s}{L\,sin\,A_p} \tag{3.32}$$

A_p could then be estimated from the following relation (after Putnam 1965):

$$A = tan^{-1}\,(2.24\,(L/u^2)^{0.5}) \tag{3.33}$$

And in the same vein as Equation 3.27, h_F and L would be incorporated as follows:

$$h_s = \frac{k_2\,h_F\,sin\,A_p}{T_L - T_a} \tag{3.34}$$

$$h_s = \frac{k_3\,L\,sin\,A_p}{T_L - T_a} \tag{3.35}$$

A 6 to 1 h_s:h_F is a commonly cited rule of thumb in prescribed burning in Australia and South Africa (e.g., Van Loon and Love 1973; Byrne 1980; de Ronde 1988; de Ronde et al. 1990). This generalized guideline apparently was first introduced by McArthur (1962) and has since been reinforced by the following statement from Luke and McArthur (1978):

> *Flame height has a considerable bearing on scorch height. Broadly speaking, flames associated with prescribed burning are likely to cause scorch within a zone equivalent to six times flame height.*

Gould (1993) and others (e.g., Beck 1994; Burrows 1994, 1995a) have shown that there are limitations to this appealing rule of thumb. The obvious limitations of this guideline is that there is some unspecified T_a (and t_r) range associated with it and the effect of wind is ignored or it is also assumed to be at some unspecified range. For example, if it was assumed that U_s = 0.0 km/h (i.e., calm or still air conditions prevailed) and T_L = 60°C, then k_2 would theoretically vary from 240 to 300 over a T_a range of 10-20°C as would be typical for fuel reduction burning as implied by McArthur (1962). Note that in using the direct temperature measurement of T_c by Packham (1970) in lieu of h_s data, that k_2 = 265 if the effect of wind on determining A_p is ignored.

3.2.5.4 Crown Scorch Height as a Surrogate for Thermocouple Measurement of Convection Column Temperatures

Shielded-aspirated thermocouple measurements above experimental surface fires can be obtained if the instrumentation is readily available. There are however several practical and technical problems or obstacles to obtaining adequate measurements of convective temperatures above the flame fronts of forest fires (Van Wagner 1970; Van Wagner and Methven 1978). Van Loon (1969) very adequately describes the inherent difficulties and frustrations with temperature measurement of wildland fires in general as a result of a prescribed burning experiment undertaken in New South Wales, Australia, during the 60s:

> *It was considered desirable to obtain some measure of temperatures and in particular temperature-time relationships, encountered in the prescribed burning. Unfortunately severe limitations existed in the availability of suitable equipment for this purpose at the time of burning, when negotiations to borrow sophisticated potentiometric recorders proved unsuccessful. ...*
>
> *Due to the excessive time needed to install and test the thermocouples and to run wires in underground trenches from the observation points to the recording stations outside the plots of each of the four blocks. ...*
>
> *The temperature measurements were handicapped throughout. Trenches dug to bury wires, and adjacent tracks caused by repeated walking between observation points during the process of thermocouple installation, interfered with the natural spread of the fire, despite efforts to cover the tracks up with natural dry fuel from adjacent areas. In one case ... the site disturbance caused the fire to go out before reaching the litter and soil sensors. On other occasions the fire enveloped all 15 thermocouples at the same time and large time intervals between readings for each point could not be avoided. Due to the rapidly fluctuating nature of heat in forest fires, maximum temperatures were almost certainly missed and information on the duration of specific heat application is scanty. ...*
>
> *... it proved impossible to adequately monitor the majority of thermocouples, to establish meaningful time-temperature relationships.*

Admittedly, great strides have been made with respect to thermocouple instrumentation in recent years that can easily be used in the field (e.g., Sackett and Haase 1992; Cheney et al. 1992; Moore et al. 1995).

From the foregoing analysis and discussion in Section 3.2.5.2, one has to conclude that Van Wagner's (1975) inclusion of k derived from his crown scorch study (Van Wagner 1973b) is also suspect. However, his overall approach to the determination of k and for that matter k_1 does have merit. A reliable value of k_1 (or for that matter k_2 and k_3) could also conceivably be deduced, using Equation 3.26 (or Equations 3.29 and 3.32), indirectly as part of any experimental study involving the documentation of surface fires in order to produce guidelines or models for predicting the behaviour and impact of understory prescribed burning (e.g., van Wagtendonk 1972, 1974; Botelho et al. 1994; Botelho 1996). This should involve a more rigorous approach of linking h_s to T_a, I_B, and $U_{1,2}$. If this is indeed a valid approach, then it could conceivably eliminate the onerous task of conducting experimental surface fires up to the crowning stage in order to develop models or guidelines for predicting crown fire initiation as Van Wagner (1977a, 1989, 1993) and others have done (e.g., Quintilio et al. 1977; Bruner and Klebenow 1979; Stocks 1987a, 1987b, 1989; Alexander, Stocks and Lawson 1991; Stocks and Hartley 1995).

It's worth re-emphasizing that the type of ignition pattern can greatly influence the resulting h_s (Henderson 1967; Sackett 1968, 1969, 1972; Cooper and Altobellis 1969; Johansen 1984, 1987; Rothermel 1985); with respect to Johansen (1987), which involved simultaneous ignition of plots using head/back, flank and spot firing patterns (six replications), "No crown scorch measurements were taken in the study, although we did note that when scorch did occur in our stands (50-60 feet [15.2-18.3 m] tall), it was far worse in the line fired plots" (Johansen 1986). For example, in point source ignitions the vast majority of the area is burnt by the flanking portions of the expanding fire perimeter where the fire intensity is less than the head but greater than the theoretical minimum at the rear or the back of the fire (Catchpole et al. 1992). It's for this reason that the data contained in Table 3.5 can't be readily used to derive any of the proportionality constants. Had the h_s data been stratified by head, flanks and back then perhaps it could have been possible to derive k, k_1 or k_2. The ideal situation for deriving the proportionality constants would be use a single line head fire ignition with near calm or very light winds. This would avoid the necessity of resorting to Equation 3.15a to adjust the h_s data in deriving the proportionality constants. Level terrain would be preferable. Plot size should vary with **SH** but normally 30 x 30 m (minimum) to 50 x 50 m plots should be sufficient. What's desired is to conduct experimental fires such that the resulting h_s is greater than z but < **SH**; h_s should be measured downwind of the ignition line. The results reported here should assist in setting the burning prescription for the initial fire and then refining thereafter.

It's quite possible that the proportionality constants could exhibit a degree of seasonality (Norum 1975; McArthur 1980) if for example a significant shrub layer exists in the understory due to variations in the mass and moisture content as a result of natural phenological changes over the growing season (Reifsynder 1961; Wendel and Storey 1962; Philpot 1963; Blackmarr 1968; Blackmarr and Flanner 1975; Anon. 1990b) or as a result of meteorological factors (e.g., severe drought, frost). Beck (1995b) has pointed out the possibility of this in the *Eucalyptus* spp. forests of southwestern Western Australia based on a reanalysis of the experimental fire haviour data collected for the development of the Western Australian Forest Fire Behaviour Tables (Sneeujwagt and Peet 1985). Burrows (1994) has also identified a number of specific seasonal changes in the jarrah (*Eucalyptus marginata*) forest fuel complex in Western Australia. Any changes in the availability of large roundwood material, should it exist, would presumably be accounted for in the determination of w.

3.2.5.4.1 Lethal Time-Temperature Relationships for Tree Foliage

One basic improvement in the crown scorch methodology would be to acknowledge that T_L for conifer needle foliage is not necessarily a constant 60°C as implied in Van Wagner's (1973b) work and in fact varies according to the duration of exposure (Byram and Nelson 1952), in addition to perhaps differences amongst species and many other factors (e.g., variations in m, dormancy, etc.). What this means is that T_L in Equations 3.26, 3.27 or 3.32 (and 3.27, 3.34 or 3.35) could be predetermined by a specified duration of heating. Alternatively, a variable T_L would be selected as, for example, Peterson and Ryan (1986) have done. They felt that bud kill or death was far more important than scorched foliage in determining the post fire survival of conifers in the Northern Rocky Mountains, U.S.A. The following set of conditions recognized differences in bud size and phenological changes amongst tree species in terms of their relative resistance to convective heat damage to the crowns as a result of hot gases rising above the flame zone of a moving fire (after Peterson and Ryan 1986):

Condition 1: assume T_L = 60 °C for species with indefinite terminal buds such as western red cedar (*Thuja plicata*), regardless of date of fire, and for species whose buds are small or unshielded by needles during periods of active stem elongation such as subalpine fir (*Abies lasiocaspa*), grand fir (*Abies grandis*), Engelmann spruce (*Picea engelmannii*), western hemlock (*Tsuga heterophylla*) and Douglas-fir (*Pseudotsuga menziesii*).

Condition 2: assume T_L = 65 °C for the species noted in **Condition 1** with small buds during periods when buds are set, and for species whose buds are large or partially shielded by needles during stem elongation such as ponderosa pine (*Pinus ponderosa*), lodgepole pine (*Pinus contorta*), western white pine (*Pinus monticola*) and western larch (*Larix occidentalis*).

Condition 3: assume T_L = 70 °C for the species notes in **Condition 2** with large or shielded buds during periods when buds have set and the meristem is insulated by bud scales.

Peterson and Ryan (1986) did acknowledge that the T_L values assigned to each condition were "... somewhat arbitrary" they nevertheless produced realistic results in their modelling of postfire conifer tree mortality.

The very idea of considering T_L as a variable quantity rather than a fixed value might appear to be a trivial or completely unnecessary refinement, especially in light of the comparatively narrow critical range in T_L and rapidly increasing rate of death at higher temperatures in relation to time as reflected by t_r. However, if k_1 (or k_2 and k_3) were derived from h_s data obtained from backing fires, then it becomes important because t_r values for backfires are generally larger than head fires, especially if a moderately compacted duff (F + H horizons) layer exists. Note that de Ronde et al. (1990) contend that "The residence time of heading and backing prescribed fires is often about the same because the deeper flame zone of a heading fire compensates for its faster movement". This assertion is probably only valid for shallow litter fuelbeds of constant bulk density. For example, the D and r observations reported on by Kiil (1970) for the head fire and backfire of an operational prescribed burn in a boreal mixedwood stand in east-central Alberta, Canada, where combustion involved only the upper surface litter (chiefly deciduous leaves and dead herbaceous plants) gave identical t_r values (10 sec) according to Equation 3.1. In contrast, the t_r values associated with the head and back of an experimental fire in a boreal conifer stand in northern Alberta, Canada, exhibiting a substantial organic layer, as described by Kiil (1975), were 27 and 96 sec, respectively (Alexander 1982); similar findings have also been observed in the laboratory (Beaufait 1965).

The literature on lethal plant temperatures has been reviewed extensively by Hare (1961) and many others (e.g., McArthur 1980; Ryan 1982; Wade and Johansen 1986) and will not be repeated here. However, a few pertinent observations are in order. As Brown and Davis (1973) note, "Studies of heat injury to plant tissues consistently show the zone of minimum critical temperatures to be rather narrow for a given time of exposure". In this regard, Nelson's (1952) work is commonly referenced. He examined T_L versus t_d relationships for the one-year-old live needles of four pine species common to the southeastern U.S.A., namely slash pine, longleaf pine, loblolly pine and pitch pine (*Pinus rigida*) using the hot water bath technique (Fig. 3.16a); to avoid clutter with the relationships for the four individual species, his "average for all species" relationship is presented separately in Figure 3.16b. Injury or death was judged simply on the basis of discoloration (i.e., yellowing of the previous green needles); some subjectivity in the determination was acknowledged. Nelson (1952) felt that there was very little real difference between the four species examined and his average curve, which is based on the following tabulated data in his report (Nelson 1952, p. 6), has come to be commonly cited in prescribed burning guides for the southeastern U.S.A. (Moberly et al. 1978; Wade and Lunsford 1989) and in various forest fire science textbooks and manuals (e.g., Davis 1959; McArthur and Cheney 1972; Brown and Davis 1973):

T_L (°C):	64	62	60	58	56	54	52
t_d (min:sec):	0:03	0:05	0:31	1:24	3:15	5:54	11:18

where t_d is the lethal duration of heat exposure (sec). Employing Equation 3.28 to the above data gives the following result:

$$T_L = 66.23 - 2.04 \ln t_d \tag{3.36}$$

where in this case the units for t_d are seconds rather than seconds and/or minutes ($r^2 = 0.97$). In the interest of completeness, the plotted data for the individual pine species extracted from Figure 2 of Nelson's publication (1952, p. 5) is given below (n.d. = no data):

Slash pine

T_L (°C):	64	62	60	58	56	54	52
t_d (min:sec):	0:03	0:05	0:15	1:00	2:48	5:18	9:30

Loblolly pine

T_L (°C):	64	62	60	58	56	54	52
t_d (min:sec):	0:03	0:05	0:31	1:12	3:30	6:21	13:15

Longleaf pine

T_L (°C):	64	62	60	58	56	54	52
t_d (min:sec):	0:03	0:09	0:31	2:00	2:48	5:00	11:18

Pitch pine

T_L (°C):	64	62	60	58	56	54	52
t_d (min:sec):	n.d.	n.d.	0:54	1:30	4:00	7:00	n.d.

The following tree species specific equations were derived from the above data using Equation 3.28 as well:

$$T_L = 65.95 - 2.08 \ln t_d \tag{3.37}$$

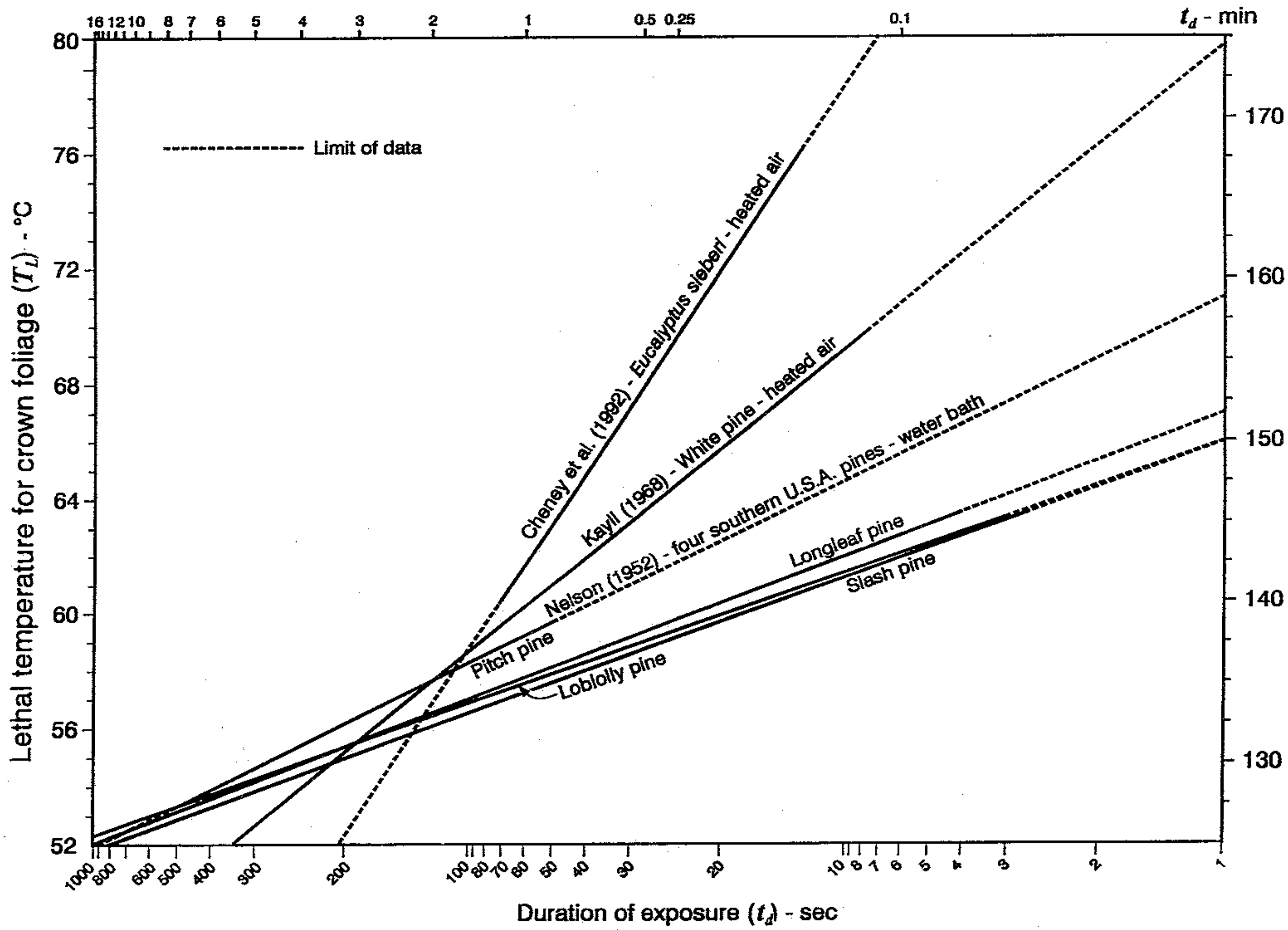


Figure 3.16a: Lethal time-temperature relationships reported for various species using both the water bath technique and heated air treatments.

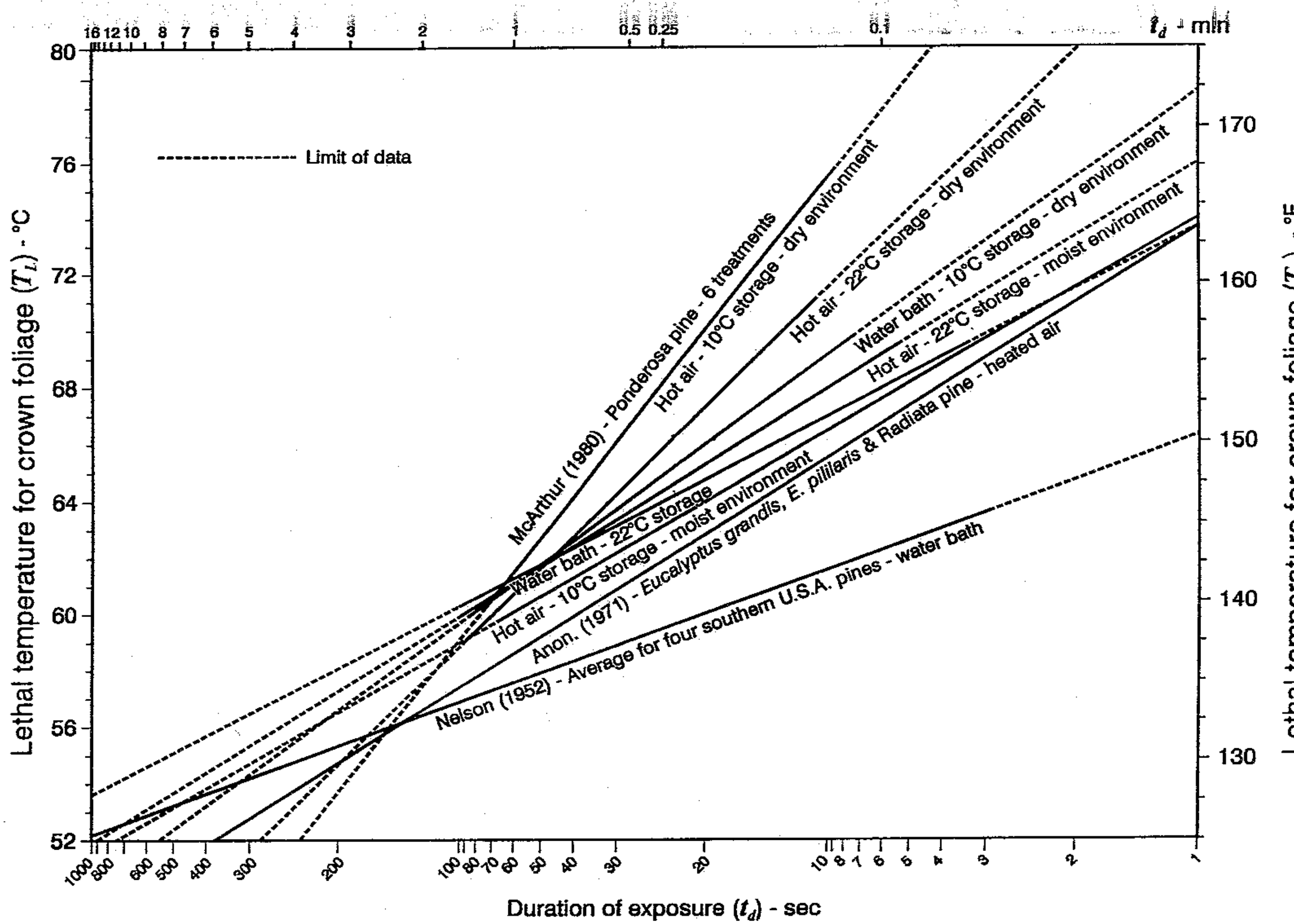


Figure 3.16b: concluded.

$$T_L = 66.95 - 2.17\ ln\ t_d \tag{3.38}$$

$$T_L = 66.13 - 2.00\ ln\ t_d \tag{3.39}$$

$$T_L = 70.81 - 2.76\ ln\ t_d \tag{3.40}$$

where Equations 3.37 ($r^2 = 0.98$), 3.38 ($r^2 = 0.97$), 3.39 ($r^2 = 0.98$), and 3.40 ($r^2 = 0.98$) pertain to slash pine, loblolly pine, longleaf pine and pitch pine, respectively.

If one wishes to determine t_d for a specific T_L (or interpreted in terms of the sum of ($\Delta T + T_a$) as implied by Nelson's (1952) average curve, which has been reproduced graphically in various forms (e.g., Byram 1958; Davis 1959; McArthur and Cheney 1972; Brown and Davis 1973; Mobely et al. 1978; Wade and Lunsford 1989), then this is accomplished by transposing Equation 3.36 as follows:

$$t_d = e^{(66.23 - T_L)/2.04} \tag{3.41}$$

Equations 3.37 to 3.40 can similarly be transformed. Note that the equation plotted out on the t_d versus T_L graph of Martin et al. (1969, Fig. 8, p. 284) for Nelson (1952) would roughly be:

$$t_d = e^{(72.54 - T_L)/2.83} \tag{3.42}$$

There is either an error in their graph or the authors did not use Nelson's (1952) average curve data in developing the equation used to plot out the T_L versus t_d relationship on their graph.

Kayll (1968) on the other hand subjected the stems of potted conifer tree seedlings to heated air of known temperatures for various lengths of time from 15 sec to 10 min. Tests were replicated five or six times. Viability of the cambium tissue was determined by a chemical test. The combination of temperature and duration of heat causing mortality in 50 percent of the tests for five-year-old eastern white pine seedlings are summarized below:

T_L (°C):	>70	65	60	60	60	53	55	55	52	52
t_d (min:sec):	0:15	0:30	0:45	1:00	2:00	3:00	4:00	6:00	8:00	10:00

Other than the anomaly at the combination of $T_L = 53\,°C$ and $t_d = 4$ min, the most obvious differences between the results obtained by Nelson (1952) in relation to the above is generally the greater heat tolerances of seedling stems compared to just needles and the greater range in t_d with T_L. The above data fitted to Equation 3.28, less the one anomalous combination noted above, gives the following result ($r^2 = 0.93$):

$$T_L = 79.68 - 4.40\ ln\ t_d \tag{3.43}$$

The result is also graphically presented in Figure 3.16a.

Earlier on, Kayll (1963) pointed out that immersing test material in heated water prevents heat dissipation, whereas using heated air does not. He felt that estimates of heat tolerance using heated air may therefore be higher and have greater relevance in terms of fire in the natural environment. This may very well be true although it's felt that the water bath technique provides for more immediate and uniform heating (i.e., there may be a lag time in using hot air and far more variable results might be expected).

In a lethal temperature-time study undertaken by the Fire Research Sub-section at the Australian Forestry and Timber Bureau's Forest Research Institute (Anon. 1971) using heated air, seedling leaves of two *Eucalyptus* species (*E. grandis* and *E. pilularis*) and radiata pine were exposed to a stream of hot air at different temperatures. No marked differences were noted between species in the temperatures and duration of exposure that could be endured before being killed by the convected heat. The following results were obtained:

T_L (°C):	65	58-60	50
t_d (sec or min):	15-30 sec	1 min	> 10 min

These results are somewhat similar to those of Nelson (1952) for $T_L < 60$°C even though seedlings were the test material as opposed to just needles. Strict comparisons are difficult to make because the criteria for leaf death was not specified. It was noted, however, that "At temperatures above 60°C the time taken to cause scorching varied with the ambient temperature. It appeared to take 10-15 seconds to raise the leaf temperature to 60°C from an ambient temperature of 18°C ...". The following equation is based on the above data with t_d = 10 sec (i.e., a 10-15 sec reduction in t_d at T_L = 65°C and then the midpoint of 5-15 sec selected for t_d) at T_L = 65°C:

$$T_L = 73.65 - 3.67 \ln t_d \tag{3.44}$$

In comparison to Nelson's (1952) findings, an apparent higher heat tolerance or heat capacity is evident (Fig. 3.16b).

McArthur (1980) examined the T_L versus t_d relationships of 1-year-old needles for five western U.S.A. conifer tree species, namely ponderosa pine grand fir, lodgepole pine, western hemlock and Douglas-fir, using both the water bath technique and exposure to hot air in "dry" (**RH** < 10%) and "moist" (**RH** > 75%) environments. Foliage samples were stored at either T_a = 10°C (**RH** 50%) or T_a = 22°C (**RH** 55%) for 24 hours prior to being subjected to the heating treatments. Leaf death was determined by an electrical response technique developed by the author; some problems and subjectivity in interpreting the output were encountered. McArthur's (1980) findings for the six ponderosa pine treatments are summarized in Figure 3.16b and obviously deviate from those of Nelson (1952), even for the water bath treatment, no doubt due in part to the differences in the techniques and criteria for evaluating leaf death between the two studies.

For the sake of completeness, the equations used to reproduce McArthur's (1980) results as presented in Figure 3.16b are provided here in condensed form. The general equation is as follows:

$$t_d = e^{(\mathbf{A} - T_L)/\mathbf{B}} \tag{3.45}$$

where the **A** and **B** regression coefficients are in turn listed below:

Heating treatment	A	B
Water bath - 10°C storage	78.52	4.20
Water bath - 22°C storage	73.60	2.99
Hot air - 10°C storage - dry environment	90.15	6.96
Hot air - 10°C storage - moist environment	73.90	3.29
Hot air - 22°C storage - dry environment	83.72	5.61
Hot air - 22°C storage - moist environment	75.86	3.49

McArthur (1980) found that there was not a great deal of difference between testing in water or heat moist air but the lethal time-temperature relationships were higher in hot dry air although he acknowledged that the apparatus constructed for the hot air treatment was "... an attempt to crudely simulate the action of hot air rising in a fire plume" and that "Far more variability in results occurred in these tests, especially at lower temperatures (60-65°C) ..." and for the hot air - dry environment treatments. McArthur's (1980) results for ponderosa pine substantiates the importance of T_{lc} in leaf death, at least for the water bath and hot dry air treatments. McArthur (1980) did note that even though the concept that foliage with higher T_{lc} values require less heat to reach their critical T_L level for a given time may be true, he concluded that his results were "... not conclusive enough".

Cheney et al. (1992) investigated the threshold conditions for leaf death of *E. sieberi* seedlings using heated air under various combinations of temperature, duration of heating and two air speeds (4.6 and 9.2 m/sec). The criteria for leaf death in the seedlings was 20-80% crown scorch. The T_L versus t_d relationship for *E. sieberi* leaves were higher than those obtained by other investigators (Fig. 3.16a). No equation was provided, only plotted data. However, at a reference level of t_d = 30 sec they stated that the T_L "... would be about 68°C". Interestingly, they found that the speeds of hot air tested had no influence on the outcome. The 10 data points from Figure 24 of their publication, as confirmed by Knight (1995), are as follows:

	4.6 m/sec air speed						9.2 m/sec air speed			
T_L (°C):	60	65	65	75	75	75	60	60	65	75
t_d (sec):	45	30	60	10	15	15	60	90	60	15

when this data is applied to Equation 3.28, the following result is obtained (r^2 = 0.84):

$$T_L = 96.54 - 8.34 \ln t_d \tag{3.46}$$

Note in reference to the comment above that when T_L = 68.2°, t_d = 30 sec by Equation 3.46.

Other than the equations presented by McArthur (1980), Figure 3.16 and the equations formulated in this section constitute a unique summary not previously undertaken to date. Obviously a great deal of uncertainty remains with respect to determining lethal temperatures in relation to time as a result of how and what kind of heat is artificially applied (e.g., water bath versus heated air), the test material used (e.g., leaves are less resistant to heat damage than woody stems), the number, increment and replication of T_L versus t_d combinations tested, and finally the criteria and/or method used for determining mortality. For present purposes, it's felt that Nelson's (1952) relationship is still reasonably valid, especially in light of very similar yet to be published findings recently for maritime pine (Botelho 1995; Rigolot 1995). More importantly perhaps, is the close agreement evident in Figure 3.15 between Byram's (1958) theoretical curves, which apparently incorporated Nelson's (1952) findings, and his own experimental fire data. Therefore, Equation 3.36 will be used in specifying the T_L in Equations 3.26, 3.29 and 3.32 (as well as 3.27, 3.34 and 3.35) where in a manner analogous to t_r being used to represent t_i, t_d will be inferred from t_r as well.

In arriving at the above conclusion, it's readily acknowledged that T_L may in fact vary seasonally as mentioned earlier on, as well as annually. Jameson (1961), for example, found that T_L for the live twigs of pinyon pine (*Pinus edulis*) in Arizona, U.S.A., varied up to 15°C throughout the year, with the highest T_L in the winter months as evident by the following tabulation:

Date (dd/mm/yy)	T_L (°C)	Date (dd/mm/yy)	T_L (°C)	Date (dd/mm/yy)	T_L (°C)
05.03.57	80.0	17.09.57	73.8	01.05.58	74.4
03.04.57	78.8	17.10.57	78.8	23.05.58	70.0
29.04.57	76.2	07.11.57	81.2	24.06.58	66.8
29.05.57	73.8	10.12.57	77.5	21.07.59	65.0
27.06.57	76.2	07.01.58	76.2	19.08.58	66.2
29.07.57	76.2	07.02.58	74.4	18.09.58	70.6
19.08.57	78.8	12.04.58	75.0	**Average**	74.5

One will notice that the times of lowest heat resistance differed between the two years that the investigation was carried out. In the first year of the study (1957), the lowest point occurred in late spring (May), with a secondary low in the fall (September). In the second year (1958), the lowest T_L occurred in early summer. Jameson (1961) suggested that the low heat resistance coincided with periods of hot, dry weather, which in turn might influence variations in $\boldsymbol{m}$ (Jameson 1966) which in fact might actually be the real underlying factor (Van Wagner 1973b).

3.2.5.4.2 An Actual Worked Example from Western Australia

The prescribed burning research undertaken by Burrows, Smith and Robinson (1988) in Western Australia will serve to illustrate the principles of using crown scorch data to derive a k_1 value by Equation 3.26, k_2 by Equation 3.29 or k_3 by Equation 3.32, while fully recognizing that this study was never designed specifically for this purpose (Tables 3.6a, 3.6b, and 3c). Thirteen 50 x 50 m experimental burning plots were established in a 14-year-old radiata pine (*Pinus radiata*) plantation that had been commercial thinned from 750 to 200 stems/ha; all of the remaining trees had been pruned to 2.1 m (Burrows 1995a). The resultant fuelbed "... consisted of a uniform layer of compacted ground needles ... overlain by discontinuous and aerated heaps of non-commercial tree tops and branches ..." (Burrows, Smith and Robinson 1988); the depth of the forest floor layer likely averaged ≈ 1.6 cm based on the average fuel load of 7.5 t/ha according to Table 7.2.1 in Sneeuwjagt and Peet (1985) and the slash height was probably ≈ 0.6 m (Burrows 1980b). At the time of the burning (i.e., August and September 1978 **not** 1979 as the authors stated in their report), the thinning slash

Table 3.6a: Attendant environmental conditions, fire impacts and fire behaviour characteristics associated with experimental fires conducted in 8- and 9-year-old commercial thinning slash within a 14-year-old radiata pine plantation in Western Australia (adapted from Burrows, Smith and Robinson 1988).

Exp. fire no.	T_a (°C)	RH (%)	U_s (km/h)	Needle and forest floor moisture contents (%)			Preburn fuel load and fuel consumption (kg/m²)								Hw[b] (kJ/m²)
				Aerated[c]	Surface	Profile	Aerated needles		Forest floor		Roundwood[a]		Total		
							m	w	m	w	m	w	m	w	
1	14	65	2.2	20	22	112	0.65	0.65(100)[d]	0.89	0.17(19)[d]	0.85	0.07(8)[d]	2.39	0.89(23)[d]	16 208
2	15	58	1.8	16	18	148	0.74	0.74(100)	0.91	0.16(18)	0.96	0.11(11)	2.61	0.95(24)	18 491
3	14	64	2.5	17	19	125	0.54	0.54(100)	1.01	0.16(16)	0.82	0.16(20)	2.37	0.86(22)	15 723
4	15	61	2.9	17	18	55	0.63	0.63(100)	0.62	0.23(37)	0.78	0.20(26)	2.03	1.06(26)	19 384
5	16	58	3.9	16	18	81	0.66	0.66(100)	0.59	0.21(36)	0.71	0.23(32)	1.96	1.10(32)	20 138
6	18	45	2.6	16	16	62	0.51	0.51(100)	0.63	0.08(13)	0.70	0.10(14)	1.84	0.69(23)	12 638
7	20	45	3.3	14	15	60	0.53	0.53(100)	0.70	0.12(17)	0.72	0.18(25)	1.95	0.83(26)	15 239
8	19	45	3.1	17	18	32	0.36	0.36(100)	0.48	0.14(29)	0.44	0.0(0)	1.28	0.50(24)	9143
9	19	45	3.0	16	17	34	0.38	0.38(100)	0.49	0.17(35)	0.49	0.09(18)	1.36	0.64(30)	11 718
10	18	55	3.1	17	18	40	0.34	0.34(100)	0.52	0.17(33)	0.43	0.03(7)	1.29	0.54(24)	9874
11	18	55	3.1	17	18	40	0.30	0.30(100)	0.49	0.15(31)	0.41	0.03(7)	1.20	0.48(21)	8777
12	20	52	3.5	17	18	150	0.48	0.48(100)	1.07	0.33(31)	0.60	0.17(28)	2.15	0.98(30)	17 918
13	20	50	3.1	16	17	110	0.52	0.52(100)	1.40	0.42(30)	0.64	0.16(25)	2.56	1.10(27)	20 138

[a]Less than 2.5 cm in diameter.

[b]Numerically equal to the prduct of the low heat of combustion, using a standard value of 18 700 kJ/kg (Alexander 1982), reduced for fuel moisture (24 kJ/kg per moisture content percentage point) as per Van Wagner (1972b) and Alexander (1982), times the fuel consumed as per Equation 2.1.

[c]In the thinning slash.

[d]Percent reduction noted in parantheses.

Table 3.6b: continued.

Exp. fire no.	h_s (m)	L[d] (m)	h_F (m)	h_s:h_F ratio	r (m/sec)	I_B[e] (kW/m)	D[f] (m)	D[g] (m)	D[h] (m)	t_r[i] (sec)	t_r[j] (sec)	t_r[k] (sec)	T_L[l] (°C)	A_p[m] (°)	sin A_p	k_1[n]
1	5.3	1.2	1.0	5.3	0.0111	180	0.18	1.50	0.66	16	135	59	57.9	55	0.819	8.9
2	6.5	1.5	1.4	4.6	0.0167	309	0.14	2.10	0.54	8	126	32	59.2	63	0.891	7.1
3	3.5	1.4	1.3	2.3	0.0122	192	0.24	1.95	0.52	20	160	43	58.9	52	0.788	6.0
4	5.8	1.4	1.3	4.5	0.0156	302	0.29	1.95	0.52	19	125	33	59.1	52	0.788	7.2
5	10.0	2.3	2.1	4.8	0.0217	437	0.45	3.15	0.93	21	145	43	58.9	48	0.743	10.0
6	6.6	1.4	1.3	5.1	0.0125	158	0.22	1.95	0.52	18	156	42	58.6	50	0.766	12.0
7	9.0	2.0	1.6	5.6	0.0206	314	0.33	2.40	1.20	16	117	58	57.9	49	0.755	9.8
8	3.6	1.1	1.0	3.6	0.0094	86	0.26	1.50	0.46	28	160	49	58.3	40	0.643	11.3
9	4.0	1.4	1.2	3.3	0.0111	130	0.26	1.80	0.72	23	162	65	57.7	44	0.695	8.7
10	2.5	0.9	0.8	3.1	0.0069	68	0.27	1.20	0.41	39	174	59	57.9	38	0.616	9.7
11	2.5	0.9	0.8	3.1	0.0067	59	0.26	1.20	0.41	39	179	61	57.8	37	0.602	10.9
12	8.0	1.7	1.5	5.3	0.0208	373	0.37	2.25	0.80	18	108	38	58.8	49	0.755	7.9
13	8.0	1.8	1.6	5.0	0.0208	419	0.32	2.40	0.82	15	115	39	58.8	53	0.799	6.9

[d]From Burrows (1984c).

[e]Calculated by Equation 2.1 in contrast to Burrows, Smith and Robinson (1988) estimates using Equation 2.2.

[f]Estimate deduced using Equation 3.48 (Nelson and Adkins 1988, Equation 15) based on the total w and U_s in lieu of u.

[g]Computed from Equation 3.49 (Leicester 1985) based on the observed h_F.

[h]Estimate deduced from Equation 3.50 based on the observed h_F and L.

[i]Computed from Equation 3.1 using the estimate of D obtained by Equation 3.48 (Nelson and Adkins 1988, Equation 15).

[j]Computed from Equation 3.1 using the estimate of D obtained by Equation 3.49 (Leicester 1985).

[k]Computed from Equation 3.1 using the estimate of D obtained by Equation 3.50.

[l]Computed from Equation 3.36 where t_r, based on the determination of D by Equation 3.50, was substituted for t_d.

[m]Computed from Equation 3.15a; the *sin* of the computed angle is given in the next column.

[n]Computed from Equation 3.26.

Table 3.6c: concluded.

Exp. fire no.	A^{o} (°)	sin A	A^{p} (°)	sin A	A^{q} (°)	sin A	k_2^{r}	k_2^{s}	k_2^{t}	k_2^{u}	k_2^{v}	A^{w} (°)	sin A	k_3^{x}	k_3^{y}
1	70	0.940	54	0.809	49	0.755	232	284	248	288	308	76	0.970	237	200
2	75	0.966	60	0.866	59	0.857	205	230	212	237	239	80	0.985	215	194
3	68	0.927	54	0.809	49	0.755	120	152	130	148	159	75	0.966	141	115
4	68	0.927	52	0.788	45	0.707	197	250	212	250	278	73	0.956	232	191
5	65	0.906	51	0.777	44	0.695	203	273	224	261	292	75	0.966	249	192
6	66	0.914	53	0.799	48	0.743	206	269	226	258	277	75	0.966	250	198
7	66	0.914	51	0.777	45	0.707	213	282	233	274	302	74	0.961	226	177
8	58	0.848	48	0.743	40	0.643	141	220	167	190	220	70	0.940	200	137
9	62	0.883	50	0.766	43	0.682	129	186	146	168	189	73	0.956	159	116
10	56	0.829	47	0.731	37	0.602	125	202	150	171	207	66	0.914	180	121
11	55	0.819	47	0.731	37	0.602	124	207	152	170	207	66	0.914	184	121
12	66	0.914	50	0.766	42	0.669	207	274	226	270	309	72	0.951	242	192
13	69	0.934	52	0.788	46	0.719	194	243	208	246	270	74	0.961	216	179

[o]Computed from Equation 3.14 (after Nelson and Adkins 1986, Equation 10); the *sin* of the computed angle is given in the next column.

[p]Computed from Equation 3.30 (after Nelson and Adkins 1986, Equation 8); the *sin* of the computed angle is given in the next column.

[q]Computed from Equation 3.31 (Albini 1981a); the *sin* of the computed of angle is given in the next column.

[r]Computed from Equation 3.29 where A_p is assumed to = 90°.

[s]Computed from Equation 3.29 (i.e., A_p was determined by Equation 3.15a).

[t]Computed from Equation 3.29 where A, as determined by Equation 3.14 (after Nelson and Adkins 1986, Equation 10), was substituted for A_p.

[u]Computed from Equation 3.29 where A, as determined by Equation 3.30 (after Nelson and Adkins 1986, Equation 8), was substituted for A_p.

[v]Computed from Equation 3.29, where A, as determined by Equation 3.31 (Albini 1981a), was substituted for A_p.

[w]Computed from Equation 3.33 (Putnam 1965); the *sin* of the computed angle is given in the next column.

[x]Computed from Equation 3.32 (i.e., A_p was determined by Equation 3.15a).

[y]Computed from Equation 3.32 where A, as determined by Equation 3.33 (Putnam 1965), was substituted for A_p.

was 8-9 months. Of the 50 or so possible sample trees in each plot, the $\boldsymbol{h_s}$ and tree height (**TH**) of "... about 10 ..." stems (Burrows 1995a) were measured along the plot centre line. A larger sample would have been desirable from the standpoint of deriving the three separate proportionality constants (i.e., $\boldsymbol{k_1}$, $\boldsymbol{k_2}$ and $\boldsymbol{k_3}$) for this specific fuel complex. **SH** varied from 18.4-22.6 m (Burrows 1995a).

Burrows, Smith and Robinson (1988) used Byram's (1959a) $\boldsymbol{I_B}$ - $\boldsymbol{L}$ relationship (i.e., Equation 3.24 to infer the $\boldsymbol{I_B}$ for each experimental fire (*cf.* Burrows 1984c) rather than using the observed $\boldsymbol{r}$ and measured $\boldsymbol{w}$ to calculate $\boldsymbol{I_B}$ by Equation 2.1 (Tables 3.6a and 3.6b). The $\boldsymbol{h_s}$ - $\boldsymbol{I_B}$ relationship derived by this author from the basic data contained in Burrows, Smith and Robinson (1988) as depicted in Figure 3.14a is:

$$\boldsymbol{h_s} = 0.1579\ \boldsymbol{I_B}^{2/3} \qquad (3.47)$$

Equation 3.47 ($r^2 = 0.97$) is based on $\boldsymbol{I_B}$ values as derived here (Table 3.6b).

Unfortunately no $\boldsymbol{D}$ or $\boldsymbol{t_r}$ data is available in order to estimate $\boldsymbol{T_L}$ by Equation 3.36; Burrows, Smith and Robinson (1988) stated that "... flame depth, flame angle were recorded ..." but the data could not be located. This simpliest solution might be to use Nelson and Adkins' (1988, Equation 15) formulation for predicting the horizontal flame depth by combining Equations 2.12 and 3.1 (where $\boldsymbol{U_s}$ would be substituted for $\boldsymbol{u}$):

$$\boldsymbol{D} = 0.39\ \boldsymbol{w}^{0.25}\ \boldsymbol{u}^{1.51} \qquad (3.48)$$

This would appear to offer a very promising solution that could quite possibly be applied to a multitude of fuel complexes. However, when Equation 3.48 was applied to the Western Australia data of Burrows, Smith and Robinson (1988) it tended in this author's opinion to underestimate the $\boldsymbol{t_r}$ values for many of the experimental fires (Table 3.6b); this is no doubt due in part to the fact that the vast majority of the experimental fires that Nelson and Adkins (1988) used in their analysis would: (*i*) not have taken place in fuel complexes possessing the distinct gradients in moisture content and bulk density evident in the forest floor layers of radiata pine plantations and (*ii*) have exhibited a very high degree of homogeneity in fuelbed structure, composition and moisture status in contrast to the radiata pine plantation commercial thinning slash fuel complex comprised of needle-bearing roundwood material (of various sizes) overlaid the forest floor layer.

Given the unsatisfactory results of the Nelson and Adkins (1988) model, the following equation suggested by Leicester (1985) was in turn examined for its relevancy:

$$\boldsymbol{D} = 1.5\ \boldsymbol{h_F} \qquad (3.49)$$

In contrast to the computations for $\boldsymbol{t_r}$ obtained usng Nelson and Adkins' (1988) model for predicting $\boldsymbol{D}$, Leicester's (1985) simplistic relationship resulted in $\boldsymbol{t_r}$ values that appear much too high for the prevailing environmental conditions (Table 3.6b) so an alternative approach was therefore sought. The following simplistic relation (*cf.* Simard et al. 1989) was used to approximate $\boldsymbol{D}$ from the observed $\boldsymbol{h_F}$ and $\boldsymbol{L}$ and was felt to yield quite reasonable estimates of $\boldsymbol{t_r}$ (Table 3.6b) which tended to be supported by studies in similar slash fuel complexes (Anderson et al. 1966; Rothermel and Anderson 1966, p. 34; Brown 1972):

$$D = (L^2 - h_F^2)^{0.5} \tag{3.50}$$

The uncertainty associated with the estimation of D and in turn t_r was not viewed as a critical limitation to the derivation of the proportionality constants given in Tables 3.6b and 3.6c in this case. For example, if one were to assume that I_B = 250 kW/m, h_s = 6 m, U_s = 2 km/h and T_a = 20°C, then for t_r = 30, 40, 50 and 60 sec, the derived k_1 values are in turn 10.46, 10.36, 10.27 and 10.21, respectively.

The basic data set from the Burrows, Smith and Robinson (1988) study and the relevant computations as outlined in Sections 3.2.5.2 and 3.2.5.3 are summarized in Tables 3.6a, 3.6b and 3.6c. The average calculated k_1 was 9.0 ± 1.9 (Table 3.6b) which when viewed in relation to values derived earlier on is in keeping with the concept that k_1 will in fact exhibit a lower value for more elevated surface fuelbeds. The use of h_F or L as a surrogate for $I_B^{2/3}$ did little to reduce the variation in the derived proportionality constant, in fact it accomplished quite the opposite in this particular case. Experimental fire no. 3 and to a certain extent nos. 8-11 tended to give anomalous results and this may be due to the nature of the fuel distribution across the plots (i.e., they may be distinctly different from the vast majority). This points out the general need in fire hehaviour documentation for including supplementary comments such as Quintilio et al. (1977, Appendix III) and Marsden-Smedley (1993, Appendix 2), for example, have done, in addition to the basic statistical or tabular data.

3.2.6 Sample Model Predictions

The step-by-step computational procedures to determine whether the onset of crowning or initial crown combustion is possible or not are as follows (Fig. 3.17):

Step 1: Compute A_p from U_s and I_B using Equation 3.15a (or Equation 3.15b if $U_s = 0$).

Step 2: Compute the temperature increase above ambient conditions (ΔT) for z (or z_o using Equation 3.18 if a slope is involved) of interest from k_1, I_B and A_p using Equation 3.17 (for needlebed surface fuel complexes k_1 = 16 and for thinning slash or dense understory vegetation k_1 = 9).

Step 3: Compute the convection column temperature (T_c) by adding T_a to ΔT determined at Step 2.

Step 4: Check to see if $T_c \geq 400$ °C. If so, go to Step 5, otherwise if $T_c < 400$°C then presumably crowning is not possible.

Step 5: Compute the time to ignition (t_i) from T_c and m using Equation 3.3.

Step 6: Check to see if the flame front residence time (t_r) is $\geq t_i$. If so, then crown fire initiation is possible, otherwise crowning presumably is not.

To illustrate the use of the model, a sample prediction based on a thinned and pruned radiata pine plantation is offered where it's assumed that U_{10} = 30 km/h and the U_{10}/U_s ratio is 4:1 (*cf.*

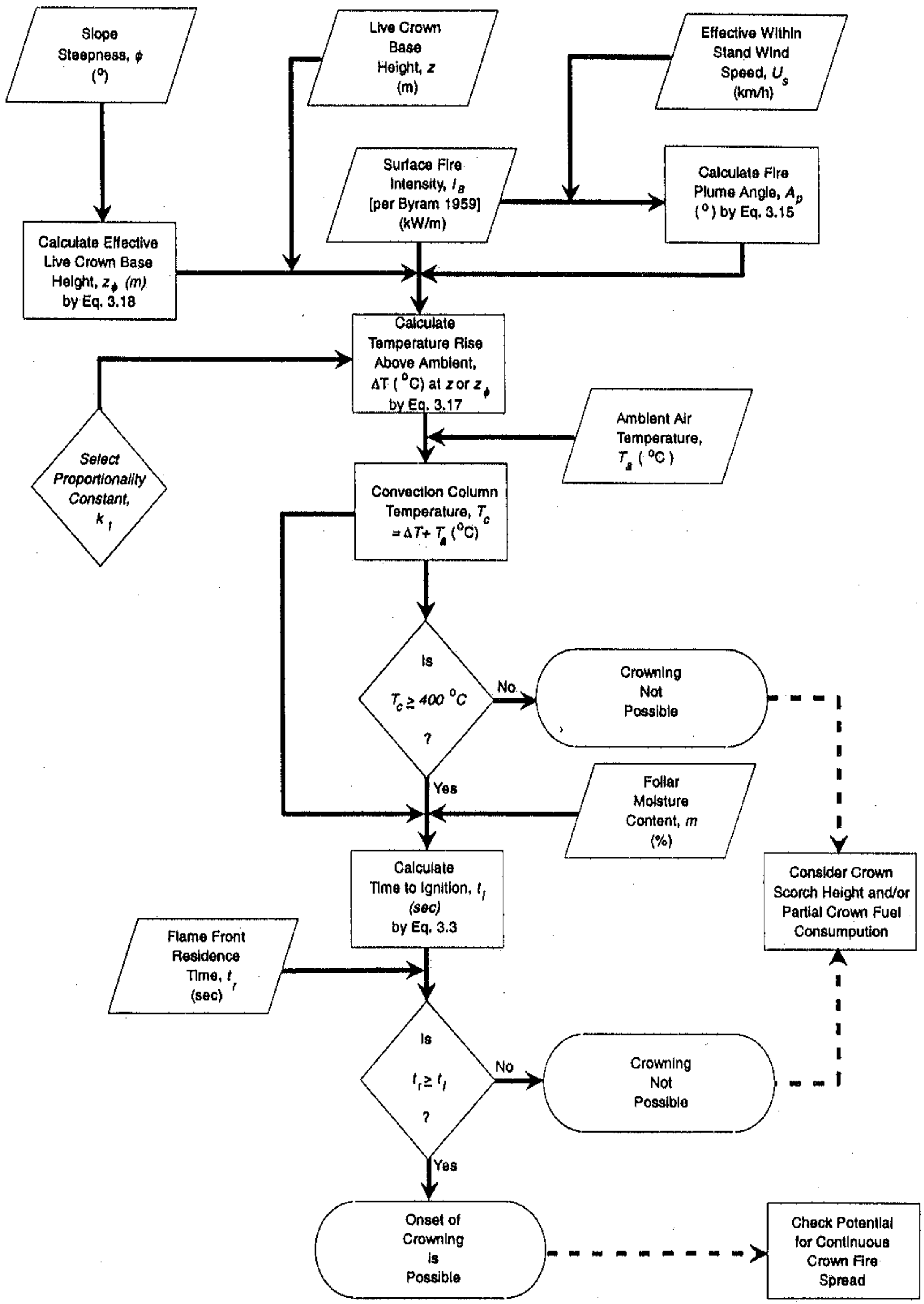


Figure 3.17: Flow diagram for the onset of crowning predictive model and related considerations.

Sneeuwjagt and Peet 1985) and $\theta = 0°$. Values for the six required user inputs, as previously discussed in Section 3.1, are as follows:

$$T_a = 20°C$$
$$U_s = 7.5 \text{ km/h}$$
$$m = 145\%$$
$$z = 5 \text{ m}$$
$$I_B = 2700 \text{ kW/m}$$
$$t_r = 40 \text{ sec}$$

$A_p = 47°$ by Equation 3.15a and $sin\ 47° = 0.731$. Assuming that k_l very conservatively equals a value of at least 16 based on the reanalysis of the data presented by Byram (1958), Packham (1970) and Van Wagner (1968, 1977a) for structurally similar fuel complexes (i.e., a relatively "clean" long needle litter fuelbed), then $\Delta T = 453°C$ according to Equation 3.17. Thus, $(\Delta T + T_a) = 473°C$ meets the minimum T_c criteria of $\geq 400°C$. It therefore follows that $t_i = 36$ sec from Equation 3.3 and because the observed t_r is $\geq$ than the calculated t_i required for crown fire initiation, then the onset of crowning is thereby predicted to occur. Had t_r been ≤ 35 sec, then presumably there would have been no possibility of a crown fire developing.

3.3 Model Validation

3.3.1 Experimental Fires and Operational Prescribed Fires

Young, Pruned and Unthinned Slash Pine Plantation, Queensland. The experimental fires reported on in Table 3.5 by Just (1969, 1974) provide one readily available test of the crown fire initiation model. Because of the uncertainty associated with the derivation of the proportionality constant(s) as previously discussed, it's unfortunately not possible to examine the experimental fire in the unpruned area. However, for the pruned area, letting $k_l = 16$ should be quite appropriate. $A_p = 47°$ by Equation 3.15a and $sin\ 47° = 0.731$. Thus, according to Equation 3.17, $\Delta T = 112°C$ which when combined with the prevailing T_a obviously doesn't meet the minimum T_c criteria of 400°C and matches the resulting fire behaviour (i.e., a surface fire prevailed). It is possible to ascertain what surface I_B would be required to attain a ΔT of 380°C using Equation 3.17. Accordingly, I_B must exceed 1060 kW/m and t_r must exceed 55 sec at a nominal m of 135% (based on unpublished data obtained from foliar moisture content sampling in southeastern Queensland during 1990-92), in order for the onset of crowning to occur.

Intermediate-aged, Commercially Thinned and Pruned Radiata Pine Plantation, Western Australia. Another potential source of data for model testing is that contained in Table 3.6 where in some cases $h_F = z$, although no true crowning occurred (Burrows, Smith and Robinson 1988). The two most intense fires, nos. 5 and 13 had h_s values of 10 and 8 m, respectively. A_p would by Equation 3.15a equal 48° ($sin\ 48° = 0.743$) and 53° ($sin\ 53° = 0.799$), respectively. Using the mean k_l value of 9.0 as derived from the data contained in Table 3.6, ΔT was predicted by Equation 3.17 to be 183° ($T_c = 199°C$) and 192° ($T_c = 212°C$), respectively which also doesn't meet the minimum criteria of $T_c \geq 400°C$. Calculations made using Equation 3.17 suggest that an I_B in excess of 1250 kW/m would be required to induce crowning in this particular fuel complex provided t_r was 66 sec, this assuming that $m = 160\%$

based on foliar moisture content studies conducted in radiata pine plantations in southeastern Western Australia during 1991-92 (unpublished data of author).

Middle-aged, Pruned and Thinned Radiata Pine Plantation, Australian Capital Territory. In October and November 1965, fire researchers at the Australian Forestry and Timber Bureau's Forest Research Institute at Canberrra carried out a series of experimental fires in a 23-year-old pruned and thinned radiata pine plantation in the Australian Capital Territory (McArthur 1966b; McArthur and Cheney 1966; Nicholls and Cheney 1974). The **SH** was ≈ 18-24 m and z, although not measured was estimated to be ≈ 10 m (Cheney 1995; unpublished data of author) or in other words roughly equivalent to the live crown depth (**CD**). The most intense fire (I_B ≈ 3875 kW/m, r = 0.0660 m/sec, D = 4.6 m, h_F = 2.7 m, t_r = 69 sec) was carried out when T_a = 21 °C, **RH** = 33% and U_s = 7.9 km/h. A_p according to Equation 3.15a was 61 ° (*sin* 61° = 0.875). Again assuming that k_I = 16 is appropriate to this fuel complex, ΔT would equal 345 °C by Equation 3.17 and T_c would thus equal 367 °C. McArthur and Cheney (1966) suggested that the surface I_B would have to reach ≈ 6900 kW/m in order for a crown fire to develop. According to calculations performed using the model as presented here, crowning would begin to commence once the surface I_B attained a level of ≈ 4825 kW/m or greater (based on a minimum T_c of 400 °C). The calculated t_i for m = 145% (*cf.* Gill and Pook 1991; Pook and Gill 1993) and T_c = 400 °C is 59 sec.

Intermediate-aged, Unthinned and Unpruned Maritime Pine Plantation, Western Australia. Burrows, Ward and Robinson (1988) documented the fire behaviour associated with three operational prescribed fires carried out in southeastern Western Australia in May 1986 for training purposes within a 17-year-old unthinned and unpruned maritime pine plantation with ≈ 2000 stems/ha; *see* also synopsis by Alexander (1989b). Individual plots were about 1.3 ha in size. According to the authors, "... short bursts of crown fire activity ..." were observed and they noted that "It seemed that fuel, weather and stand conditions ... were just below the threshold for sustaining crown fires". The fire weather conditions which prevailed at the time of each fire are as follows:

Plot no.	T_a (°C)	RH (%)	U_s (km/h)	U_{10} (km/h)
1	21	37	3.2	20
2	23	33	3.4	22
3	25	30	2.9	24

The observed and calculated surface fire behaviour characteristics were in turn (an H of 18 400 kJ/kg was used to calculate I_s as per Alexander 1989b):

Plot no.	w (kg/m²)	r (m/sec)	I_s (kW/m)	A_p (°)	sin A_p
1	1.20	0.0500	1104	60	0.866
2	1.21	0.0556	1237	59	0.857
3	1.18	0.0439	953	61	0.875

Unfortunately, z for each plot was not formally measured but from the existing documentation (i.e., photos, video footage, mean stand diameter at breast height outside bark (**DBHOB**) and tree data acquired during destructively sampling for biomass) it would have appeared to have been between 2-4 m. The **SH** was approximately 10-14 m. Given the uncertainty about the exact value of z, it was therefore decided to simply use Equation 3.17 to compute the height above ground that a minimum T_c of 400°C would occur, again using $k_1 = 16$. The results are as follows:

Plot no.	z (m)
1	3.9
2	4.2
3	3.6

The relatively good correlation between the visual and inferred estimates with the above is quite encouraging. Based on foliar moisture content sampling carried out in a similar aged maritime pine plantation in southeastern region of Western Australia (unpublished data of author), an estimate of m would be 120% and for a T_c of 400°C, $t_i = 49$ sec. According to the observed spread rates and Equation 3.1, D would have had to vary from 2.2-2.7 m which from the available video and 35 mm photographic documentation appears quite reasonable.

If we assume that $z \approx 4$ m, then it's possible to compute the range in d, based on a live crown depth (**CD**) of 6-10 m, and correspondingly R_o by Equations 2.9 and 2.10 from the $\mathbf{m_F}$ data reported by Burrows, Ward and Robinson (1988):

Plot no.	$\mathbf{m_F}$ (kg/m^2)	d (kg/m^3)	R_o (m/h)	Observed R (m/h)	Final I_B (kW/m)
1	0.67	0.067-0.112	1607-2687	280-350	1647
2	0.85	0.085-0.142	1268-2118	900-1440	2106
3	0.72	0.072-0.120	1500-2500	400-800	1534

Given some uncertainty about the precise value of **CD** used in the above computations, the observed behaviour of these fires closely approximates Van Wagner's (1977a) criteria for continuous active crowning. The periods of crowning were short lived. All three fires can probably best be categorized as intermittent crown fires as Alexander (1989b) had suggested earlier on in an article dealing with these operational prescribed fires. Burrows, Smith and Robinson (1988) lamented on the fact that perhaps active or fully developed crown fires would have been possible had the winds been slightly higher. This does indeed appear to be the case.

Young, Pruned and Thinned Slash Pine Plantation, New South Wales. During the course of conducting a series of low-intensity fires within 8-year-old slash pine plantation plots (1.2 ha in size) in northern New South Wales during February-March 1969 (Van Loon and Love 1973), one of the eight plots burned (Plot A2), although initially lit as a backfire, developed into a head fire before reaching the 0.16 ha internal study plot as a result of a 180° reversal in wind direction. According to Van Loon and Love (1973), "In places it burnt as an uncontrolled crown fire and concern for the safety of the plantation and personnel made the taking of some routine measurements impossible." This unexpected incident was not unlike that experienced by Van Wagner (1964) and presented a unique opportunity to study crown fire behaviour. For this reason, a concerted effort was made to acquire additional documentation on this fire and the others from the files of the Forestry Commission of New South Wales offices in Coffs Harbour and Sydney.

The **SH** for plot to A2 was ≈ 6.5 (basis: 12 dominant trees) and the mean **DBHOB** was 8.8 cm. All of the plots had been pruned to 2.44 m (8 ft) and precommercially thinned from 1528 (2.44 x 2.44 m initial spacing) to 889 stems/ha at least a year earlier. In addition to the pruning and thinning slash, the understory vegetation was well developed due to the lack of crown closure. The weather conditions during the "crowning" phase of the fire were as follows: T_a = 30.6°C, **RH** = 50%, U_s = 3.8 km/h and U_{10} ≈ 15 km/h (estimate). The fire consumed 9.1 t/ha of fuel and the average spread rate during 17 minutes or so it took for the fire to cross the ≈ 40 x 40 m internal study plot was 133 m/h (r = 0.0371 m/sec), thus giving I_B = 617 kW/m (Hw = 16 224 kJ/m^2 based on a composite moisture content of 18%). However, in the first 7 minutes after the fire entered the internal study plot, it advanced 26.8 m (r = 0.0638 m/sec) and in the 5-7 minute interval it covered ≈ 11 m (r = 0.0917 m/sec) with I_B values in turn varying from 1061 to 1524 kW/m. Photos taken during the fire confirm that the most intense fire behaviour was experienced during this period. Sufficient data is available on four of the eight plots (2 backfires and 2 head fires) to derive a value for k_l to be used in analyzing the Plot A2 fire of Van Loon and Love (1973). However, the value (k_l = 8.9) derived for Plot D4, although technically a backing fire, was considered for practical purposes to be virtually a "still air" fire (U_s = 0.8 km/h) and was therefore favoured over the other three for this reason.

For the two time periods during the plot A2 fire (i.e., 0-7 minutes and 5-7 minutes), A_p according to Equation 3.15a would have varied only slightly (56-58° with $sin\ A_p$ = 0.829-0.848). The calculated ΔT values by Equation 3.17 were in turn 315°C and 408°C, thus giving T_c of 345°C and 438°C, respectively, with the latter of course meeting the minimum criteria for foliar ignition. For a T_c of 438°C and m of 109% (based on sampling carried out in a similar aged stand in the vicinity of the Van Loon and Love (1973) study area in February 1992), t_i = 35 sec. According to Equation 3.1, D would have had to be slightly greater than 3 m. The computed t_r values for the other two head fires would certainly collaborate the asertion being made here that the t_r for the Plot A2 fire was at least ≥ 35 sec.

3.3.2 A Wildfire Behaviour Case Study

On 22 September 1991 a wildfire (Toolara No. 7) burnt over an area of 1238 ha, including 902 ha of planted slash pine in the Swampy Logging Area of the Toolara State Forest (SF 1004) in southeastern Queensland (Hamwood 1992a, 1992b; Ward 1992). This represented the largest exotic pine plantation wildfire in the state's history[7]. On 27 September 1991 the author received an invitation from the Queensland Forest Service (QFS) to examine certain aspects of

[7] At the time it also represented the largest single loss of slash pine due to a wildfire in Australia until the Beerburrun wildfires of 1994 in southeastern Queensland which covered some 4800 ha (Hunt et al. 1995). The previous "record", if you will, was held by a wildfire which burnt over 308 ha of slash pine plantation owned by APM Forest Pty. Ltd. near Burpengary, Queensland on 8 September 1977. Prior to that, this infamous distinction was held by a 22 663 ha wildfire in the Banyabba State Forest of northeastern New South Wales which occurred during the 1968-69 fire season. On 18 November 1968, 382 ha of exotic pine plantation was burnt over according to Forestry Commission of New South Wales' fire report; slash pine comprised approximately 79% of this total and loblolly pine made up the remainder according to post-burn survey work undertaken by Mr. A.P. Van Loon, Forestry Commission of New South Wales, in December 1968.

behaviour associated with the Toolara No. 7 wildfire in light of the present research programme associated with crown fire behaviour in exotic pine plantations of Australasia. A total of five days (October 7-11) were available for on-site fieldwork and inspection of the fire area. A preliminary report was prepared for the QFS (Alexander 1992a); final conclusions are reported on here.

The vertical aerial photographs taken by the QFS Head Office staff on 30 September 1991 and the fire progress map prepared by the QFS district staff involved in the suppression action were immediately examined upon arrival in Gympie on 7 October 1991. A fixed-wing reconnaissance flight was made over the burn area that afternoon (Fig. 3.18). On the basis of this post-burn evidence it was this author's opinion, contrary to popular belief (Dildine 1992; Hamwood 1992a), that the vast majority of the "crowned out" fire areas were linked to the junction zones resulting from the forward momentum of the wildfire merging with the backfires lit by suppression personnel as opposed to crowning as a result of the free-burning nature of the wildfire front. True crowning was evident, but only to a limited extent, in those plantation stands containing significant quantities of understory scrub, especially along the downwind edges of the swamp areas; this situation tended to be exacerbated if the slash pine were unpruned and unthinned. Given the rather severe burning conditions prevailing in the Toolara State Forest during the afternoon of 22 September 1991 (Tables 3.7 and 3.8), one might ask: Why was there so very little evidence of free-burning crown fire activity? Was the fire behaviour predictable? What are the implications for fire and fuel management in the future? It was, therefore, decided to concentrate the investigation of the Toolara No. 7 wildfire within the area burnt (Tables 3.9 and 3.10) during the initial stages of the major run around 1:00 to 2:00 p.m. (Fig. 3.19) This appeared to be the most fruitful approach given the time (5 days) and resources (2 persons) available for work on site. Furthermore, the documentation of fire growth with time appeared to be the most reliable and straightforward for this phase of the fire and the plantation fuel type pattern for the area involved was relatively continuous. It also corresponds to the period of maximum fire danger reached during the afternoon of 22 September 1991.

3.3.2.1 The Fire Environment

Topography. The general elevation for the area of interest is approximately 60 m MSL. The terrain is essentially level to very gently undulating. Maximum ground slope over very short distances (less than 50 m) would be less the 5° and this was largely confined to the swamp areas traversing Compartment 7-8 and 10-11 (Fig. 3.19). However, θ for the area burnt between 1:00 and 2:00 p.m. would for practical purposes be considered as 0°.

Weather and Fire Danger Ratings. A weather station maintained and operated by the QFS is located at the Toolara Forest Station (FS) which is about 6.3 km west-southwest of the fire's origin. According to the latest statistical summary published by the Bureau of Meteorology (Anon. 1988b), Toolara FS averages 227 mm of rain between June and September (basis: 16 years of record). In 1991, only 50.7 mm of rain were recorded during this time is, as illustrated in Figure 3.20, reflected in the Keetch and Byram (1968) Drought Index (**KBDI**) trace for the Toolara FS. The **KBDI** on 22 September 1991 was 472 (units: 0.01 in.)[8]. The last measurable

[8]This value was arrived at by computer calculation as opposed to tabular computation. The **KBDI** according to the QFS records was 524 (units: 0.01 in.) on 22 September 1991. This kind of difference is to be expected between tables versus computer derived values (Deeming 1975). Please note that the author has observed that the Toolara FS staff are using the maximum temperature recorded at 9:00 a.m. (i.e., yesterday's maximum as the value in computing the **KBDI** on the same day.

Figure 3.18: Post-burn oblique aerial view of the Toolara No. 7 wildfire (22 September 1991) in southeastern Queensland, Australia, looking from west to east over the area. Photo date: 7 October 1991. Photo by: M.E. Alexander.

Table 3.7: Fire weather observations made at Toolara Forest Station before and during the major run of the Toolara No. 7 wildfire in southeastern Queensland, Australia, on 22 September 1991.

Local time (hrs)	T_a (°C)	Wet-bulb temperature (°C)	RH (%)	Wind direction (from)	Beaufort scale wind strength (number)	U_{10}[b] (km/h)
0900	24.5	16.2	38	SW	2	10
1000	27.5	15.0	19	SW	1-2	7
1100	29.1	15.9	18	W	1-2	7
1200	30.0	15.4	14	SW	2	10
1330	31.0	15.5	11	W	4	28
1400	30.8	15.4	12	W	4	28
1500	31.1	15.6	12	W	3	18
1530	31.4	15.5	10	W	3	18
1600	30.6	15.1	12	W	3	18
1700	29.7	15.5	15	W	3	18
1735	24.8	18.8	54	E	1	4
1800	23.0	18.2	61	E	1	4

[a]Determined from non-ventilated dry- and wet-bulb thermometer readings (station elevation: 61 m MSL) based on computer calculation as opposed to tabular computation.

[b]Estimate based on the mid-point of the range in wind speed associated with each Beaufort scale number (List 1951, p. 119, Table 36) and then adjusted by a 15% increase (Turner and Lawson 1978) for the height of the anemometer (a Dwyer II wind speed indicator) above ground (6.0 m).

Table 3.8: Fire danger ratings and potential fire behaviour characteristics based on the McArthur (1973) Mk.5 Forest Fire Danger Meter according to the burning conditions at Toolara Forest Station before and during the major run of the Toolara No. 7 wildfire in southeastern Queensland, Australia, on 22 September 1991.

Local time (hrs)	Forest fire danger[a] Index value	Class level	Head fire rate of spread (m/h)[b] 12.5 t/ha	20.0 t/ha	Head fire flame height (m) 12.5 t/ha	20.0 t/ha	Maximum spotting distance (m)[c] 12.5 t/ha	20.0 t/ha
0900	9.6	Moderate	145	232	2.9	5.8	185	454
1000	19.2	High	288	460	4.7	8.8	722	1255
1100	21.0	High	314	503	5.1	9.3	820	1406
1200	27.5	Very High	413	661	6.4	11.4	1192	1960
1330	46.5	Very High	697	1116	10.1	17.3	2259	3557
1400	46.2	Very High	693	1108	10.0	17.2	2244	3528
1500	36.9	Very High	554	886	8.2	14.3	1722	2750
1530	38.6	Very High	579	926	8.5	14.8	2176	2890
1600	36.3	Very High	544	871	8.1	14.1	1684	2697
1700	30.7	Very High	460	736	7.0	12.4	1368	2223
1735	4.9	Moderate	73	117	2.0	4.3	0	51
1800	3.6	Low	54	86	1.7	3.9	0	0

[a]Based on **DF** = 10.0. The **KBDI** = 120.0 mm or 472 points (0.01 in.), assuming a total annual rainfall of 750 mm (Anon. 1988b), **N** = 62 and **P** = 10.2 mm.

[b]Based on θ = 0° ground slope.

[c]Applicable to eucalypt forests. From an analysis of documented spot fires associated with several wildfires in radiata pine plantations, Douglas (1974b) suggested that spotting distances were roughly a quarter of those commonly experienced in eucalypt forests assuming that the fuels were double the standard load (i.e., **W** = 25 t/ha).

Table 3.9 Establishment and silvicultural histories of the slash pine plantation stands burnt during the initial stages of the major run of the Toolara No. 7 wildfire in southeastern Queensland, Australia, on 22 September 1991.

Swampy Logging Area Cpt. no.	Unit no.	Size (ha)	Planting date (month/yr)	Initial stem spacing (m)	Pruning history Height (m)	Pruning history Date (month/yr)	Thinning history[a] Density (no./ha)	Thinning history[a] Date (month/yr)	Prescribed burn history Date(s) (month/yr)
7	1	9.0	06/70	3.0 x 2.4	5.4	05/79	547(T1)	03-09/90	04/82 & 06/85
7	2	12.5	06/70	3.0 x 2.4	unpruned	-	577(T1)	03-09/90	04/82 & 06/85
7	3	1.9	06/70	3.0 x 2.4	unpruned	-	unthinned	-	04/82 & 06/85
8	1	27.9	06/70	3.0 x 2.4	5.2	05/79	372(T2)	05-09/90	06/85
8	2	16.1	06/70	3.0 x 2.4	unpruned	-	581(T1)	05-09/90	06/85
10	1	49.0	06/71	3.0 x 2.4	5.2	09/79	326(T2)	5/89-03/90	05/83 & 06/87
10	2	5.7	06/71	3.0 x 2.4	unpruned	-	502(T1)	05/89-03/90	05/83 & 06/87
11	1	34.6	06/71	3.0 x 2.4	5.2	09-10/79	307(T2)	04/89-03/90	05/83 & 06/87
11	2	48.9	06/71	3.0 x 2.4	unpruned	-	591(T1)	04/89-03/90	05/83 & 06/87

[a]T1 = first precommercial thinning; T2 - second precommercial thinning. Cpt. 7/Unit 3: an inventory undertaken in October 1990 indicated 1172 stems/ha. Cpt. 8/Unit 1 and Cpt. 10/Unit 1: T1 took place 06-08/83 and the resultant density waas assessed at 609 and 700 stems/ha, respectively. Cpt. 11/Unit 1: T1 took place 03/84-04/85 and the resultant density was assessed at 690 stems/ha.

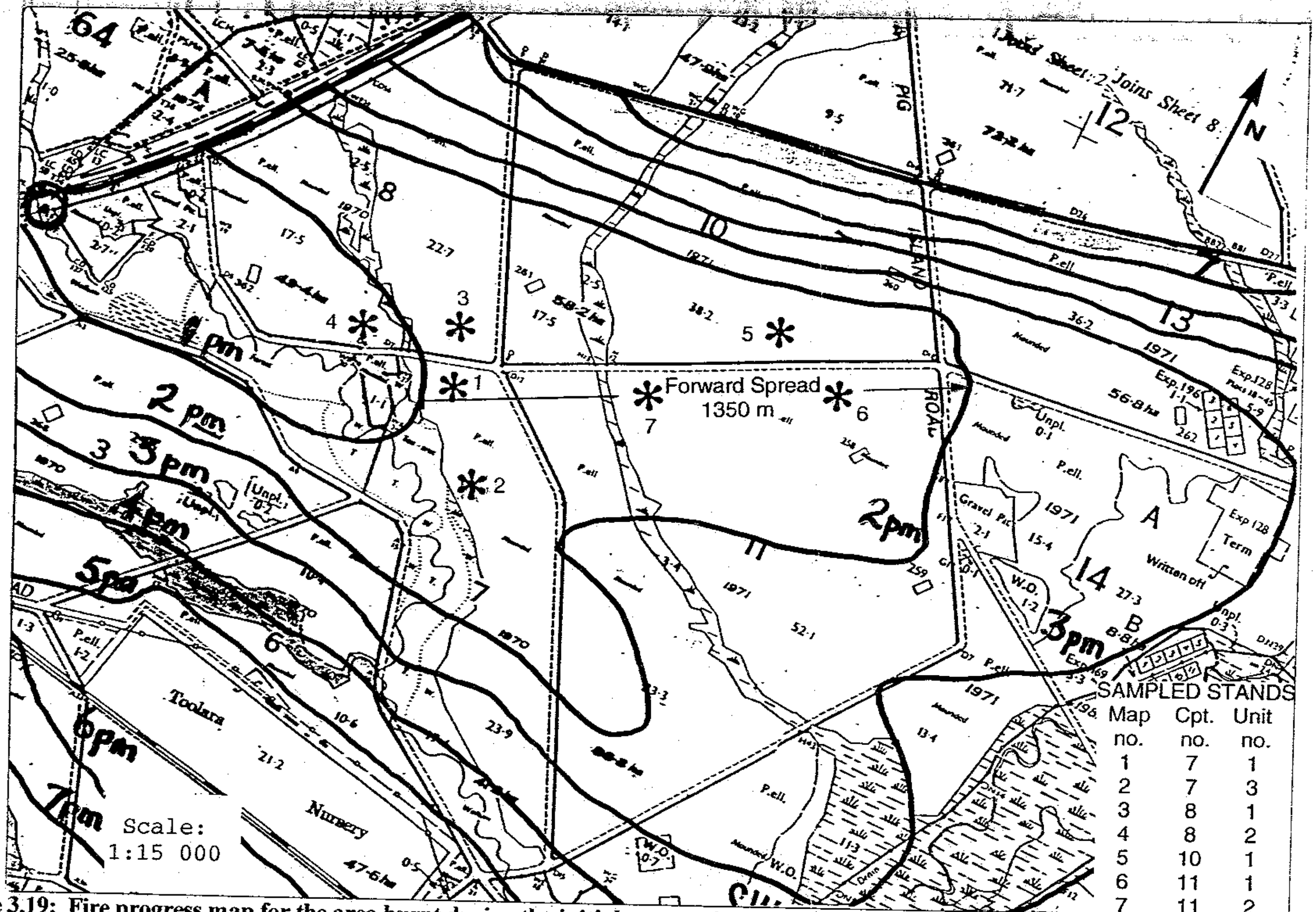
Table 3.10: Preburn stand characteristics/crown fuel properties and post-fire observations of sampled Pinus slash pine plantation stands burnt during the initial stages of the major run of the Toolara No. 7 wildfire in southeastern Queensland, Australia on 22 September 1991.

Logging Swampy Area Cpt. no.	Unit no.	DBHOB[a] (cm)	SH[a] (m)	BA (m^2/ha)	z (m)	m_F (kg/m^2)	CD (m)	d (kg/m^3)	HFC[a] (m)	HSF[a,b] (m)
7	1	24.2±3.3	21.7±1.1	25.6	14.3	0.73	7.4	0.10	12.1±1.4	14.3±1.1(23)
7	3	18.8±4.8	14.0±2.7	34.5	8.0	1.12	6.0	0.19	8.8±1.6	-[c]
8	1	28.4±3.0	22.0±1.2	23.8	12.4	0.61	9.6	0.06	10.5±1.0	12.4±2.1
8	2	23.6±3.1	21.4±1.4	25.8	15.0	0.75	6.4	0.12	12.9±2.3	19.1±2.6(7)
10	1	26.6±2.1	21.5±0.9	28.0	13.0	0.76	8.5	0.09	11.2±1.1	13.0±1.0
11	1	27.8±2.4	21.1±0.9	18.8	12.9	0.49	8.2	0.06	10.6±0.6	12.9±1.3
11	2	25.1±4.0	20.5±1.8	30.1	14.1	0.82	6.4	0.13	12.1±1.3	16.2±2.5(21)

[a]Basis: 25 measurements per stand. Both the mean and standard deviation are given.

[b]In all cases, the maximum crown scorch height exceeded the SH.

[c]Cpt. 7/Unit 3: this stand experience complete flame defoliation in the crown space.



Map no.	Cpt. no.	Unit no.
1	7	1
2	7	3
3	8	1
4	8	2
5	10	1
6	11	1
7	11	2

Figure 3.19: Fire progress map for the area burnt during the initial stages of the major run of the Toolara No. 7 wildfire in southeastern Queensland, Australia, on 22 September 1991. The locations in which post-burn sampling was undertaken are noted.

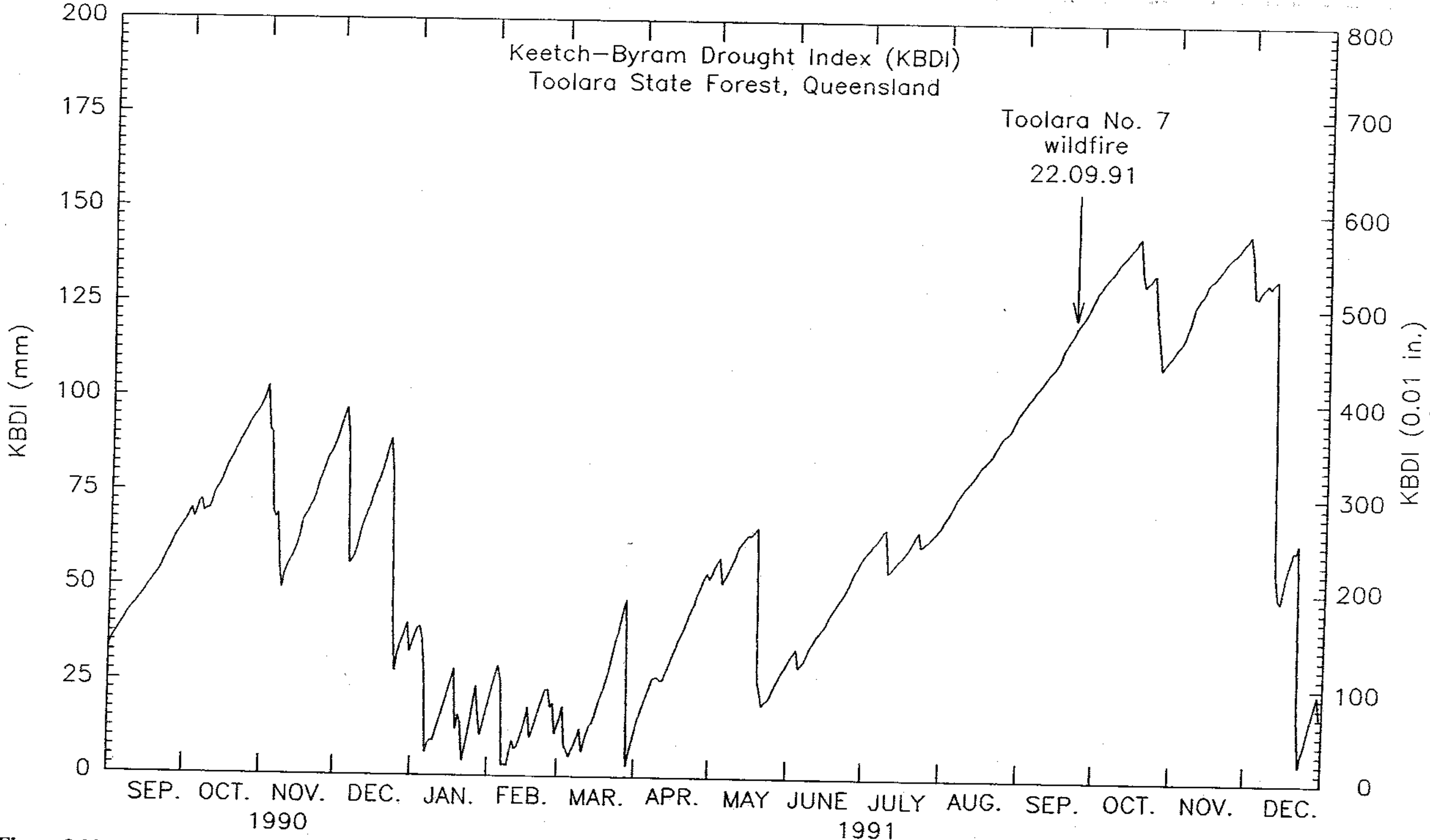


Figure 3.20: Seasonal trend in the Keetch-Byram Drought Index at the Toolara Forest Station in southeastern Queensland, Australia, during 1990-91.

rain (0.6 mm) occurred on August 16, 37 days previously. The Mount (1972) Soil Dryness Index (**MSDI**) was calculated to be 161 (units: mm) for interception class E although the **MSDI** is not operationally used in Queensland. The seasonal stage of drought severity experienced in 1991 as evident by the **KBDI** is certainly comparable to that of 1968 which has been generally considered as a benchmark fire season in southeastern Queensland (Just 1978), at least in recent memory although higher **KBDI** values and extending for much longer periods have occurred in the past. The maximum **KBDI** value at Toolara FS in 1968 (on October 11) was only 345 (units: 0.01 in.) but the period of below-normal precipitation extended into 1969 (Hawkes 1979). The maximum **KBDI** at Toolara in 1969 (on February 11) was 506 (units: 0.01 in.).

The equation used to calculate McArthur's (1973) Forest Fire Danger Index (**FFDI**) values as contained in Table 3.8 is as follows (after Noble et al. 1980):

$$\mathbf{FFDI} = 2.0e^{(-0.450 + 0.987\, ln\, \mathbf{DF} - 0.0345\, \mathbf{RH} + 0.0338 T_a + 0.0234\, U_{10})} \qquad (3.51)$$

Where **DF** is McArthur's (1973) Drought Factor, not to be confused with Keetch and Byram's (1968) "drought factor" (Crane 1982), **RH** is the relative humidity (%), T_a is the ambient air temperature (°C), and U_{10} is the 10-m open wind speed (km/h). The **DF** is a proportional measure of the total fuel availability and varies from zero to a maximum value of 10.0 (Sirakoff 1985). The **DF** is in turn computed from the following equation (after Noble et al. 1980; Sirakoff 1985):

$$\mathbf{DF} = 0.191(\mathbf{KBDI} + 104)\, (\mathbf{N} + 1)^{1.5} / 3.52\, (\mathbf{N} + 1)^{1.5} + \mathbf{P} - 1 \qquad \text{, set } \mathbf{DF} = 10 \text{ if} > 10 \quad (3.52)$$

where **N** is the time since last rain (days) and **P** is the amount of last rain or precipitation (mm). The **MSDI** can be substituted in place of the **KBDI** in Equation 3.52 without any appreciable effect on the **FFDI** (*cf.* Gill et al. 1987). McArthur's (1973) meter also provides for the output of the three fire behaviour characteristics as well (after Noble et al. 1980; Cheney 1981; Shugart and Noble 1981):

$$R_\theta = \mathbf{FFDI}\ 1.2\ \mathbf{W} e^{0.069\theta} \qquad (3.53)$$

$$h_F = 0.013\, R + 0.24\, \mathbf{W} - 2.0 \qquad (3.54)$$

$$\mathbf{S} = R\, (4.17 - 0.033\, \mathbf{W}) - 360 \qquad (3.55)$$

here R_θ is the head fire rate of spread on a slope (m/h), **W** is the total available fuel load (t/ha), θ is the slope steepness (°), h_F is the head fire flame height (m), R is the head fire rate of spread on level terrain (m/h), and **S** is the maximum likely spotting distance (m). **W** in Equations 3.53, 3.54 and 3.55 was nomially set at 12.5 t/ha although it can be treated as a variable quantity or assigned another reference level. For example, Douglas (1973) set **W** = 25 t/ha for the purposes of his initial attack/fire behaviour and growth simulations in South Australian radiata pine plantations. An estimate of I_B can be made directly from McArthur's (1973) **FFDI**, if **W** is known or can be estimated, by combining Equations 2.1 and 3.53 into a single equation (after Wilson 1988a):

$$I_B = \mathbf{FFDI}\ 0.6\ \mathbf{W}^2 e^{0.069\theta} \qquad (3.56)$$

In formulating Equation 3.56 it's assumed that H = 18 000 kJ/kg.

Regardless of the level of drought severity experienced in the Toolara State Forest in 1991, the **DF** of the McArthur (1973) Mk. 5 Forest Fire Danger Meter had already reached a maximum value of 10 by August 16, indicating that the total fine fuel load was completely available for combustion. The fire weather observations (and subsequent revisions and interpretations made by the author) taken at the Toolara FS during the morning and afternoon of 22 September 1991 are summarized in Table 3.7. The maximum T_a reached during the afternoon of September 22 was 31.5 °C. During the 1:00 to 2:00 p.m. interval of interest, the following weather conditions would have prevailed:

$$T_a = 31\,°\mathrm{C} \qquad \mathbf{RH} = 11\% \qquad U_{10} = 28 \text{ km/h}$$

Given the above conditions and **DF** = 10, this yielded a computer calculated **FFDI** of 46.5 -- i.e., a *Very High* fire danger classification (Table 3.8).

An estimate of U_s could possibly be deduced from the reported U_{10} using the following equation as adapted from Cooper (1965):

$$U_s = 0.1033 - 0.0084U_{10} + 2.3179/\mathbf{BA} + 0.0211(\mathbf{SH})U_{10} \qquad (3.57)$$

where **BA** is the stand basal area (m²/ha). Cooper's (1965) relation, which has been used by others (e.g., Lawson 1972; Hough and Albini 1978), is based on paired measurements of in-stand (at a height of 1.22 m) versus 6.1-m (20-ft) open wind speeds in two slash pine and five loblolly pine plantations (free of heavy understory vegetation) in Georgia, U.S.A., in which **BA** varied from 4.6-10.7 m²/ha and **SH** ranged from 6.1-19.8 m. In converting the wind speed coefficients in Cooper's (1965) original equation with respect to the 6.1-m (26-ft) versus 10-m open wind, the reduction factor (1.15) suggested by Turner and Lawson (1978, p. 37, Appendix 6) was used. Note that if one wished to estimate U_{10} from U_s then the following equation would apply:

$$U_{10} = (U_s - 0.1033 - (2.3179/\mathbf{BA}))/(0.0211\ \mathbf{SH} - 0.0084) \qquad (3.58)$$

For U_{10} = 28 km/h, U_s = 12 km/h based on **BA** = 27 m²/ha and **SH** = 20.3 m (i.e., the average of the seven stands given in Table 3.9). This constitutes a 2.3:1 ratio. For "thinned coniferous plantations 30-40 m high" Luke and McArthur (1978) state that the $U_s \approx 10$ km/h when U_{10} = 28 km/h (i.e., a 2.8:1 ratio) whereas Sneeuwjagt and Peet (1985) suggest a U_s/U_{10} ratio of 4:1 for "thinned stands" of pine plantation (i.e., U_s = 7 km/h). Perhaps a reasonable compromise is to assume that U_s = 9.5 km/h (i.e., the midpoint of 7-12 km/h).

Smallengange (1991) has indicated that the atmosphere was very unstable. Radiosonde soundings from both Brisbane (160 km south of the fire area) and Gladstone (285 km northwest of the fire area) showed the environmental lapse rate close to the dry adiabatic lapse rate in the lowest 3000 m of the atmosphere.

Fuels. The slash pine plantation stands in the area under consideration were 19 and 20 years old at the time of the fire (Table 3.9 and Fig. 3.21). All compartments had been planted up at approximately 1389 stems/ha. The silvicultural histories of the units varied, but the bulk of the area had been high pruned to 5+ m and precommercially thinned twice. All of the units had been prescribed burned at least once and several had been treated twice. About half of the a: Cpt. 7, Unit 1

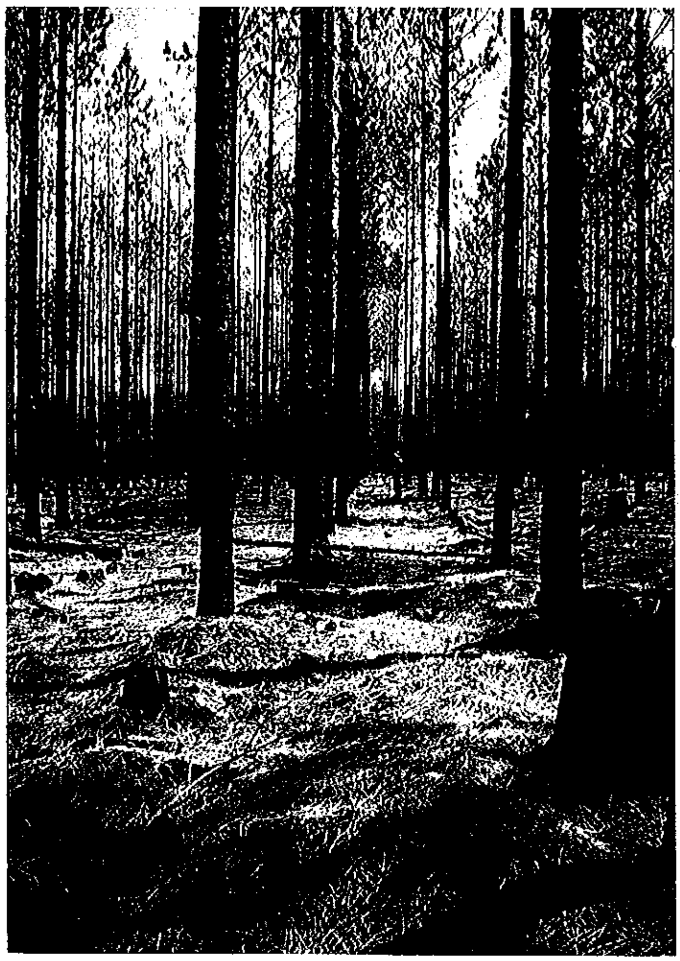


Figure 3.21: Post-burn interior ground views of sampled stands burnt during the initial stages of the major run of the Toolara No. 7 wildfire in southeastern Queensland, Australia, on 22 September 1991. Photo dates: 9 October 1991. In Cpt. 7, Unit 3 and Cpt. 8, Unit 2 note the lack of scorched needles in the tree crowns and on the ground. In the remaining stands, note the relative dense covering of scorched needles on the ground. Photos by: M.E. Alexander.

b: Cpt. 7, Unit 3

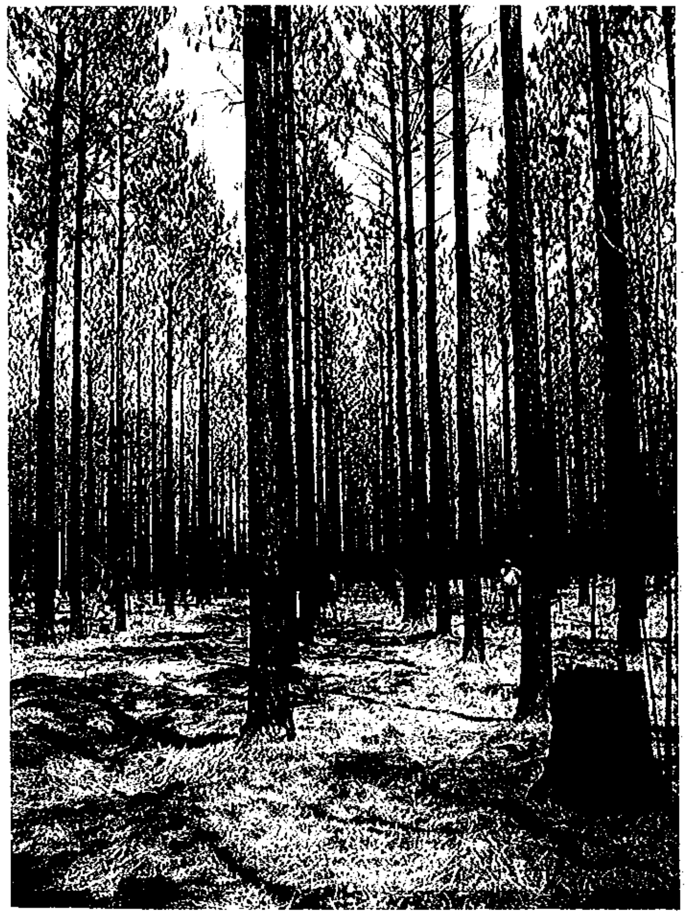
c: Cpt. 8, Unit 1

Figure 3.21: continued.

d: Cpt. 8, Unit 2

e: Cpt. 10, Unit 1

Figure 3.21: continued.



f: Cpt. 11, Unit 1

g: Cpt. 11, Unit 2

Figure 3.21: concluded.

area had last been prescribed burnt four years earlier. The surface fuels were generally of the Fuel Type 2 variety as recognized in the QFS prescribed burning guide for slash pine plantations (Queensland Department of Forestry 1976; Byrne 1980; Byrne and Just 1982; Hunt 1986) which is described as follows:

> *Fuel suspension caused by understorey species on 50 to 80 per cent of the area. Suspension depth is in the range 15 to 45 cm. Fuel weights range from 10 to 20 tonnes per hectare, the lower values being associated with kangaroo grass (**Themeda australis** (R. Br.) Stapf.) ... and the higher values with grass tree (**Xanthorrhoea** sp.). Drying of the fuel is reasonably rapid especially when the understorey species causing the suspension are grasses occurring on exposed ridge sites. The fire behaviour of the fuel type is fairly uniform, some flaring occurring in the suspended fuels.*

Fuel Type 2 is the most common fuel type in most south-eastern Queensland exotic pine plantations and the QFS prescribed burning guide for slash pine plantations is based on research carried out in this average fuel condition or standard benchmark fuel type (Queensland Department of Forestry 1976).

In order to quantify the effects of stand structure on the ensuing fire behaviour, seven stands were sampled for **TH** and **DBHOB** of the overstory trees. As well, two fire impact measurements were made in order to gauge the relative fire intensity experienced in these areas -- i.e., height of fuel consumption (**HFC**) and height to scorched foliage (**HSF**). The **HFC** is defined as the height to which all bole branches (and by inference, foliage if applicable) have been consumed. The **HSF** on the other hand is the height to which scorched foliage, if any, is first encountered. A selection of 25 stems was deemed to be sufficient to characterize each selected unit; for stem densities, the results of the QFS plantation inventory work undertaken in 1990 were used. The data are listed in Appendix B along with a description of the sampling methods and the results are summarized in Table 3.10. Representative photos of the seven sampled stands are presented in Figures 3.21 a-g. The **BA** for each stand was determined from the stem density (Table 3.9) and the mean **DBHOB** (Table 3.10). An estimate of z for each stand was obtained from the **SH**-z relationship (Fig 3.22) developed from data supplied by Henry (1989) or by inference from the **HSF**. The $\mathbf{m_F}$ for each stand was calculated from the **DBHOB** size class distribution and the **DBHOB**-dry foliage weight (W_F) relationship (Fig. 3.23) as described in Appendix C.

An estimate of the amount of surface fuel consumed by the fire was considered crucial to the fire behaviour analysis being undertaken. Unfortunately, there were no unburned sections of the compartments left in which to undertake any fuel load sampling. A very concerted effort was made by the author and Mr. Taylor to find compartments in the immediate fire area with similar stand histories, but to no avail. As a result, it became necessary to venture further a field and quite subjectively pick spots to sample which were deemed to exhibit similar type(s) of surface fuel burnt in the area of the Toolara No. 7 Fire under investigation. In the end, a single 0.25 m^2 (50 x 50 cm) sample was taken in nine different plantation compartments (Table 3.11); inorganic materials (e.g., mineral soil and small rocks) were eliminated from the samples by the water bath technique (*cf.* Sackett 1979) prior to ovendrying to a constant weight.

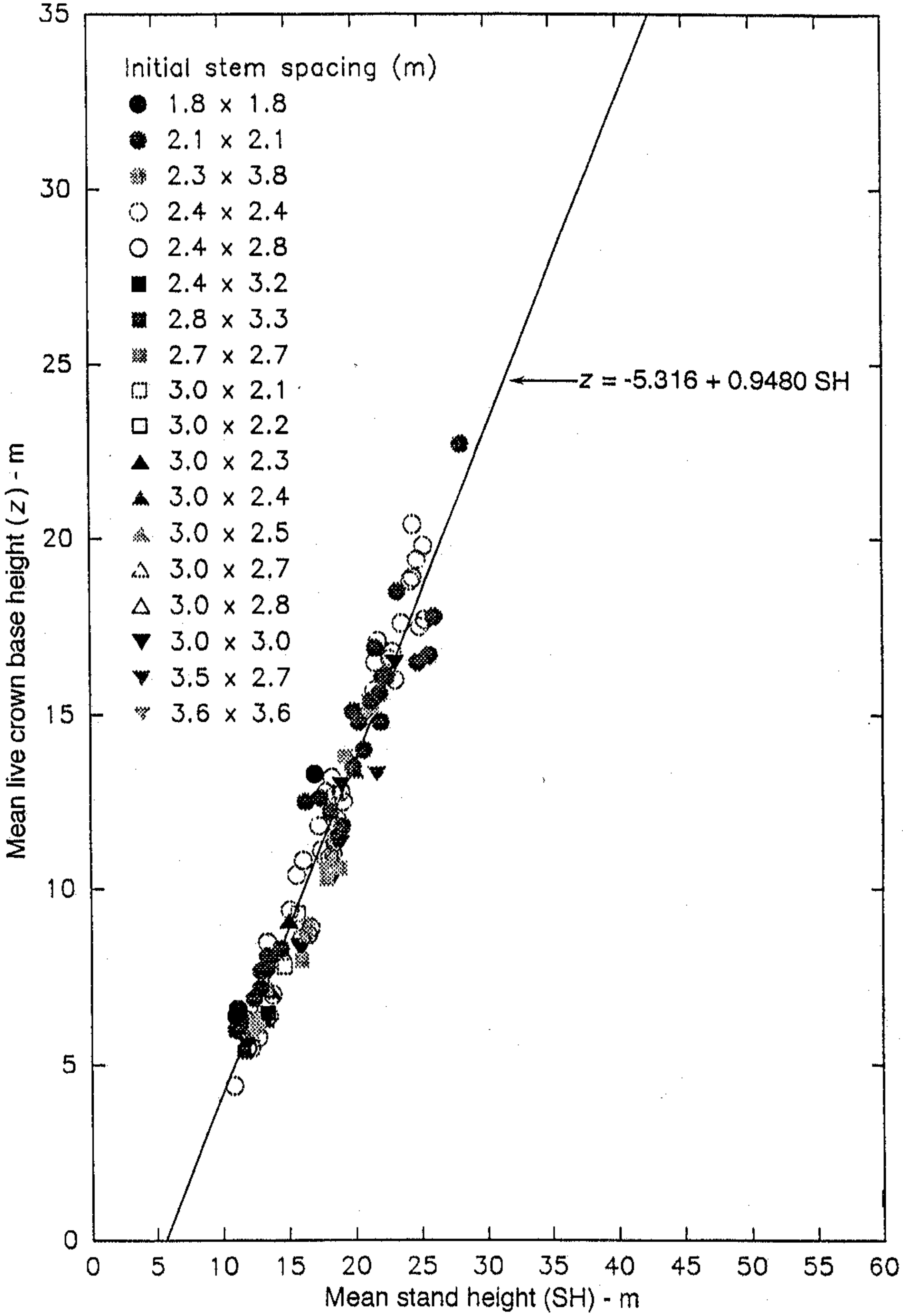


Figure 3.22: Relationship between mean stand height and live crown base height in slash pine plantations of southeastern Queensland, Australia.

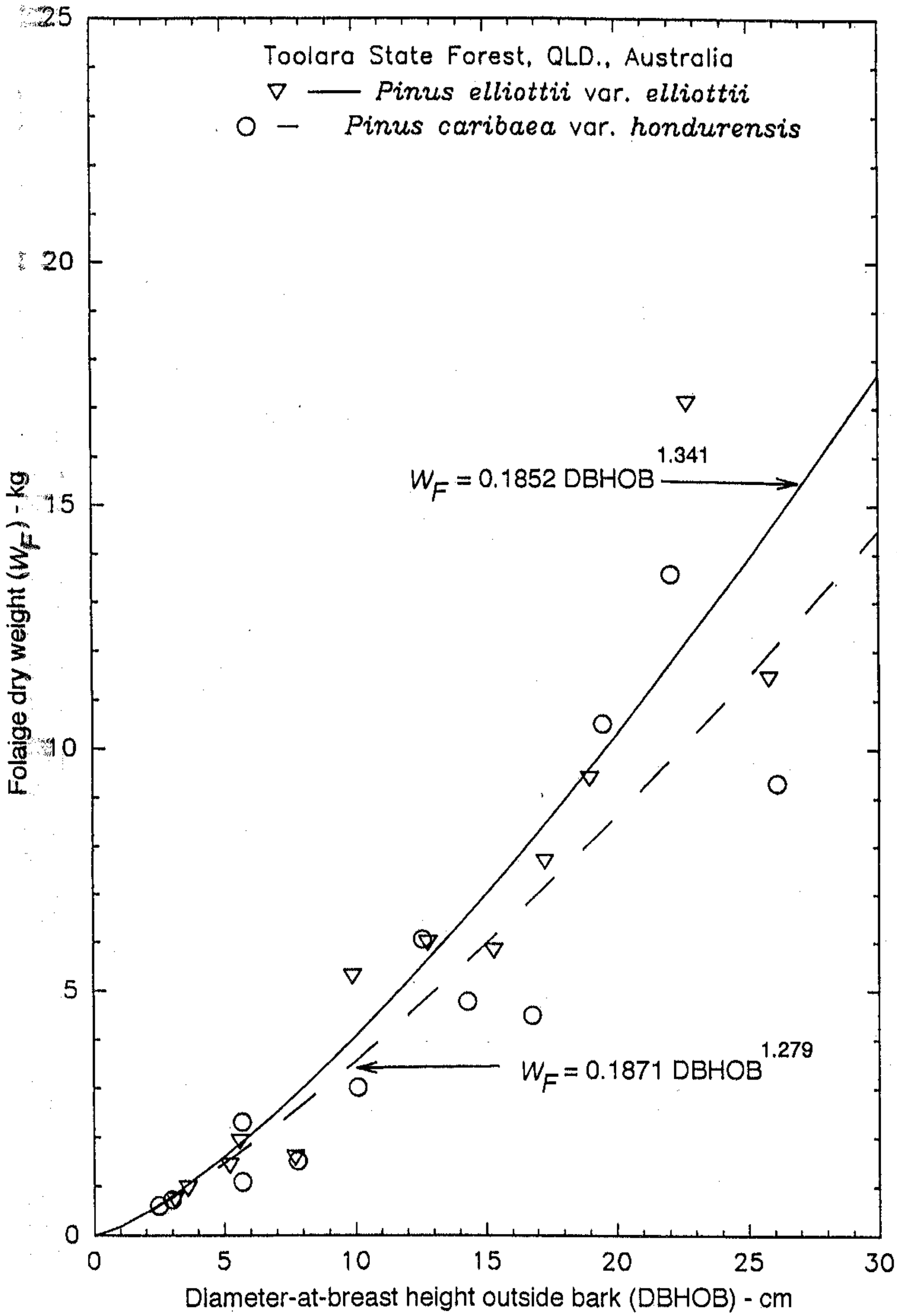


Figure 3.23: Relationships between diameter at breast height outside bark and the dry weight of needle foliage for slash pine and Honduras Caribbean pine in the Toolara State Forest of southeastern Queensland, Australia.

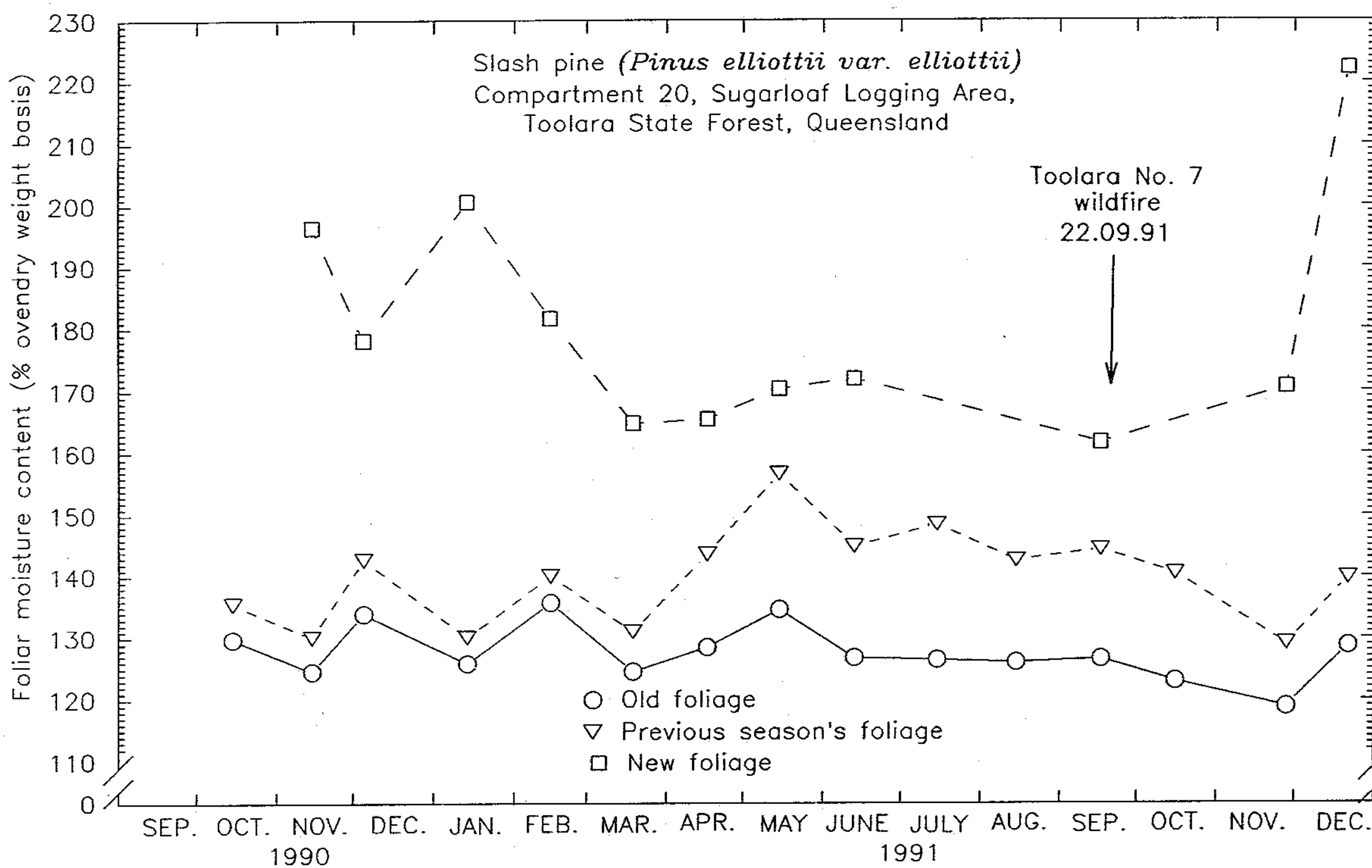


Figure 3.24: Seasonal trends in the moisture content of slash pine foliage in the Toolara State Forest of southeastern Queensland, Australia, during 1990-91.

Table 3.11: Summary of the forest floor weight sampling carried out to characterise the available ground and surface fuel loads in the slash pine plantations burnt during the initial stages of the major run of the Toolara No. 7 wildfire in southeastern Queensland, Australia, on 22 September 1991.

Fuel sample no.	Location: Logging area	Location: Compartment no.	Predominate surface fuel composition/cover type	Fuel load[a] (t/ha)
1	Swampy	36A	Grass & needle litter	16.7
2	Swampy	36A	Grass & needle litter	26.0
3	Swampy	36A	Needle litter	20.4
4	Swampy	45B	Needle litter	17.6
5	Swampy	45B	Xanthorrhoea & needle litter	19.2
6	Swampy	45B	Xanthorrhoea & needle litter	24.7
7	Elliott	23	Xanthorrhoea & needle litter	22.6
8	Elliott	23	Needle litter	10.9
9	Elliott	23	Sedge & needle litter	17.0

An estimate of the moisture content of the live needles in the slash pine overstory was also required to complete the assessment of crown fire potential. Fortunately, samples were taken just five days prior to the fire's occurrence (17 September 1991) as part of a study initiated by the author in September 1990 (Fig. 3.24); the field and laboratory work was undertaken by Mr. A.T. Ward (then Fire Research Technician, QFS Forest Research Centre, Gympie). The sampling site consisted of 12 slash pine trees located in the nearby Sugarloaf Logging Area (Cpt. 20) of the Toolara State Forest. The slash pine stand was 11 y.o. with an average **DBHOB** and **TH** of 21.4 ± 1.6 cm and 14.5 ± 1.0 m, respectively. On September 17, the old foliage and previous season's foliage averaged 126.9 ± 6.5% and 144.4 ± 7.1%, respectively (basis: 12 samples of each); only a single sample of new growth was available (161.7%). Assuming that the older foliage comprises the majority of the total foliage dry weight, the composite foliar moisture content was judged to be ≈ 135%.

3.3.2.2 Documentation of Actual Fire Characteristics

Impact on Overstory Canopy. On the basis of 150 stem measurements, the mean **SH** in Compartments 7, 8, 10 and 11 was calculated to be 20.3 m (or 21.4 m if Cpt. 7/Unit 3 is excluded). The height to the base of the live crown zone was found to be around 12.8 m (or 13.6 m if Cpt. 7/Unit 3 is excluded). In no instance were any trees found in the main path of the head fire retaining a proportion of live or green crown. In other words, individual trees or stands varied from fully scorched (e.g., Fig. 3.21c) to complete flame defoliation of the crown fuel layer (e.g., Fig. 3.21b). However, the overall impression of the area was that of maximum possible crown scorch height with some consumption of the lower green crown length.

Surface Fuel Consumption. As would be expected for the level of dryness prevailing at the time of the fire, very little surface fuel remained. The reduction of the forest floor layer an understory vegetation was essentially 100%; some charred shrub stems (assumed to be alive prior to the fire) were evident. Roundwood debris from the precommercial thinning operations was almost totally consumed.

The average surface fuel load based on the nine samples collected (Table 3.11) is 19.5 ± 4.6 t/ha. Mr. M.T. Taylor (a career forester with QFS), who served as the Fire Research Forester at the QFS Forest Research Centre in Gympie from 1987-1991) and accompanied the author during the week of sampling in the fire area, casually speculated in the field that the average surface fuel load would be approximately 15 t/ha. Considering all the sources of information (i.e., Table 3.11, Taylor's informal comment, and existing research documentation at hand -- for example, Byrne 1980), for the purpose of this fire behaviour analysis its been assumed that the total available surface fuel load would not have exceeded 20 t/ha -- the upper limit for QFS slash pine plantation prescribed burning guide Fuel Type 2. Admittedly, the manner in which this figure arrived at is somewhat subjective Note that **W** was set equal to 20 t/ha in the calculations of $\boldsymbol{R}$, $\boldsymbol{h_F}$ and S contained in Table 3.8.

Forward Spread Rate. In the sixty minutes between 1:00 and 2:00 p.m., the head fire advanced 1350 m in a westerly direction (Fig. 3.19). The extent to which spotting contributed to the resulting spread rate is unknown. Examination of the stands burnt during this stage of the fire from both the ground and air suggest there was some variation in the mean spread rate (1350 m/h), and in turn fire intensity, as evident by the degree of crown fuel consumed (Table 3.10). This variation would be attributed to changes in wind velocity and differences in the structure of the fuel complex encountered during the course of the fire run. According to Equation 3.53, if **W** = 24.2 t/ha than McArthur's (1973) predicted spread rate would have matched the observed value.

Fire Intensity and Flame Height. Byram's (1959a) fireline intensity for the period from 1:00 to 2:00 p.m. $\boldsymbol{I_B}$ was calculated from Equation 2.1 to be 13 875 kW/m. In arriving at this value, the net $\boldsymbol{H}$ was taken to be 18 500 kJ/kg (i.e., a nominal moisture content of ≈8% for the entire forest floor layer was assumed), $\boldsymbol{w}$ was assumed to be 2.0 kg/m^2 and the mean value of $\boldsymbol{r}$ was used (0.375 m/sec). As a matter of interest, the predicted $\boldsymbol{I_B}$ from Equation 3.56 on the other hand would have been 11 160 kW/m. Based on the $\boldsymbol{L}$-$\boldsymbol{I_B}$ relationships of Byram (1959a), Nelson and Adkins (1986) and Thomas (1963) represented by Equations 2.2, 2.3 and 2.13, coupled with Equation 3.33 and some simple geometry (*cf.* Alexander 1982, Equation 7), the estimates of $\boldsymbol{h_F}$ would be 4.3, 3.4 and 12.8 m, respectively. Similarly, according to the $\boldsymbol{h_F}$ versus $\boldsymbol{u}$ and $\boldsymbol{I_B}$ relation of Nelson and Adkins (1986, Equation 6) represented by Equation 2.4 and the $\boldsymbol{I_B}$ versus $\boldsymbol{h_F}$ and $\boldsymbol{r}$ relation derived by Dr. R.M. Nelson, Jr. (*see* Simard et al. 1989, Equation 6) represented by Equation 2.5, $\boldsymbol{h_F}$ estimates would be 13.7 m and 2.4 m, respectively. The largest estimate of $\boldsymbol{h_F}$ roughly matches the height of roundwood fuel consumption, which averaged 11.2 m (Table 3.10). McArthur's (1973) meter suggested 10-17 m (Table 3.8).

3.3.2.3 Analysis of Crown Fire Potential

A_p = 54° according to Equation 3.15a (sin 54° = 0.809). Again applying $\boldsymbol{k_1}$ = 16 to Equation 3.17 gives a $\Delta \boldsymbol{T}$ = 584°C when $\boldsymbol{z}$ = 12.8 m ($\boldsymbol{T_c}$ = 615°C) and $\Delta \boldsymbol{T}$ = 550° when $\boldsymbol{z}$ = 13.6 m ($\boldsymbol{T_c}$ = 581°C). The minimum $\boldsymbol{T_c}$ of 400°C was therefore met regardless of whether Cpt 7, Unit 3 is included in the computation of a representative $\boldsymbol{z}$ or not. The calculated $\boldsymbol{t_i}$ values at $\boldsymbol{m}$ = 135% by Equation 3.3 are 14 and 16 sec, respectively, which means $\boldsymbol{D}$ (according to Equation 3.1 if $\boldsymbol{r}$ = 0.375 m/sec) would have had to have been greater than ≈ 5-6, at least for short periods of time as evident by the partial consumption of the lower crown fuel layer (Fig. 3.21 and Table 3.10) which seems reasonably plausible.

Regardless of whether t_r was $\geq t_b$, a more likely explanation for the lack of crowning in certain stands is probably related to the nature of the surface fuel structure and the crown bulk density. There was of course evidence of foliage and branch consumption above the pruning height levels (Table 3.10). The average d for the area in Compartments 7, 8, 10 and 11 was 0.11 kg/m^3 and so R_o = 1636 m/h according to Equation 2.9. The actual observed R averaged 1350 m/h. However, for brief periods of time the spread rate must have exceeded this due to variations in wind speed (*see* Table 3.12) and understory fuel structure. For example in Cpt 7/Unit 3 which experienced complete flame defoliation of the canopy, the computed R_o is only 947 m/h. The understory scrub no doubt facilitated "lifting" the flame front into the crowns and realistically a different k_1 value should be used. However, once the fire front entered an area where the d was significantly less, the fire dropped back down to the surface no doubt due to the fact that the wind speed was below a critical level relative to d for continuation of crown to crown fire spread to occur. This occurred even though with the development of crown to crown spread the fire had full access to ambient wind field. This suggests that there is a possibility for two distinct spread rates (i.e., surface and crown), especially with moderately strong instand winds which results in the fire plume being bent over at an acute angle and thereby negating the full convective heating from the surface fire. Others have speculated about this possibility but for slightly different reasons (e.g., Thomas 1965a, 1967; Van Wagner 1989; Forestry Canada Fire Danger Group 1992). Had the QFS not managed the plantation stands to the extent that they did (i.e., by pruning, thinning and prescribed burning), the area burnt could have easily been four to six times larger (Alexander 1985a).

The cyclic pulsing or surging of the advancing flame front or active flaming combustion zone is a commonly observed feature of free-burning surface fires as a result of the gusts and lulls in the mean wind speed (Anon. 1970; Albini 1982a, 1982b; Cheney and Gould 1995a, 1995b) as illustrated in Table 3.12. These variations in wind do alter the pattern of convective heat transfer to the overstory canopy as discussed for example by Burrows (1984b) and Burrows, Ward and Robinson (1988). The immediate visual effect of an increase in wind speed is to flatten and at the same time deepen the flame front with the thermal plume being bent over at a somewhat of an acute angle and thereby contributing to the preheating of the surface fuels. As the winds slacken, the plume straightens up and the flames become more erect and their general level markedly increases in size, thereby greatly enhancing the overall effectiveness of the upward convective activity directed at the crown bases; the more intense the fire becomes, the stronger the convection thus making it more difficult for the ensuing wind to tilt the flame and thermal plume. However, enhanced preheating of the crowns gradually diminishes with the subsidence of the flame front and subsequent narrowing of its width or depth as the available fuel is consumed. This cycle is repeated over and over and for a given plantation fuel complex and mean wind speed. The possibility for the onset of crowning is largely a function of fuel moisture content assuming there's a plentiful quantity of surface fuel. Once a crown fire has been initiated, then for continuous crowning to occur, a minimum mean wind speed must be maintained for the fire to spread at a certain critical minimum rate that is in turn a function of the crown bulk density and wind speed (Thomas 1967, 1970a, 1970b, 1971). If this doesn't take place, then the fire will drop back to the surface. The formation of certain types of "tree-crown streets" (Haines 1982; Windisch 1987; Windisch and Good 1991)

Table 3.12: Gust estimating table for wind speeds at the standard height of 10 m in the open on level terrain (adapted from Crosby and Chandler 1966).[a]

Standard 10-min average (km/h)	Probable 1-min speed (km/h)	Probable momentary gust speed Average (km/h)	Probable momentary gust speed Maximum (km/h)
2	6	11	17
4	10	16	23
6	12	21	29
8	15	24	32
10	17	29	35
12	20	31	38
14	21	34	41
16	23	36	44
18	25	40	47
20	27	42	50
22	31	46	53
24	33	48	55
26	35	52	59
28	37	54	62
30	39	56	65
32	41	60	68
34	43	62	71
36	45	64	73
38	47	67	76
40	49	70	79
42	51	72	81
44	53	74	84
46	55	76	87
48	57	79	90
50	59	81	93

[a] The values reported by Crosby and Chandler (1966) at a height of 6.1 m (20 ft) in the open were increased by 15% to approximate a 10-m open wind value as per Turner and Lawson (1978, p. 37, Appendix 6).

NOTE: According to U.S. National Weather Service observing practice, gusts are reported when the peak wind speed reaches at least 30 km/h and the variation in wind speed between the peaks and lulls is a least 17 km/h (Huschke 1959). However, in Canada for example, the practice is to report gusts when the wind speed fluctuates by 18 km/h or more between peaks and lulls (Atmospheric Environment Service 1977). The Australian Bureau of Meteorology routinely reports wind gusts when they are 18 km/h or greater than the mean wind speed recorded in the previous 10 minutes; routine observations are taken at either 30 or 60 minute intervals and non-routine observations occur when gusts exceed 18 km/h when the mean wind speed is greater than 28 km/h. In New Zealand, reporting of wind gusts varies according to the type of meteorological observing station (Pearce 1995). For stations administered by the Meteorological Service of New Zealand, gusts are reported when they exceed the mean wind speed by 18 km/h.

in exotic pine plantations is thought to be a reflection of this variability in mean wind speed and/or direction (Alexander et al. 1991).

3.4 Discussion and Conclusions

Simply stated, the purpose of developing any fire behaviour model is "...to enable you to predict the outcome of some phenomenon before it happens" (Van Wagner 1985). Scientifically, the choices of approach to fire behaviour model development have traditionally been small-scale test fires coupled with mathematically modelling versus field observation of real fires, either of accidental (i.e., wildfires) or planned (i.e., experimental and/or operational prescribed fires) origin. The pros and cons of each distinctive approach have been explored by Van Wagner (1971) and Van Wagner (1979a) who adequately sums up the resultant difficulty:

> *This means that the researcher studying fire behaviour is continually faced with the choice between the theoretical and empirical approaches. He* [or she] *cannot solve his* [or her] *problem by pure physics. Then if he* [or she] *relies on miniaturized laboratory modeling, he* [or she] *is up against awesome difficulties in scaling all the dimensions and energy transfer processes of a phenomenon that may be so much greater in size and intensity than anything he can mount in the laboratory. Next, taking a more empirical approach, he* [or she] *may seek to light experimental fires in the real forest. He must sacrifice some control over burning conditions, but his* [or her] *main problem is to sample the whole range of intensity. It is easy enough to accumulate plenty of data in the low intensity range, but the main interest is in what happens when the fire weather is at its most severe; these moments come rather seldom and the practical difficulties of controlling the experiments are obvious. However, much good information about fire behaviour in a particular fuel can be gained from a very few successful experimental fires of say 1/2 to 5 ha in extent ... His* [or her] *final recourse is to chase and observe accidental forest fires, a most frustrating business as anyone who has tried it will tell you. Nevertheless, by being in the right place at the right time on a very few choice occasions, some valuable information obtainable in no other way can be gathered, including various bits of detective work that can be done after the fire has cooled down.*

The model developed in this thesis for predicting the onset of crown fires in exotic pine plantations of Australasia readily exemplifies the art and science of wildland fire behaviour research as advocated by Van Wagner (1985):

> *If one could boil down the whole science of fire behavior to its practical essence, it might just be to put in the hands of the fire boss a decent estimate of how fast his newly-reported fire will advance. Fire behavior predictions may not be infinitely valuable; but as long as the forest fire people continue to want better ones, and there are researchers to work on them, it is safe to say that next year's predictions will be better than last year's. And because, in a subject as complex as fire science, pure scientific logic just doesn't seem to be enough, the researcher had better be something of an artist as well as a scientist.*

In many respects this thesis constitutes a critical analyses and comprehensive synthesis of existing knowledge aimed at solving a problem and, in so doing makes " ... an original contribution ..." in a socially responsible manner in order to meet the pressing environmental issues of the day (Trevitt 1989). Wildland fire research exists to support wildland fire management (Anon. 1987) and ultimately mankind, present and future. It is not an end unto itself. In order to produce a model for crown fire initiation, basic theoretical principles of combustion and heat transfer have been integrated with the results of selected laboratory and field studies, supplemented by simple logic and reasoning. Furthermore, observations of experimental, operational prescribed and wild fires have been utilized to validate the model. This holistic approach to wildland fire behaviour research is gradually emerging (Weber 1995) as the most promising means of developing and testing models to predict certain fire characteristics and/or various sorts of free-burning fire phenomenon in the future. This thesis constitutes one such example. It also constitutes a further example of international cooperation in wildland fire research (Alexander and Andrews 1989; McCaw and Alexander 1994).

The present model overcomes several deficiencies that have gradually become evident in Van Wagner's (1977a) crown fire initiation model. The first major improvement concerns the fact that the angle of the surface fire plume in terms of its influence on the efficiency of the convective heating is now considered a variable rather than a constant and the same could be said for the ambient air temperature and flame front residence time. Certainly the importance of t_r in the crown fire initiation process has now been clearly enunciated; as Van Wagner (1964) indicated several years ago "... a deep burning front seems to necessary to initiate and sustain crowning". The very fact that fires in different surface fuel complexes (e.g., grass understory vs. a moderately compacted forest floor layer vs. precommercial thinning slash) could for the same intensities produce quite dissimilar residence times clearly shows that far too much emphasis has been placed on surface fire intensity as the sole fire behaviour characteristic dictating the onset of crowning in conifer forest stands. These improvements should provide for a more discriminating model than Van Wagner (1977a) developed. For example, on the wildfire that occurred 21 April 1991 in the Myalup Plantation of Western Australia, Smith (1992) pointed out the lack of crown fire activity even though I_B values (up to 32 600 kW/m) for the ensuing surface fire activity were more than sufficient to induce crowning according to Van Wagner's (1977a) criteria. No doubt the strong winds (10-min U_{10} averages of 40 km/h; certainly momentary and sustained gusts would have been considerably higher -- *see* Table 3.12) and various prior management activities (e.g., prescribed underburning, thinning, pruning) contributed to the lack of crown fire development. Documented examples in other Australian fuel types exist such as the 1988 Bemm River Fire in eastern Victoria that occurred primarily in eucalypt forest and exhibited an I_B of 33 900 kW/m with a U_{10} of 75 km/h (Buckley 1990, 1992).

Van Wagner's (1977a) crown fire model lacks the ability to distinguish crowning potential based on differences in fuel type characteristics (e.g., presence/absence of ladder or bridge fuels) other than z unless one is willing to resort to deriving the empirical constant C using Equation 2.8 by measuring z and m and then determining the I_B just prior to the initiation of crowning as Catchpole (1987) has done for a shrubland fuel complex. In other words, it would be necessary to conduct an experimental crown fire in order to derive C which in most instances would simply not be tolerated by exotic forest plantation owners. One would still be faced with the problems that any value derived for C would still suffer the same limitations alluded to in the preceding paragraph, namely it effectively implies a constant A_p (and thus U_s

and I_B), t_r and T_a. Furthermore, recall that Van Wagner (1977a) assumed that $T_a = 20°C$ in his formulation of Equation 2.7 (*see* Section 2.4.1).

The proposed model as developed in this chapter offers some flexibility to be fuel type specific. This is made possible by the manner in which the needed empirical constant k_l can be derived using the novel methodology based on h_s data as outlined and demonstrated in Section 3.2.5.4.2. For example, generic k_l values for thinning slash or dense understory vegetation ($k_l \approx 9$) and needlebed ($k_l \approx 16$) fuel complexes which presumably can also be applied to young, dense pine plantations of either planted (unthinned and pruned stands) or of natural origin (i.e., wildings). Lethal crown scorch data is generally a by-product of prescribed underburning research. Thus, h_s data serves a dual purpose, namely it allows for the derivation of the empirical constant k_l using Equation 3.26 which is ultimately needed to assess the potential for crown fire initiation and in Equation 3.27 to judge the likelihood of lethal crown scorching of foliage and/or buds and if so, to what heights. In a broader sense, a number of significant revelations concerning the characteristics of k_l have emerged as a result of the analyses described in Section 3.2.5.

Comparisons of model predictions with observational data not utilized in the model development as presented in Section 3.3 were judged to be very favourable although further model testing would obviously be very desirable. Watts (1987) makes some pertinent comments concerning the validation of fire models in general that bear worth repeating in their entirety here:

> *To many, computer models are the proverbial "black box" -- we put something in and we get something else back out. Our confidence in the output may be solely a function of the reputation of the modeler. We may recognize the need to understand the important and fundamental principles involved, but there may not be time to work through all the aspects of the model. Validation should be rigorously pursued despite time and constraints, however, because it is the vital link between science and its application.*
>
> *Yet if validation is a process for determining that the outputs of a model conform to reality, no model can be validated in an absolute sense; i.e.; a model can never be proved correct, it can only be proved wrong. Acceptance of a model does not imply certainty, but rather a sufficient degree of belief to justify further action. Thus, in practice, validating a fire model is really a problem of invalidation. The more difficult it is to invalidate the model, the more confidence we have it it. To increase our confidence we can subject the model to tests and comparisons designed to reveal where it fails. One approach used to validate models... is to compare the results of those of another model in which one already has great confidence....*
>
> *Correct "invalidation" of a fire model is also difficult. The fire modeler is working in an area in which relations among important variables are not precisely known. To build a model many aspects o the real world must be aggregated or simplified. Simplifications are introduced for analytical or computational convenience or sometimes as a compromise to the cost of gathering data. Documentation should clearly state what has been assumed and what sort of uncertainty or bias the*

assumption is likely to introduce in the model output. It should also be made clear how the aggregations and simplifications restrict the types of predictions the model can and cannot make.

Development of a model to predict the spread rate and intensity of crown fires in exotic pine plantations was considered a distinctly separate problem and therefore beyond the scope of this thesis. However, the question of whether horizontal fire spread between tree crowns could take place was addressed by evaluating the relevance of Van Wagner's (1977a) criteria for continuous active crowning as discussed in Section 2.4.2. The results based on the detailed wildfire behaviour case study of the Toolara No. 7 wildfire in southeastern Queensland and three previously documented operational prescribed fires in Western Australia (Burrows, Smith and Robinson 1988) were exceedingly encouraging.

In our zeal to apply the model for predicting the onset of crowning as diagrammatically illustrated in Figure 3.17, one should bear in mind the following thoughts of Brown and Davis (1973) concerning the limitations of models for predicting wildland fire behaviour:

All fire models simulate reality but fall short of it in varying degrees. In meeting the objective of simplifying relationships, minor factors are neglected and the model is usually based on a single set of idealized conditions. If fire-modelling laws are observed, this will permit approximations close enough for many purposes, but it is easy to forget that they are approximations only. Consequently, there is a strong tendency to apply models beyond their field of usefulness. To avoid this, the assumptions on which they are based and the range of conditions under which the model is valid need to be carefully defined and frequently rechecked.

Wildland fire behaviour researchers very often are reluctant to point out the data limitations of their models for fear that they won't be accepted by the users they were intended for. The present crown fire initiation model covers a far wider range of conditions than Van Wagner's (1977a) model in which basically a single experimental fire was used to derive a needed proportionally constant to achieve model closure. The present model has received **limited** testing but over a **relatively wide range** of surface fire behaviour and environmental conditions (e.g., I_B, T_a, and U_s up to about 10 000 kW/m, 30°C and 10 km/h, respectively) for a couple of broad surface fuelbed situations with z values up to slightly in excess of 10 m. However, individual submodels or model relationships are far more restricted in their breadth of coverage. For example, Equation 3.15a for predicting A_p was formulated from experimental fires for I_B and equivalent U_s values up to 800 kW/m and ≈ 17 km/h, respectively, although it has been independently tested against a slightly more severe case. Furthermore, Equation 3.3 for predicting t_i is based on simulated T_c conditions spanning a range in m (≈ 78-197%) that easily covers any situation likely to be encountered in Australasia.

One should presumably be wary of wildland fire research for which the "limitations on applicability are not spelled out in practical terms. Rothermel (1991a), for example, has done an excellent job of enunciating the 18 assumptions embedded in his guidelines for quantitatively predicting crown fire behaviour in the Northern Rocky Mountain forests of the U.S.A., as has others with their fire prediction models (e.g., Davis and Dieterich 1976; Albini et al. 1978; Albini 1979, 1981b; Albini and Chase 1980; Chase 1981). The general underlying assumption made here with respect to crown fire initiation is that the convective heating by the surface fire supported by radiation drives off sufficient moisture in the lower tree crowns to enable the ignition or initial crown combustion to take place from a pilot flame source(s) thereby "triggering" an unhibited chain reaction (Curl 1966). The 13 assumptions associated with the present crown fire initiation model have been discussed in considerable detail in Section 3.1. Here these simplifying assumptions are explicitly set out:

1. Homogenous fuel, weather and topographic conditions prevail.
2. Direct flame contact with the live crown base is not necessary to initiate crowning.
3. The surface fire's plume trajectory has stabilized.
4. The main period of convective heating at the crown base is equivalent to the residence time of the actively spreading flame front.
5. Bryam's fire intensity is an adequate physical descriptor of surface fire behaviour.
6. The primary crown fuel property defining the potential for crown fire initiation other than the live crown base height is the live needle moisture content.
7. The effects of soliar radiation on crown foliar temperatures are negligible considering the minimum likely wind strength to be prevailing.
8. The pre-fire ambient air temperature at the crown base, regardless of the height above ground, is equivalent to the "screen" level meteorological standard.
9. Variation in wind speed with height above ground in the lower trunk space of a pine plantation is not significant.
10. The user can readily estimate and/or measure the six or seven required model inputs.
11. As slope steepness increases, the potential for crowning is gradually overestimated.
12. On slopes, the uphill sides of the tree crowns is considered to be the effective live crown base height.
13. Once the requirements for initial combustion are met at the crown base, vertical fire spread in the crown fuel layer occurs spontaneously.

As previously mentioned in Chapter 1, the present model was intended primarily for use as a decision making aid for long-term planning as opposed to use on a daily operational basis for assessing crown fire potential (Table 1.9). Further testing would be desirable, if not essential, before the model could be utilized in near real-time predictions and/or in other fuel types distinctly different from the ones considered in this thesis.

CHAPTER 4:

IMPLICATIONS FOR WILDLAND FIRE MANAGEMENT AND FIRE RESEARCH

4.1 Implementation and Future Research Needs

For years, Australasian exotic pine plantation managers have had to make fuel and fire management decisions or judgements with respect to crown fire potential without the benefit of quantitative tools. The following statements made by Waldon (1978) with respect to radiata pine plantation fire protection in New Zealand typifies matters:

> *... forest fires are initiated almost without exception at ground level ... and require a ladder of flammable material to reach the foliage canopy, where a crown fire may be formed. The possibility of a crown or canopy fire forming, however, depends on the age of the stand, on the nature of the silvicultural operations which have been carried out, and on the hazard conditions at the time; in particular, the strength of the wind.*
>
> *In young timber stands, or those which have not been pruned, sufficient fuel exists from ground level to the canopy for a fire to advance on a vertical front with the crown fire being continuously supported from the ground. In stands of intermediate size in which both ground cover and lower branches have been removed, a crown fire will have greater difficulty in forming. In this case, "torching" occurs in individual or small groups of trees, but fire is likely to remain in the canopy only under very high wind conditions. Finally, mature stands usually have a considerable break between fuel on the ground and in the crown, and where this condition is continuous, a crown fire is unlikely. If, however, adjacent bush or a poorly attended area allows a fire in the canopy to start, unusually high hazard conditions would be necessary for the fire to remain travelling in the crown. Factors such as wind and topography would, of course, influence the spread of such a fire.*

As a result of the model formulated in Chapter 3, exotic pine plantation managers in Australasia now have for the very first time a means of quantitatively assessing the potential for crown fire development under most fuel, weather and topographic situations in order to address various fire and fuel management issues (e.g., Burrows et al. 1989). It will still be necessary for managers to "... use art, experience, science and judgement to solve problems" though (Thomas 1992).

In order to apply the model for predicting the onset of crowning as outlined in Chapter 3 (Fig. 3.17) the user is required to supply six inputs assuming level terrain, otherwise a seventh input, slope steepness $\varnothing$, would be required, thereby necessitating the need to evoke Equation 3.18 to compute the effective live crown base height on a slope (z_θ). These six inputs are:

- ambient air temperature, T_a
- in-stand wind speed, U_s
- surface fire intensity, I_s
- flame front residence time, t_r
- foliar moisture content, m
- live crown base height, z

How should plantation fire managers or planners in Australasia go about obtaining the required inputs and what should Australasian wildland fire behaviour scientists be considering in future initiatives? T_a would logically be obtained from either current weather observations, forecasts or climatological data archives. The significance of T_a levels above ≈ 30°C beyond a simple increase in fuel temperature should be explored for the possible role that volitales might play in lowering the threshold for ignition.

Similarly to T_a, given the measured, estimated or forecasted U_{10}, U_s could be approximated from existing rules of thumb (e.g., Van Loon and Love 1973; Sneeuwjagt and Peet 1985; S.M. Hunt *in* Gill et al. 1987), empirically derived guidelines (e.g., Cooper 1965; McArthur 1971; Luke and McArthur 1978) or more sophisticated models (Albini and Baughman 1979; Baughman and Albini 1980; Beer 1990a). As Cheney (1981) notes:

> *... the problem of predicting what the wind in the forest will be from some standard meteorological measure* [e.g., U_{10}] *is enormous. This must take into account such factors as tree and canopy density, a roughness factor for the forest floor, the instability of the atmosphere and the location of the standard measure. This problem is large enough in a uniform forest on level ground, and exteremely difficult in broken mountainous topography.*

Beer (1990c) has specifically recommended that the numerical wind flow model of Li et al. (1990) be evaluated for its relevance to Australian exotic pine plantations.

The equation derived for predicting A_p is based on a data set (Fendell et al. 1990) that is virtually unparalleled in terms of the time, effort and expense to acquire the basic information (Fendell 1996). The video photography associated with the experimental fires (Fendell et al. 1990) should be analysed for possible correlations between flame dimensions and A_p along the lines of what McMahon et al. (1986), Nelson and Adkins (1986), Adkins (1987, 1995) and Adkins et al. (1994) have done with A or A_T versus u and h_F. Few facilities exist in which to carry out such fundamental work (Pitts 1991) and the TRW wind tunnel is exceedingly unique in its construction and function (Fleeter et al. 1984). The extent to which convection from smouldering combustion and isolated flaming following passage of the main fire front influences the effective wind speed (Cheney 1983; Rothermel 1994) in Equation 3.15a for calculating A_p is unknown, although the test against the observation made by Cheney et al. (1992) was certainly encouraging. The effect of slope steepness (via flame attachment) on predictions of A_p remains uncertain. The possibility of deriving a separate A_P relationship for backfires should be investigated in order to extent the concepts of crown scorch modelling as outlined in Chapter 3.

Presumably both surface fire rate of spread and the available surface fuel load (ground and surface strata) can be determined for a given set of specified burning conditions (i.e., moisture content, slope and wind) using the existing fire behaviour guides as discussed in Section 1.3 (e.g., Luke 1961. 1962; McArthur 1973; Burrows 1984c; Sneeuwjagt and Peet 1985; Crock 1985; Hunt and Crock 1987) which may be coupled with techniques for assessing fuel quantities (McCormick 1971a, 1973; Sneeuwjagt 1972, 1973; Williams 1975, 1976, 1977a, 1977b, 1978; Burrows 1980a; Woodman 1982b). An estimate of I_s would quite easily be made directly from McArthur's (1973) **FFDI** using Equation 3.56 based on the standard fuel load or on some other predetermined value (*cf.* Douglas 1973). Values for t_r may for the interim have to be estimated for example, from experimental fire and wildfire observations or inferred from the available fuel load based on known combustion rates (*cf.* McArthur and Cheney 1966, 1972). Further research is needed to develop the means of predicting flame depth D based on known burning conditions such as Nelson and Adkins (1988) have attempted to do in order to deduce more reliable values of t_r. This is a critical need because of the importance of t_r in terms of determining the threshold durations for foliar heating. Recent analyses of experimental fires conducted in the wind tunnel appear promising (Nelson 1996b). However, any model for predicting D or t_r must take into account the fact that bulk density, moisture content and inorganic matter of the forest floor layer typically varies with depth in many fuel complexes; perhaps the bulk density of the fuel consumed would be a worthy independent variable or simply fuel consumed (e.g., Burrows 1994). Nelson and Adkins' (1988) relation for predicting D based solely on w and u (which would in practice be replaced by U_s) for inputs as given by Equation 3.48 would appear to constitute an immensely appealing component of the present crown fire initiation model but unfortunately it appears to have a tendency to under predict D and in turn t_r (*see*, for example, Table 3.6b) for the reasons outlined in Section 3.2.5.4.2; testing against another data set (Lawson 1972) with similar forest floor properties as an exotic pine plantation produced the same result. Finally, the simplistic approach or assumption of inferring the duration of convective heating from t_r as used here (Fig. 3.3) and by others (e.g., Johnson and Gustell 1993; Johnson and Miyanishi 1995; Gustell and Johnson 1996) should eventually be examined for its validity.

There is in general a paucity of published information on the seasonal variation in m for the exotic pines of Australasia although "spot" observations exist (e.g., Attiwill and Cromer 1982; Norman 1986); a recent study by Pook and Gill (1993) in the Australian Capital Territory is the one exception. This has been somewhat rectified by this author during the course of his Ph.D. studies (Alexander 1991d). Monthly m samplings have been undertaken at this author's urging by the forest services and forest industry at several locations in Australia and New Zealand (*see*, for example, Fig. 3.24); these results will be summarized and reported on separately. Similar work is needed in Fijian exotic pine plantations since only a limited amount of sampling has been undertaken there (Waterloo 1992). Nominal m values based on species, site and perhaps age and stage of drought should be sufficient. A model to predict m from tree, site and weather variables, (Howard 1978; Running 1978; Tunstall 1991) derived for perhaps a host of non-fire applications as well, would be a worthwhile undertaking. The present data sets could be utilized for model validation purposes. Interestingly, the average m values for radiata pine obtained though monthly samplings are considerably higher (≈ 130 - 160%) than that exhibited by North American conifer species (Van Wagner 1967c; Chrosciewicz 1986a), which maybe in keeping with high moisture contents of radiata pine sapwood (Fielding 1952; Danbury and Wolfe 1967) although Fernandes and Soares (1981) found similar high m values in Brazilian slash pine plantations. In unpruned/unthinned pine plantations with considerable dead needle mass in the lower trunk space, m would in this case be estimated from models like that of Pook (1993) which use current weather elements as inputs (e.g., T_a and **RH**).

A number of relationships or guidelines for predicting z from tree and/or stand structure characteristics already exist (e.g., Beekhuis 1965; Lewis et al. 1976; Byrne 1980; West et al. 1982). Relevant unpublished data collected for other purposes (e.g., Lewis 1954) has been acquired from the forest services in South Australia, Victoria, Tasmania and Queensland in order to produce relationships for other species such as slash pine (Fig. 3.22) and to evaluate existing ones; this work will also be reported on separately. There are quite distinct differences amongst species and so individual *z* relationships are required and in some cases stocking is a factor.

To the extent possible, this thesis contains all the essential elements that are generally considered required to increase the confidence in predictive models (e.g., model structure, parameterization, validation), except perhaps the completion of a sensitivity analysis, which is not routinely done in wildland fire behaviour research, although a few exceptions exist (e.g., Bevins and Martin 1978; Hirsch et al. 1979; Salazar 1985; Dimitrakopoulos 1987). However, all the sub-model relationships have been graphically displayed so that the user may obtain a "feel" for the model's responsiveness. Albini (1976a) points out that "... the *internal consistency* of a well-disciplined mathematical model allows one to use it to assess the impact of changes in important variables for specific situations, even if the model overpredicts or underpredicts systematically, whether due to model inapplicability, model inaccuracy, or data errors". Certainly a sensitivity analysis along the lines of what Trevitt (1991) has undertaken for the rate of spread component of McArthur's (1973) forest fire danger meter would be a very worthwhile undertaking.

Many wildland fire researchers have established fire ignition, spread or growth thresholds in various vegetation complexes based on fuel and weather variables (Krueger 1961; Lindenmuth and Davis 1973; Davis and Dieterich 1976; Bruner and Klebenow 1979; Neuenschwander 1980; Bryant et al. 1983; Clark 1983; Clark et al. 1985; Burrows et al. 1991; Gill et al. 1995; McCaw 1995). The research as outlined here has achieved a similar endpoint with regards to the surface fire-crown fire transition phase of wildland fire behaviour. However, one shortcoming of the present crown fire initiation model is that the output is a discrete entity (i.e., the likelihood for the onset of crowning is either "yes" or "no"). A significant advancement would be to place the output from the model on a probabilistic basis (e.g., Burgan 1966; Lawson 1973; Anon. 1980; Cheney 1981; Wilson 1985, 1987; Wilson and Ferguson 1986; Wilson 1988a, 1988b; Lawson et al. 1994; Hirsch 1996b; Lawson and Dalrymple 1996; Frandsen 1997; Lawson et al. 1998) as opposed to a deterministic one.

In order to judge whether continuous active crowning is possible, it will be necessary to calculate ***d*** values. Of course, if the stand height **SH** is known and *z* can be predicted, then the crown depth **CD** can be in turn estimated. The only remaining crown fuel property required to calculate ***d*** is the available crown fuel load, $\mathbf{m_F}$ which as a matter of interest typically averages ~1.0 kg/m^2 following crown closure for most stand conditions (*cf.* Madgwick 1994). This is done from a knowledge of the number of stems per **DBHOB** size class using **DBHOB** versus W_F relationships. Fortunately, Australia and New Zealand are blessed with a myriad of biomass studies (e.g., Dargavel 1970; Williams 1976, 1977a, 1977b, 1978 *see* also Madgwick's 1994 compendium on the subject)[1]; in this regard, summaries similar to that of Grigal and Kernik (1984) would constitute a worthwhile project. A limited amount of sampling has been

[1] Madgwick's (1994) compendium, although a reasonably comprehensive survey of the radiata pine biomass literature, is missing several pertinent references on both surface and crown fuels in both Australia and New Zealand (e.g., Will 1959, 1967; Bridges 1968; Hayward 1968; Forrest 1969; Lamb 1972, 1975, 1976; Siemon 1973; Stafford 1976; Ballard and Will 1981; Stewart and Flinn 1981; Beets 1982; Flinn et al. 1982; Baker 1983; Will et al. 1983; Baker and Attiwill 1985; Cremer et al. 1985a, 1985b; Levett et al. 1985).

undertaken on Honduras Caribbean pine in Fiji (Claeson et al. 1984) and maritime pine in Western Australia (Turton and Keay 1970). The lack of a single biomass study for slash pine prompted the results reported on in Fig. 3.23 and Appendix C.

A high priority item for future research is to develop a model for predicting crown fire rate of spread based on the existing information that is available from documented wildfires as mentioned in Section 1.3. Ideally, this would take the form of the model proposed by Thomas (1970a, 1970b, 1971) as discussed in Section 2.4.3 where the crown fire $\boldsymbol{R}$ would be a function of $\boldsymbol{d}$ and U_{10} or a fire danger index incorporating both U_{10} and some measure of dead fuel moisture content such as McArthur's (1973) or perhaps the Initial Spread Index component of the Canadian Forest Fire Weather Index System (Van Wagner 1987). The Toolara No. 7 wildfire of 1991, for example, provides solid evidence that for $\boldsymbol{d} \simeq 0.11$ kg/m^3 that U_{10} must be greater than 28 km/h, even for very dry fuel conditions. Albini (1994) has recently been working under Canadian Forest Service and USDA Forest Service sponsorship on a physically-based theoretical model for predicting crown fire rate of spread which may eventually prove to be superior in approach and performance. Nevertheless, documented wildfires will still be required for model validation purposes (*see* Alexander and Pearce 1992b).

Perhaps the best way to implement the model would be for forest and fire managers to integrate it into a decision support system that possesses a geographic information system (GIS) (Dunningham and Thompson 1989). In this way, individual compartment data on fuels, stand and terrain conditions can be readily stored and analysed. The advantage of this approach is that other models could also eventually be added -- for example, a fire growth model (e.g., Beer 1990b; Wallace 1993; Coleman and Sullivan 1996; Finney 1996). Coupled with this effort should be the extension or adaptation of current stand structure and biomass production/accumulation models to fuels and fire behaviour considerations (Weber et al. 1989; Bilgili and Methven 1994) as well as adding the capability to analyze past situations using fire weather climatology (e.g., Salazar and Bradshaw 1986; Gill et al. 1987).

4.2 Concluding Remarks

Fire managers in Australia have traditionally based their policies on the interval between fuel reduction burns in native forests on the basis of fuel accumulation rates and fire climate in terms of what would be an acceptable fuel load in view of the likely fire intensities (e.g., Underwood and Christensen 1981; Gill et al. 1987; Wilson 1992a). Similarly, the present model will permit managers responsible for exotic pine plantations to evaluate crowning potential in terms of various silvicultural and fuel management strategies, such as pruning, thinning, prescribed underburning and considerations of plantation layout and planting/harvesting schedules in terms of the resulting age-class mosaic, that are designed to mitigate against crown fire occurrences. Much supposition and anecdotal evidence exists supporting these activities (e.g., Vaughn 1934; Edlin 1958; Shepherd 1961, 1967; Weaver 1961; Cumming 1964; McArthur 1965, 1966a; McArthur et al. 1966; Crosby and Loomis 1967; Wilson 1967, 1971, 1977b, 1977c; Johansen 1968; Cron 1969; Tustin and Bunn 1970; Arnold and Plotkin 1971; Brackebusch 1973; Jackson 1974; Douglas 1974b; Martin and Brackebusch 1974; Sackett 1975; Helms 1979; Wolffshon 1980; Billing 1983; Murray 1983; Zimmerman and Neuenschwander 1983; Underwood et al. 1985; Moore 1987; Schmidt and

Wakimoto 1988; Deeming 1990; de Ronde et al. 1990; de Ronde 1993; Weatherspoon and Skinner 1995; Agee 1996a 1996b; Greenlee and Sapsis 1996) or largely unverified model simulations of a theoretical nature (e.g., Alexander and Yancik 1977; Hirsch et al. 1979; Brown and Johnston 1987; Kalabokidis and Wakimoto 1992; Keeves 1996; van Wagtendonk 1996), especially with respect to crown fire behaviour. The present model would allow one to confirm or evaluate that these activities do indeed reduce the likelihood of crown fire development in exotic pine plantations under certain conditions. Other applications are foreseen. For example, Cheney (1990b) imagined that the optimum spacing for a "crown fire-free zone" is the maximum potential wood volume on an area for which the critical crown base height and bulk density remains below some threshold. Furthermore, the economic implications of fire protection and management programs could be evaluated in light of the prevailing fire climate and ignition risk in an area (Healy et al. 1985; Cooper and Ashely-Jones 1987; Geddes 1989; Robertson 1989).

Several years ago, Sando et al. (1970) posed the question, "What fuel-weather combinations are required to produce a propagating crown fire in northern flatland forests?". As well, in a fire ecology research survey of land managers and environmental scientists in western North America conducted in the early 70s, (Taylor et al. 1975) several questions were raised that dealt with aspects of crown fire potential:

> *Will fire in a thinned stand tend to stay on the ground as opposed to crowning? What are the effects of various spacings? What spacing inhibits spread of* [crown] *fire?*
>
> *Crown fires are quite a threat in the ponderosa pine of the Black Hills. Extreme burning conditions may cause crowning any time of the day or night. Based on slope, what tree spacing would allow full stocking and yet be most desirable for separating tree crowns to preclude crown fire ignition?*
>
> *How many tons/acre of fuel are required to support a crown fire in ponderosa pine and in mixed conifer forest in the Southwest?*
>
> *What stand and crown density is required to carry a fire in standing pinon-juniper stands?*

It would appear that answers to these questions, which are presumably nearly universal in nature, are still waiting in the wings to be addressed. Although exotic pine plantations have been the backdrop of this thesis, there's every reason to believe that the crown fire initiation model as developed here could with the appropriate validation be applied to answer these kinds of questions and a whole host of other more complex fire and forest management issues (Bryant et al. 1983; Davis 1986; Kilgore and Heinselman 1990; Zimmerman 1990; Anon 1993c, 1996; Turner and Romme 1994; Huff et al. 1995; Johnson and Miyanishi 1995; Whelan 1995; Albini and Brown 1996; Clark et al. 1996a, 1996b; Despain et al. 1996a, 1996b; Everett et al. 1996; Hardy and Arno 1996; Heinselman 1996; Keane et al. 1996; Omi 1996). Furthermore, there's no reason to feel that the basic framework could not also be extended to other very dissimilar fuel types such as eucalypt regrowth forests (McCaw et al. 1988, 1992; Cheney et al. 1992; Burrows 1994) once the proper coeffcents have been established (namely

k_1 or k_2). In this sense, the model as presented in Chapter 3 does exhibit a certain degree of universality. However, it's readily acknowledged that the crown fire initiation model and methodology needed to derive the needed proportionality constant(s) may not be amenable to all fuel complexes, one example being insect damaged fuel complexes (e.g., Stocks 1987a). Elements of the model could also be extended to any application requiring an estimate of ΔT at Z such as the problem of estimating the convective heat transfer from surface fires to overhead power or phone lines (Van Wagner 1975; Knight and Dando 1989).

It would be presumptuous to assume that the model as developed in this thesis is the last word on the subject of crown fire initiation. This author would be pleased if as a result of this thesis, others become motivated to correct, modify and/or extend the present model for predicting the onset of crowning. As wildland fire behaviour research continues to progress, some of the concepts presented here may in time be rendered obsolete. For example, Byram's (1959a) fire intensity concept, inspite of its holistic nature (Van Wagner 1977c; Richmond 1981, p. 81, Fig. 8.5), does have some limitations as alluded to in Chapters 2 and 3. What is ideally needed is a generic, physically-based model that could predict the dimensions (i.e., height, depth and length or horizontal reach) and inclination of the surface fire flame front as well as the rate of advance in any fire environment - - this of course has been a continuing challenge of wildland fire behaviour researchers for well over 50 years (Fons 1940c; 1946). Therefore it is fully expected that our understanding and ability to predict crown fire behaviour and other related phenomena will continue to evolve in the light of new knowledge generated from field experiments and observations, laboratory studies and modelling efforts.

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APPENDIX A:

FIRE PLUME ANGLE AND ASSOCIATED DATA FOR THE EXPERIMENTAL FIRES CARRIED OUT IN THE TRW WIND TUNNEL FACILITY BY FENDELL ET AL. (1990)

The basic data used in the analysis referred to in Section 3.2.3 - **Inclination of the Surface Head Head Fire Plume in Relation to Wind Speed and Fire Intensity** as presented here (Table A-1) in the interest of completeness, was extracted from the information contained in the report prepared by Fendell et al. (1990) which in turn was the basis for the papers published by Carrier et al. (1991) and Wolff et al. (1991). Fire plume angle (A_p) data was available for 54 of the 194 experimental fires carried out in the TRW wind tunnel facility located at Redondo Beach, California (*see* Fleeter et al. 1984, p. 297, Fig. 3). The actual isothermal patterns as derived from the thermocouple grid for test #s 76, 82, 85, 86 and 88 are presented in Figures 3.2b and 3.6a-d. The five types of fuel involved in the tests were:

Table A-1 no.	Description of individual fuel particle(s)
1	White pine flat toothpicks
2	Birch dowels
3	Bamboo skewers
4	Birch dowels/white pine flat toothpicks
5	White pine sandwich picks

Seven of the 54 tests involved fuelbeds 100 cm in width, the remainder being 55 cm wide. The data for A_p, fuel load (**m**), rate of fire spread (r) and wind speed (u) was taken directly from Table 5 of Fendell et al. (1990, p. 44-46). The fuel heights and bulk densities for the various fuelbeds listed in Table 3.2 based on the data given in Table A-1 are as follows (SD = standard deviation):

Table A-1 no.	Fuelbed width (cm)	Sample size	Fuel height (cm) mean	SD	range	Fuelbed bulk density (kg/m³) mean	SD	range
1	55	19	4.6	-	-	7.68	3.95	2.39-19.1
1	100	7	4.6	-	-	7.17	6.17	2.39-19.1
2	55	9	5.6	5.7	3-20	25.2	18.9	12.0-67.8
3	55	15	6.2	3.3	4.6-14	17.4	8.66	9.68-39.1
4	55	3	4.6	-	-	15.4	5.66	8.91-19.3
5	55	1	7.7	-	-	25.8	-	-

The value for ambient air temperature (T_a) contained in Table A-1 was derived by computing a mean T_a based on the T_a measured at the start and end of each test as given in Table 2 of Fendell et al. (1990, pp. 24-30); in 48 cases out of 54, the difference in T_a between the start and end of each test was either the same value or less than 2 °C.

Table A-1a: Listing of fire plume angle data along with the pertinent environmental variables and other related information associated with the experimental fires carried out the TRW a wind tunnel facility as reported on by Fendell et al. (1990).

TRW test #	Type of fuel	Fuel height (cm)	Fuelbed width (cm)	m (kg/m²)	*r* (m/sec)	I_B (kW/m)	T_a (°C)	*u* (m/sec)	N_c	A_p (°)
76	1	4.6	55	0.11	0.041	83	19.5	1.6	1.3165	28
77	3	4.6	55	1.80	0.008	266	19.5	3.4	0.40963	22
78	1	4.6	55	0.33	0.022	134	16.5	1.0	8.6985	35
82	1	4.6	55	0.44	0.027	220	20.0	2.5	0.87275	46
83	1	4.6	55	0.33	0.036	220	17.0	2.5	0.89147	31
84	3	4.6	55	0.45	0.020	166	19.0	2.5	0.65520	19
85[a]	1	4.6	55	0.88	0.003	47	16.5	0.0	∞	90
86	3	4.6	55	0.90	0.016	266	19.0	2.5	1.0448	26
88	3	4.6	55	0.45	0.036	300	22.0	4.6	0.18805	10
90	1	4.6	55	0.22	0.043	175	22.0	2.5	0.70308	24
91	1	4.6	55	0.22	0.046	187	21.5	2.5	0.75533	27
92	3	4.6	55	0.90	0.010	166	21.5	1.0	10.212	41
95	3	4.6	55	0.45	0.013	108	23.0	1.6	1.6048	26
97	1	4.6	100	0.44	0.042	342	19.0	1.0	23.418	38
98	1	4.6	55	0.44	0.019	155	22.0	1.0	9.7839	45
99	1	4.6	55	0.44	0.025	203	23.0	1.6	3.0858	28
101	3	9.2	55	0.90	0.017	283	24.0	2.5	1.0942	28
103	1	4.6	100	0.88	0.027	440	21.0	1.0	28.561	54
105	1	4.6	100	0.11	0.060	122	21.5	3.4	0.19545	23
107	1	4.6	100	0.44	0.033	269	22.0	0.7	54.021	53
110	3	4.6	55	0.65	0.017	204	23.0	2.5	0.79144	31
111	1	4.6	100	0.11	0.075	153	20.5	4.6	0.098908	21
114	2	4.6	55	0.78	0.015	216	22.5	2.5	0.83738	23
116	1	4.6	100	0.22	0.033	134	19.5	0.7	30.834	44
117	3	6.2	55	0.60	0.016	178	23.0	1.6	2.6599	35
118	2	6.2	55	1.02	0.015	283	27.0	1.6	4.1647	29
119	1	4.6	55	0.44	0.030	244	20.5	3.4	0.38185	30
120	1	4.6	55	0.44	0.030	244	21.5	3.4	0.38056	29
122	1	4.6	100	0.11	0.040	81	17.0	0.7	17.079	46
123	4	3.0	55	0.50	0.020	185	15.5	3.4	0.29193	14
124	1	4.6	55	0.44	0.016	130	20.0	3.4	0.20128	32
125	1	4.6	55	0.22	0.091	370	21.0	4.6	0.24133	21
126	3	6.2	55	0.60	0.028	311	19.5	4.6	0.19558	19
127	2	6.2	55	0.93	0.025	430	20.0	4.6	0.26942	21
129	3	6.2	55	1.10	0.018	366	21.0	4.6	0.22750	17
130	1	4.6	55	0.88	0.029	472	19.5	4.6	0.29702	23
131	3	7.2[b]	55	0.71	0.024	315	20.0	2.5	1.2451	27
132	2	3.0	55	1.14	0.005	103	21.5	0.7	18.302	40
133	3	14	55	3.77	0.005	349	23.0	0.7	61.743	53
135	3	4.6	55	1.34	0.016	397	18.0	4.6	0.24898	25

[a]Because this experimental fire was conducted at a no wind condition it was not included in the analyses reported on in Table 3.2 or Figures 3.7, 3.8, 3.9, 3.10 and 3.11.

[b]This was actually a "mix" test were individual materials were 5.4 and 9.0 cm in height.

Table A-1b: concluded.

TRW test #	Type of fuel	Fuel height (cm)	Fuelbed width (cm)	**m** (kg/m²)	***r*** (m/sec)	I_B (kW/m)	T_a (°C)	***u*** (m/sec)	N_c	A_p (°)
138	2	3.0	55	1.06	0.012	235	21.5	3.4	0.36071	21
139	3	14	55	1.88	0.023	800	20.0	4.6	0.50059	27
140	1	4.6	55	0.44	0.019	155	18.0	2.5	0.61314	26
141	1	4.6	55	0.44	0.012	98	20.1	1.0	6.0967	32
143	2	14	55	1.68	0.015	466	22.0	0.7	86.397	43
144	1	4.6	55	0.44	0.012	98	19.0	1.0	6.1175	35
146	4	4.6	55	0.89	0.014	231	21.5	2.5	0.89749	32
147	1	4.6	55	0.11	0.030	61	19.5	1.6	0.94735	40
148	5	7.7	55	1.99	0.012	442	21.5	2.5	1.7161	39
151	4	4.6	55	0.83	0.019	292	19.5	2.5	1.1492	31
152	2	4.6	55	3.12	0.008	450	20.0	3.4	0.69170	30
153	4	4.6	55	0.41	0.017	129	23.5	2.5	0.49962	17
154	1	4.6	55	0.22	0.010	41	27.0	1.0	2.4761	62
157	1	4.6	55	0.11	0.065	132	20.5	3.4	0.21315	27
159	2	2.0	55	1.63	0.007	223	21.5	3.4	0.34078	21

Byram's (1959a) fire intensities associated with the TRW experimental fires were calculated from Equation 2.1 (i.e., $I_B = Hwr$) by: (*i*) assuming a constant value for the net low heat of combustion = 18 500 kJ/kg - - i.e., a low heat of combustion (***H***) 18 700 kJ/kg subsequently reduced by a nominal value for the presence of moisture (Van Wagner 1972b; Alexander 1982) which averaged ≈ 8% during the tests (Fendell et al. 1990); (*ii*) equating **m** to the fuel weight consumed per unit area (***w***) because as Fendell et al. (1990) notes, "... here the fuel elements are thin, so the fuel consumed is identical with the fuel loading intially present, if fire propagates at all" (*see* Wolff et al. 1991, p. 269, Fig. 6); and (*iii*) using the observed ***r*** as reported by Fendell et al. (1990). The values for Byram's convection number (N_c) were computed from Equations 2.15, 2.16 and 2.17 based on the observed ***r*** and ***u***, the derived T_a, and the computed I_B.

APPENDIX B:

POST-BURN OVERSTORY TREE SAMPLING OF THE TOOLARA NO. 7 WILDFIRE AREA IN SOUTHEASTERN QUEENSLAND, AUSTRALIA

The compartment/unit locations selected for study (Fig. 3.19) were sampled by running a transect roughly down the centre of each area, parrallel to the direction of fire spread (i.e., east-west orientation). The starting point was somewhat subjectively determined. However, to avoid any bias in the trees selected for sampling, every fifth tree along a row or rows in some cases was choosen and the following measurements undertaken (abbreviations are as used in Table B-1):

DBHOB - Diameter-at-Breast Height Outside Bark
TH - Tree Height
HFC - Height of Fuel Consumption
HSF - Height of Scorched Foliage

DBHOB was measured with a diameter tape to the nearest 0.1 cm. All heights were determined using a clinometer and measuring tape based on a known distance back from the tree. The angle from clinometer was recorded to the nearest whole degree after sighting on the point or level of interest. Heights were then computed from simple geometry -- i.e., **TH** = *tan* angle x distance + eye level height (Avery 1967, p. 78).

Storey and Merkel's (1960) post-fire impact assessment of overstory trees was particularly helpful in selecting the **HFC** and **HSF** criteria (Fig. B-1). **HFC** was the height above ground before any branches or branch stobs on the stem bole were encountered. **HSF** was the height above ground before any scorched foliage was encountered, if any.

All the remaining information on the sampled areas (Table 3.9) was extracted from the compartment archives held at the Toolara State Forest work centre. It was not possible to determine *z* directly because of the severity of the crown fuel consumption in the lower canopy in most cases. There appeared to be no value in measuring the height of bole charring since in most cases it generally extended 8-10 m or higher.

Table B.1a: Listing of basic data collected on the tree and fire impact characteristics associated with the Toolara No. 7 wildfire in the Swampy Logging Area, Toolara State Forest, southeastern Queensland, Australia, on 22 September 1991.

Cpt. no.	Unit no.	DBHOB (cm)	TH (m)	HFC (m)	HSF (m)	Cpt. no.	Unit no.	DBHOB (cm)	TH (m)	HFC (m)	HSF (m)	Cpt. no.	Unit no.	DBHOB (cm)	TH (m)	HFC (m)	HSF (m)
7	1	22.8	21.1	10.5	13.9	7	3	24.2	15.3	8.7	-[a]	8	1	32.4	23.6	11.4	12.4
7	1	22.8	21.4	11.4	15.5	7	3	17.6	13.7	9.1	-	8	1	27.2	21.8	11.2	13.4
7	1	24.0	22.1	13.4	15.5	7	3	10.2	10.3	10.3	-	8	1	26.1	21.8	10.9	11.9
7	1	26.2	22.9	12.9	15.8	7	3	15.3	11.1	7.9	-	8	1	28.5	21.1	9.3	11.4
7	1	29.0	23.6	12.9	14.7	7	3	17.2	10.4	8.6	-	8	1	33.5	22.9	10.2	20.1
7	1	14.3	19.1	7.3	8.6	7	3	12.9	10.7	6.1	-	8	1	26.2	21.8	11.4	12.4
7	1	25.0	21.8	11.9	13.9	7	3	14.5	9.9	5.6	-	8	1	35.9	22.5	11.7	11.4
7	1	21.8	21.4	12.6	-	7	3	23.7	14.5	6.7	-	8	1	33.9	23.2	11.2	11.9
7	1	20.5	20.7	12.1	-	7	3	13.3	10.7	7.3	-	8	1	27.4	22.5	12.1	13.4
7	1	27.6	22.5	14.5	16.7	7	3	21.0	15.0	7.8	-	8	1	27.6	23.2	10.0	9.5
7	1	23.2	22.1	12.4	13.9	7	3	21.0	14.1	9.5	-	8	1	27.9	22.1	9.8	10.5
7	1	27.3	21.8	11.9	13.4	7	3	27.2	16.5	8.8	-	8	1	25.5	22.5	11.7	15.0
7	1	23.2	20.4	10.9	13.4	7	3	20.9	15.8	10.4	-	8	1	30.3	23.2	9.3	10.9
7	1	27.5	22.5	13.4	13.4	7	3	22.2	16.7	8.4	-	8	1	29.3	21.1	10.9	12.4
7	1	23.0	22.1	13.7	15.3	7	3	15.4	14.4	9.0	-	8	1	27.3	23.2	10.0	12.9
7	1	26.9	22.5	12.6	15.0	7	3	18.1	14.0	9.6	-	8	1	28.7	22.9	11.4	13.4
7	1	22.5	21.8	12.4	13.9	7	3	20.2	15.1	10.1	-	8	1	28.5	23.2	10.9	12.9
7	1	26.0	21.1	10.9	19.1	7	3	23.9	17.3	9.8	-	8	1	29.8	23.2	10.0	11.4
7	1	22.7	20.4	10.9	13.4	7	3	17.1	12.8	7.6	-	8	1	27.8	22.5	10.9	13.9
7	1	31.5	24.0	11.9	14.5	7	3	22.8	16.6	9.2	-	8	1	28.8	21.4	9.1	12.9
7	1	25.0	22.5	13.4	15.5	7	3	19.9	16.4	10.3	-	8	1	23.3	19.1	8.6	10.9
7	1	23.6	21.8	11.9	13.4	7	3	17.8	14.9	10.4	-	8	1	26.2	21.1	11.4	13.4
7	1	23.8	21.8	11.9	14.5	7	3	27.7	19.4	11.4	-	8	1	24.6	21.1	11.4	12.9
7	1	23.9	21.8	13.4	13.4	7	3	16.2	16.5	11.2	-	8	1	27.2	20.4	9.3	10.0
7	1	21.3	20.4	11.2	12.9	7	3	9.1	9.8	6.2	-	8	1	25.4	19.1	8.8	9.3

[a]Implies complete flame defoliation of all foliage.

Table B.1b: continued

Cpt. no.	Unit no.	DBHOB (cm)	TH (m)	HFC (m)	HSF (m)	Cpt. no.	Unit no.	DBHOB (cm)	TH (m)	HFC (m)	HSF (m)	Cpt. no.	Unit no.	DBHOB (cm)	TH (m)	HFC (m)	HSF (m)
8	2	24.2	23.6	15.3	-[a]	10	1	29.2	21.1	10.5	13.4	11	1	25.1	20.7	11.4	13.4
8	2	28.0	23.2	13.4	-	10	1	27.1	21.8	11.4	13.9	11	1	28.2	21.1	10.7	14.2
8	2	22.7	21.8	14.2	-	10	1	26.7	21.1	10.0	13.4	11	1	27.3	21.1	10.5	12.9
8	2	28.3	22.5	11.4	-	10	1	24.5	21.4	11.9	13.4	11	1	23.6	19.7	11.2	13.2
8	2	23.5	22.9	15.0	21.1	10	1	23.1	21.1	10.0	11.7	11	1	26.6	21.1	10.5	12.9
8	2	21.3	19.1	11.4	-	10	1	24.9	21.4	11.7	13.4	11	1	30.5	21.8	10.0	13.7
8	2	20.1	21.1	12.1	-	10	1	23.5	20.4	11.7	12.9	11	1	32.8	21.4	11.4	13.9
8	2	26.8	21.4	11.7	-	10	1	24.0	20.4	10.0	13.4	11	1	26.0	20.7	9.8	12.4
8	2	23.9	21.1	12.6	-	10	1	25.3	21.1	10.5	12.9	11	1	26.8	20.7	11.2	11.7
8	2	22.4	21.1	14.5	-	10	1	29.3	22.5	9.5	11.9	11	1	26.5	19.1	10.0	17.3
8	2	20.5	21.1	12.4	-	10	1	25.3	21.1	12.6	13.4	11	1	26.9	21.1	11.7	14.5
8	2	21.1	21.4	15.5	-	10	1	28.2	22.5	12.6	13.4	11	1	28.6	22.5	10.5	12.9
8	2	27.6	22.5	12.4	-	10	1	26.0	21.1	11.9	13.9	11	1	26.6	19.4	9.5	10.9
8	2	20.5	22.5	21.4	13.9	10	1	27.8	22.5	12.1	13.9	11	1	28.8	21.1	11.4	12.4
8	2	26.1	23.2	12.6	-	10	1	26.0	22.1	10.9	14.5	11	1	23.3	20.1	10.5	12.9
8	2	22.1	21.1	10.7	-	10	1	25.3	20.7	12.1	13.2	11	1	28.0	22.5	10.0	12.9
8	2	24.0	21.1	12.9	20.4	10	1	28.3	22.9	11.9	12.4	11	1	30.2	22.5	10.5	11.9
8	2	23.1	21.4	11.4	20.7	10	1	28.3	20.7	8.8	10.5	11	1	32.5	21.1	10.9	11.4
8	2	28.9	23.2	13.2	-	10	1	27.2	21.8	12.9	13.4	11	1	31.1	21.4	10.0	11.7
8	2	22.3	20.7	12.9	20.1	10	1	30.9	24.0	11.9	13.4	11	1	26.4	20.7	11.4	13.2
8	2	25.7	21.1	12.4	-	10	1	25.7	19.7	9.8	10.5	11	1	30.3	22.5	10.5	12.9
8	2	21.9	19.4	11.2	-	10	1	29.1	21.8	11.4	13.9	11	1	27.6	22.1	10.5	11.4
8	2	22.8	19.1	9.5	-	10	1	28.0	21.8	11.4	12.9	11	1	26.0	20.4	9.3	11.9
8	2	26.8	21.1	11.2	20.1	10	1	23.7	21.8	10.9	12.9	11	1	27.7	21.8	11.4	13.9
8	2	15.4	18.5	12.4	17.6	10	1	27.1	21.8	10.5	13.4	11	1	27.8	21.1	10.6	12.9

[a]Implies complete flame defoliation of all foliage.

Table B.1c: concluded.

Cpt. no.	Unit no.	DBHOB (cm)	TH (m)	HFC (m)	HSF (m)
11	2	28.9	21.8	12.6	15.3
11	2	28.4	22.1	13.9	15.0
11	2	25.6	21.1	13.4	17.9
11	2	29.3	23.2	13.4	20.4
11	2	28.7	23.6	13.9	20.4
11	2	28.7	22.1	14.5	20.4
11	2	22.7	21.1	10.9	18.5
11	2	23.3	21.1	11.4	12.9
11	2	22.9	19.7	12.9	14.5
11	2	20.9	19.4	11.9	14.5
11	2	28.1	20.4	11.2	13.4
11	2	23.1	19.1	10.9	16.1
11	2	35.8	21.1	10.0	19.7
11	2	22.1	18.5	11.9	15.5
11	2	20.6	19.4	13.4	18.5
11	2	20.8	17.9	11.2	-[a]
11	2	20.9	17.9	11.2	-
11	2	18.4	17.3	10.5	-
11	2	21.0	19.7	10.7	-
11	2	26.6	21.1	12.4	15.5
11	2	25.4	21.4	13.9	15.5
11	2	24.1	21.1	10.9	12.9
11	2	30.5	21.8	11.9	14.5
11	2	25.5	20.7	12.1	14.2
11	2	26.3	21.4	11.7	15.0

[a]Implies complete flame defoliation of all foliage.

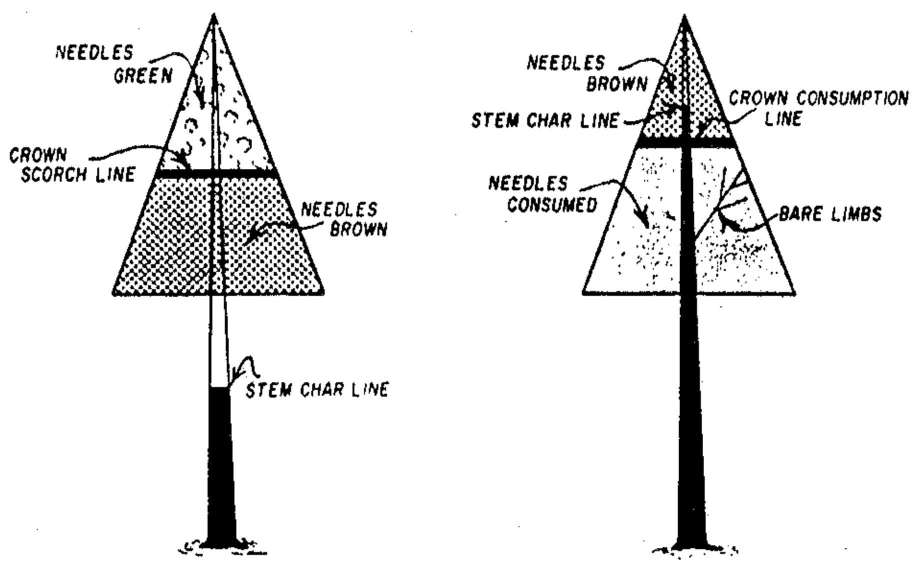

Figure B-1: Variation in readily evident impacts of fire on coniferous tree crowns and stems (from Storey and Merkel 1960).

APPENDIX C:

CROWN FUEL WEIGHTS OF SLASH PINE AND HONDURAS CARIBBEAN PINE IN SOUTHEASTERN QUEENSLAND, AUSTRALIA

Foliage dry weight data were collected by destructively sampling a dozen trees of slash pine and Caribbean pine each (Table C-1) using more or less standard crown biomass sampling procedures (*cf.* Stocks 1980). Care was taken to avoid sampling trees with noticeably irregular crown forms. The sample trees were somewhat subjectively selected in order to achieve a nominal height of the sample trees for the (**DBHOB**) and the diameter-at-ground line outside bark (**DGLOB**) was measured to the nearest 0.1 cm with a diameter tape before felling the tree. After felling the tree, total tree height **TH**, height to live crown base (*z*), diameter-at-crown base outside bark (**DCBOB**) and crown width was measured with a tape to the nearest 0.1 m. Branches were then cut flush with the tree bole and crown fuels separated into the following categories as per McCaw (1991): needle foliage, live < 6 mm **d**, live > 6 mm **d**, dead < 6 mm **d**, dead > 6 mm **d** and cones. Crown fuel separation was done on plastic sheeting in order to prevent particle loss. After weighing of all the invidual fuel components in the field, samples of each were taken for moisture content determination (over-drying at 100°C for 24 hours). The percent moisture content was then used to calculate the oven-dry weights of each fuel component based on the "fresh" weights obtained in the field. Details of the silvicultural history of each compartment sampled in was acquired from the compartment archives held at the Toolara State Forest work centre.

Table C-1a: Sample tree and crown fuel component data for slash pine (*Pinus elliottii* var. *elliottii* (PEVE)) and Honduras Caribbean pine (*Pinus caribaea* var. *hondurensis* (PCVH)) stems collected in the Toolara State Forest (SF 1004) of southeastern Queensland, Australia.

Sample tree no.	Sample date (day/month/year)	Location sample tree Cpt.	Location sample tree Logging area	Needle foliage	Oven-dry weights (kg) Twigs and branches by condition/roundwood diameter Live <6 mm	Live >6 mm	Dead <6 mm	Dead >6 mm	Female cones
PEVE 1	04.01.91	18	Swampy	11.450	0.336	13.350	0.315	10.329	0.009
PEVE 2	05.01.91	105	North Dempster	5.299	0.150	1.750	0.0	0.0	0.0
PEVE 3	05.01.91	105	North Dempster	5.982	0.198	4.039	0.027	0.432	0.0
PEVE 4	05.01.91	105	North Dempster	1.578	0.111	0.442	0.014	0.026	0.0
PEVE 5	07.01.91	82	North Dempster	17.096	1.039	19.023	0.233	2.693	1.583
PEVE 6	07.01.91	82	North Dempster	9.396	0.366	7.654	0.453	6.716	1.325
PEVE 7	08.01.91	51	Como	7.684	0.262	7.269	0.310	3.926	2.157
PEVE 8	08.01.91	51	Como	5.831	0.187	4.493	0.098	1.241	0.025
PEVE 9	09.01.91	95	North Dempster	1.905	0.085	0.502	0.007	0.0	0.0
PEVE 10	09.01.91	95	North Dempster	1.408	0.107	0.515	0.022	0.0	0.0
PEVE 11	09.01.91	95	North Dempster	0.948	0.036	0.143	0.002	0.0	0.0
PEVE 12	09.01.91	95	North Dempster	0.723	0.035	0.125	0.014	0.0	0.0
PCVH 1	04.01.91	36A	Kelly	9.309	0.986	9.944	0.141	4.298	0.056
PCVH 2	05.01.91	105	North Dempster	3.019	0.071	1.299	0.034	0.046	0.0
PCVH 3	05.01.91	105	North Dempster	6.064	0.128	3.310	0.028	0.488	0.0
PCVH 4	05.01.91	105	North Dempster	1.516	0.074	0.455	0.017	0.039	0.0
PCVH 5	06.01.91	18	Ulirraba	13.585	0.967	1.535	0.306	4.546	0.006
PCVH 6	06.01.91	18	Ulirraba	10.515	0.861	10.533	0.398	2.853	0.094
PCVH 7	08.01.91	50	Como	4.503	0.554	3.894	0.234	0.861	0.0
PCVH 8	08.01.91	50	Como	4.783	0.827	3.858	0.068	0.218	0.0
PCVH 9	09.01.91	101	North Dempster	1.084	0.050	0.445	0.008	0.005	0.0
PCVH 10	09.01.91	101	North Dempster	2.307	0.048	0.386	0.004	0.006	0.0
PCVH 11	09.01.91	110	North Dempster	0.732	0.036	0.096	0.0	0.0	0.0
PCVH 12	09.01.91	110	North Dempster	0.609	0.039	0.083	0.0	0.0	0.0

Table C-1b: concluded.

Sample tree no.	Planting date (month/year)	Initial stem spacing (m)	**DBHOB** (cm)	**TH** (m)	Live crown Length (m)	Live crown Width (m)	**DGLOB** (cm)	**DCBOB** (cm)	Silvicultural history: Pruning Ht. (m)	Pruning Year	Thinning Sph	Thinning Year
PEVE 1	06/71	2.3 x 2.7	25.8	23.1	7.5	2.6	35.5	13.2	5.4	1981[a]	304	1991[a]
PEVE 2	06/86	4.5 x 2.5	9.9	6.1	5.6	1.8	13.0	11.9	-	-	750	1990
PEVE 3	06/86	4.5 x 2.5	12.8	7.0	5.5	2.9	16.6	12.4	-	-	750	1990
PEVE 4	06/86	4.5 x 2.5	7.7	4.9	4.3	1.6	10.6	9.5	-	-	750	1990
PEVE 5	06/78	2.4 x 2.7	22.7	14.4	9.3	3.5	32.0	18.5	-	-	750	1984
PEVE 6	06/78	2.4 x 2.7	19.0	14.6	6.4	2.6	26.8	12.9	-	-	750	1984
PEVE 7	07/82	3.0 x 3.0	17.3	10.8	5.6	2.6	25.4	11.9	-	-	750	1986
PEVE 8	07/82	3.0 x 3.0	15.3	10.1	5.8	2.3	21.6	11.6	-	-	750	1986
PEVE 9	06/86	4.5 x 2.5	5.6	4.5	3.8	1.5	9.6	6.6	-	-	733	1990
PEVE 10	06/86	4.5 x 2.5	5.2	3.5	3.0	1.7	9.7	7.0	-	-	733	1990
PEVE 11	06/86	4.5 x 2.5	3.6	3.0	2.4	1.2	7.5	5.5	-	-	733	1990
PEVE 12	06/86	4.5 x 2.5	3.1	2.6	2.0	1.2	7.7	5.4	-	-	733	1990
PCVH 1	06/63	2.4 x 2.4	26.1	21.9	8.9	2.9	31.9	15.1	6.4	-[b]	880	1979
PCVH 2	06/86	4.5 x 2.3	10.1	6.8	5.3	1.9	13.4	9.9	-	-	750	1990
PCVH 3	06/86	4.5 x 2.3	12.6	7.8	6.4	2.4	16.9	12.5	-	-	750	1990
PCVH 4	06/86	4.5 x 2.3	7.8	4.5	3.5	1.6	11.3	8.4	-	-	750	1990
PCVH 5	06/77	3.0 x 2.6	22.1	19.6	12.8	3.5	26.6	17.3	5.4	1986	750	1983
PCVH 6	06/77	3.0 x 2.6	19.5	18.0	10.8	2.6	26.0	15.5	5.4	1986	750	1983
PCVH 7	06/82	3.2 x 3.2	16.8	10.0	5.7	2.2	23.1	12.0	5.4	1990	745	1986
PCVH 8	06/82	3.2 x 3.2	14.3	8.8	7.7	2.2	19.4	14.6	5.4	1990	745	1986
PCVH 9	06/86	4.5 x 2.3	5.7	2.8	0.8	2.0	9.9	7.3	-	-	729	1990
PCVH 10	06/86	4.5 x 2.3	5.7	3.7	3.4	1.3	10.5	9.3	-	-	729	1990
PCVH 11	05/87	4.5 x 2.1	3.0	2.4	1.9	1.0	6.0	4.9	-	-	750	1991
PCVH 12	05/87	4.5 x 2.1	2.5	2.2	2.0	1.0	6.1	5.3	-	-	750	1991

[a]Initially pruned to 3.0 m in 1979 and thinned to 510 stems/ha in 1985.
[b]Unknown.