Alexander, M.E. 1998. Crown fire thresholds in exotic pine plantations of Australasia. Australian National University, Canberra, ACT, Australia. Ph.D. Thesis. 228 p.

DECLARATION OF ORIGINALITY

I certify that this thesis contains no material which is being or has been used for the award of any degree or diploma in any University unless otherwise acknowledged.

I also certify that the experimentation and analysis, interpretation and presentation of the results in this thesis are my own work, and any assistance received in preparing this thesis and all sources used, have been acknowledged.

Martin E. Alexander

February 1998

(Martin Edward Alexander)

ABSTRACT

Fire managers in Australasia currently lack the basis that would permit them to objectively evaluate the potential for crown fire development in exotic pine plantations under any specified set of fuel, weather and topographic conditions. The existing crown fire initiation models all have inherent weaknesses or lack applicability, thereby rendering their utility questionable. A model that would enable them to predict the onset of crowning has been developed from a combination of physical insights and mathematical modelling coupled with relevant field and laboratory experiments. The six model inputs include at least two environmental parameters (ambient air temperature, in-stand wind speed) and possibly a third (slope steepness) where applicable, two surface fire behaviour characteristics (line-fire intensity, flame front residence time) and two crown fuel properties (foliar moisture content, live crown base height).

The most fundamental principle incorporated in the model is that temperature rise above ambient conditions is determined by the intensity of the heat source at the ground surface, the height above ground in question, and the angle formed between the ground surface and the surface fire plume. Ignition or initial combustion of the needle foliage at the base of the live or green crown layer is in turn judged to be a function of the duration of heating experienced and the temperature achieved in the convection column at this height, assuming the presence of a pilot flame source(s). One of the unique features of the present crown fire initiation model is that the influence of within stand wind speed on the trajectory of the thermal plume has been considered in terms of its relative effectiveness in the convective heating of the lower live crown layer. This is considered to be a very significant improvement over C.E. Van Wagner's criteria for crown fire initiation and coupled with variable allowances for ambient conditions and duration of convective heating should thereby permit extrapolation to a wider range of burning conditions. Furthermore, a simplistic methodology has been formulated for deriving the needed empirical constant in the model, that essentially reflects the surface and bridge or ladder fuel characteristics of structurally dissimilar plantation stand types, based on the height of lethal crown scorching that could be obtained from low-to moderate-intensity surface fires, thereby negating the need for direct temperature measurement above the surface fire flame front. This has in turn resulted in new insights into the modelling and prediction of crown scorch height.

The model has been tested against independent documentation obtained from experimental fires, operational prescribed fires and wildfires, with exceedingly encouraging results. The validity of C.E. Van Wagner's concept of a critical minimum crown fire rate of spread in relation to the crown bulk density in order to achieve continuous crowning has been substantiated for the first time in an operational setting. Also emerging from a detailed wildfire behaviour case study is evidence that under certain conditions, two distinctly different states of fire spread and intensity could exist in a given plantation fuel complex at a specific level of fuel moisture depending on the wind speed and arrangement/character of the plantation age-class mosaic. The model will allow exotic pine plantation managers the means of quantitatively and objectively assessing the various fire and fuel management practices designed to limit the incidence and impact of crown fires such as pruning, thinning, prescribed underburning, and plantation layout/design considerations (e.g., diverse age-class mosaic). The model could easily be extended to forest fuel complexes other than exotic pine plantations with a minimal of effort.

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DEDICATION

To:

Neal Russell, Evan Payne, Graeme Frazier and Wynne Marie

With much love,
Dad

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CHAPTER 1:

INTRODUCTION

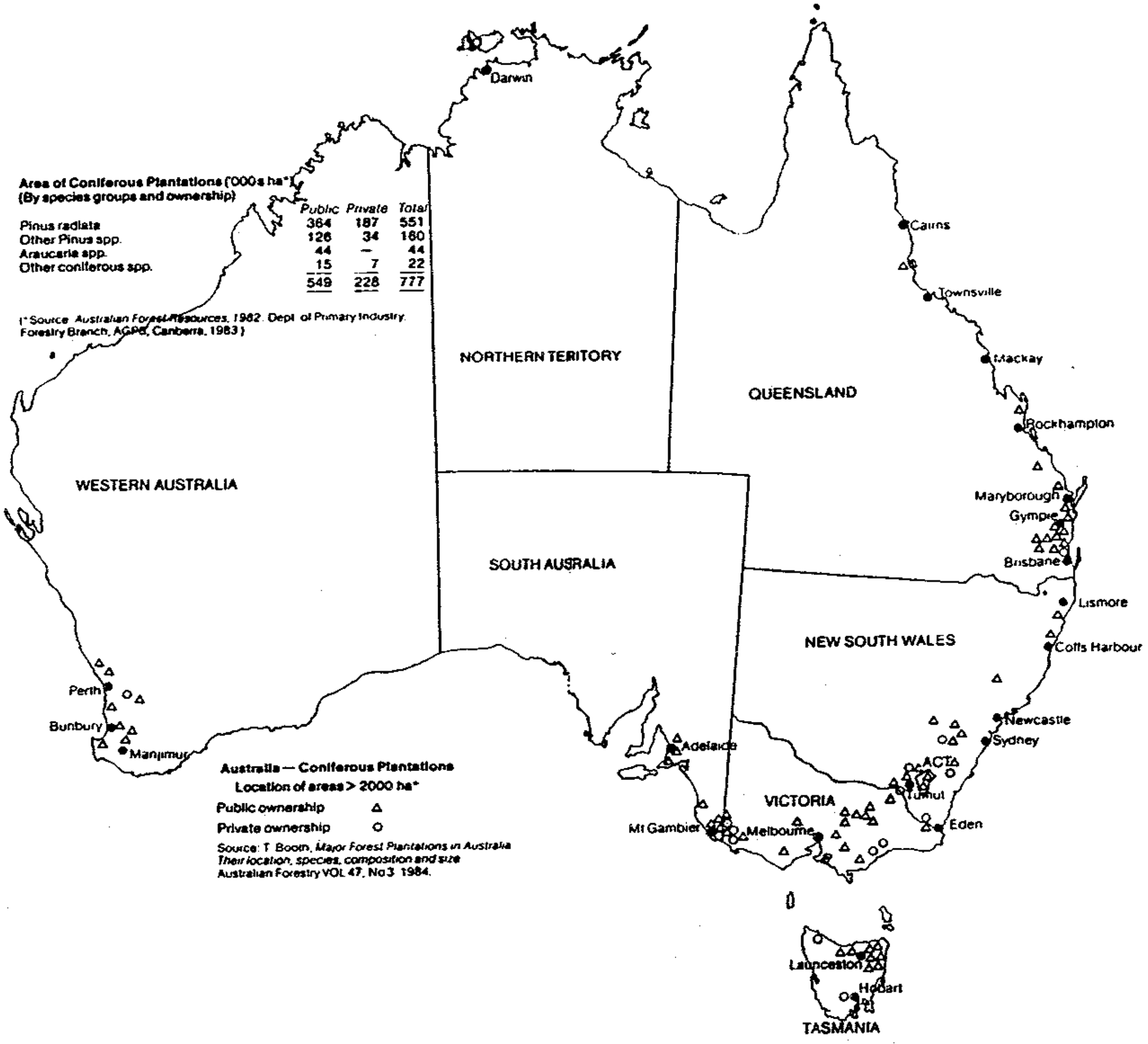
> *The management or control of forest fires in Australia will never become a reality until the behaviour of fires can be predicted accurately over the many conditions under which they occur.*
>
> Underwood (1985)

1.1 Nature and Extent of Exotic Pine Plantations in Australasia

Throughout Australasia, plantations of introduced or exotic conifer tree species have come to be established and managed on a commercial basis in order to augment or in some cases eliminate the need for harvesting of native forest vegetation in order to meet local demands for forest and wood products or for export sales (Lewis et al. 1993). Rotations of 30-45 years for sawn timber are possible, depending on site quality. Over two million hectares of industrial *Pinus* spp. plantations have now been established in Australia, New Zealand and Fiji (Figs. 1.1, 1.2 and 1.3). Planting in Australia and New Zealand began over a century ago and continues to this day (Forest Department of Western Australia 1969; Allsop 1973; Lewis 1975; Simpson 1978; Carron 1985; Grant 1989; Moulds 1991). The total area of these man-made forests in Australia and New Zealand now amounts to approximately 0.9 and 1.3 million hectares, respectively (Anon. 1992a, 1993a). In New Zealand, the primary species planted (90%) is Monterey or radiata pine (*P. radiata*). Radiata pine is also the major species in all Australian states except Queensland and the Northern Territory (Table 1.1), but the largest concentrations are in the southeastern regions of the country (Booth 1984; Lewis 1991). Conifer plantations in Queensland, northern New South Wales and the Northern Territory are comprised largely of slash pine (*P. elliottii* var. *elliottii*) and Honduras Caribbean pine (*P. caribaea* var. *hondurensis*) or hybrids of the two (Francis and Shea 1991). Sizeable plantations of maritime pine (*P. pinaster*) occur primarily in the southwestern part of Western Australia. The development of coniferous plantations in Fiji started in the late 1950s (Drysdale 1989) and now cover an area of nearly 40 000 ha, comprised chiefly of Caribbean pine (Fiji Pine Commission 1991).

The sizes of individual exotic pine plantation forests in Australasia vary over four orders of magnitude, from single isolated woodlots of 10 ha up to more or less contiguous blocks in excess of 100 000 ha such as the Kaingaroa Forest in the central North Island of New Zealand, although areas of 1000 to 10 000 ha subdivided into compartments of around 20-40 ha are more commonly the norm. Plantations have been established on both flat to gently undulating terrain and on steep slopes of up to 30-35° in a wide variety of environments.

Preparation of the sites for tree planting can be quite intensive. Plantings are made with seedling stock at initial spacings any where from about 1.4 x 1.4 m (5102 stems/ha) to 5 x 5 m (400 stems/ha). Following planting, weeding, fertilization, pruning and one or more precommercial thinnings may take place prior to commercial thinning and final harvest



Area of Coniferous Plantations ('000s ha*)
(By species groups and ownership)

	Public	*Private*	*Total*
Pinus radiata	364	187	551
Other *Pinus* spp.	126	34	160
Araucaria spp.	44	–	44
Other coniferous spp.	15	7	22
	549	228	777

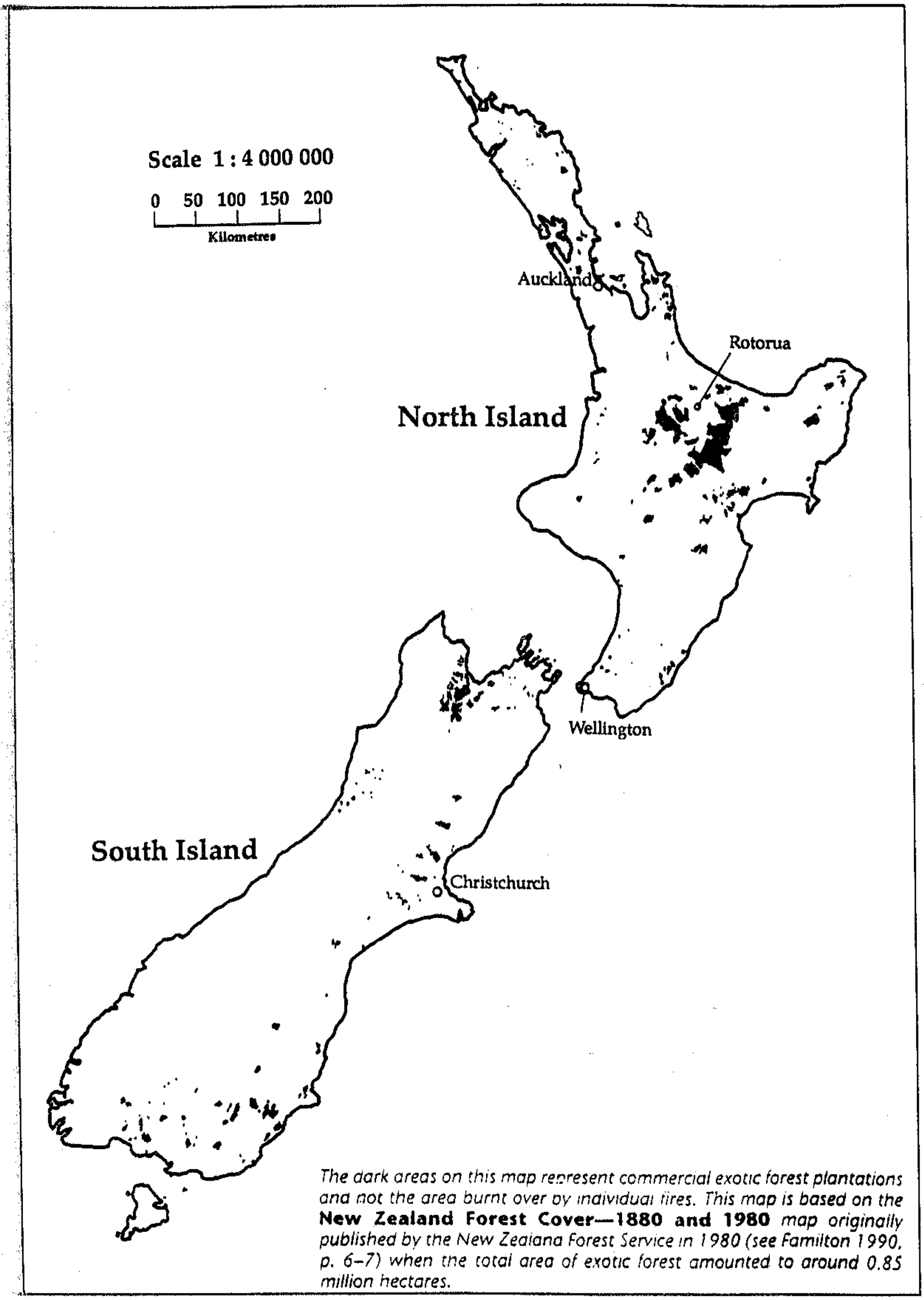
(*Source *Australian Forest Resources, 1982*. Dept of Primary Industry, Forestry Branch, AGPS, Canberra, 1983)

Australia — Coniferous Plantations
Location of areas > 2000 ha*

Public ownership	△
Private ownership	○

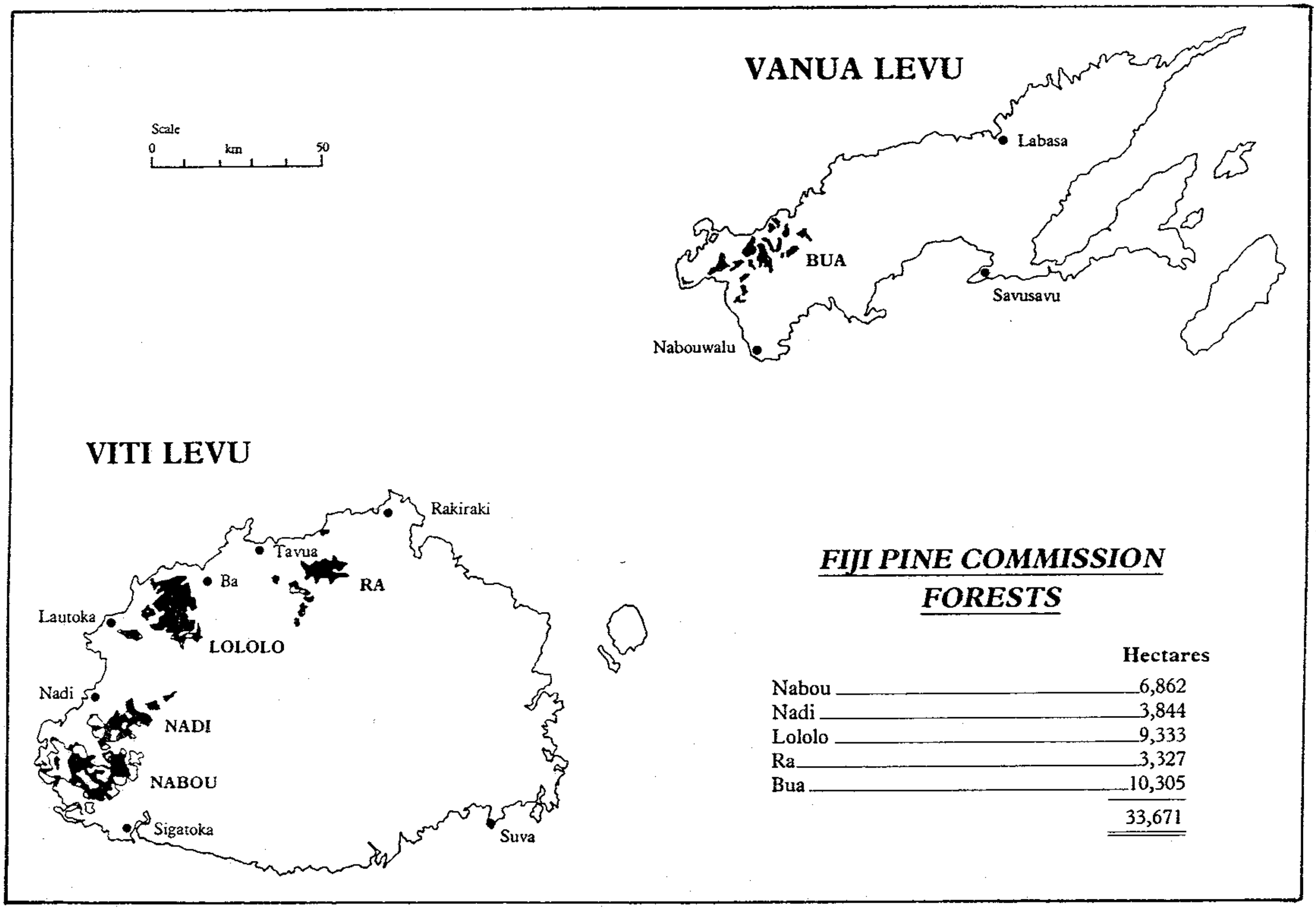
Source: T Booth, *Major Forest Plantations in Australia Their location, species, composition and size* Australian Forestry VOL 47, No 3 1984.

Figure 1.1: Geographical location and extent of the major exotic pine plantations in Australia (from Carron 1985).



The dark areas on this map represent commercial exotic forest plantations and not the area burnt over by individual fires. This map is based on the **New Zealand Forest Cover—1880 and 1980** *map originally published by the New Zealand Forest Service in 1980 (see Familton 1990, p. 6–7) when the total area of exotic forest amounted to around 0.85 million hectares.*

Figure 1.2: Geographical location and extent of the major exotic pine plantations in New Zealand (after Familton 1990).



	Hectares
Nabou	6,862
Nadi	3,844
Lololo	9,333
Ra	3,327
Bua	10,305
	33,671

Figure 1.3: Geographical location and extent of the major exotic pine plantations in Fiji (from Fiji Pine Commission 1991).

Table 1.1: Exotic pine plantation resource in Australia as of March 31, 1990 (data courtesy of the Australian Bureau of Agricultural and Resource Economics, Canberra, Australian Capital Territory).

State or territory	Area by *Pinus* species			
	P. radiata (ha)	*P. elliotti* (ha)	*P. pinaster* (ha)	*P. caribaea* (ha)
	Public ownership			
New South Wales	196 633	5263	0	2786
Victoria	102 846	3	442	3
Queensland	2258	64 385	0	50 819
Western Australia	39 062	289	28 382	0
South Australia	67 945	0	3119	0
Tasmania	39 342	0	0	0
Northern Territory	0	0	0	0
Australian Capital Territory	14 052	0	0	0
	Private ownership			
New South Wales	57 037	0	0	0
Victoria	102 839	5	919	0
Queensland	983	18 000	0	325
Western Australia	16 892	0	197	0
South Australia	26 600	0	0	0
Tasmania	32 444	0	0	0
Northern Territory	0	0	0	2386
Australian Capital Territory	0	0	0	0
	Public and private ownership			
New South Wales	253 670	5263	0	2786
Victoria	205 685	8	1361	3
Queensland	3241	82 385	0	51 144
Western Australia	55 954	289	28 579	0
South Australia	94 545	0	3119	0
Tasmania	71 786	0	0	0
Northern Territory	0	0	0	2386
Australian Capital Territory	14 052	0	0	0
Total	698 933	87 945	33 059	56 319

(Shepherd 1986). The silvicultural regimes for exotic pine plantations in Australasia vary considerably as determined by the species, site conditions and the desired end product (e.g., pulp vs. sawn timber or veneer logs). Growth rates by most standards are quite extraordinary. For example, a plantation stand of radiata pine at 45 years, having been reduced to a final stocking of 150-200 stems/ha, can average 30-40 m high and 60-70 cm diameter-at-breast height outside bark.

1.2 Forest Protection and the Wildfire Threat

The exotic pine plantations of Australasia constitute a sizeable economic investment to the governments, companies and private landowners responsible for their management. These man-made forests are vulnerable to a whole host of injurious agents, including insects, diseases, meteorological phenomena (hurricanes, snow, hail and ice storms), volcanic eruptions, native and introduced animal damage as well as wildfire (Drysdale 1989; Maclearn 1993). Certain silvicultural practices that have evolved as a result of operational experience and research results have, in some instances, tended to mitigate against larger potential losses.

Commercial pine plantations in Australasia have in most cases been established in locations without due regard for their protection from wildfires in terms of the fire climate, topography, public access, etc. (Richmond 1990). The associated fire environments in most instances encourage the potential for large, high-intensity wildfire occurrences. Plantation fuel complexes are generally quite flammable, particularly at an early age prior to and for a few years following pruning and thinning. Summer fire weather patterns are conducive to the incidence and spread of unwanted fires on a good number of days during the fire season, even in most parts of New Zealand and Fiji. Natural and human ignition agents abound (Douglas 1963; Minko 1966, 1975; Anon. 1975; Farrow 1989; Ward 1993). It's noteworthy that most of the major exotic pine plantation fires experienced in Australia to date have been the result of external as opposed to internal fire starts.

The threat of wildfire and the need for protection of these valuable timber resources is very real and may in fact be increasing with time as evident by the South Australian experience (Fig. 1.4)[1]. Notable examples include the 1946 Tahorakuri (13 217 ha) and 1955 Balmoral (3152 ha) Fires in New Zealand (Prior 1958; McLean 1992), the 1983 Ash Wednesday fires (Keeves and Douglas 1983) in South Australia (21 000 ha) and the 1987 fire season in Fiji (12 685 ha) (Fiji

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[1] Logic would dictate that the chance(s) of a high-intensity crown fire occurrence would gradually increase as the size of the total plantation estate increases. The value of a dispersed pattern of relatively small to moderately sized plantations, especially in fire-prone environments exhibiting very high ignition risk coupled with an adverse fire climate, was demonstrated during the 1983 Ash Wednesday Fires in the southeastern portion of South Australia and Victoria; an excellent map depicting the pattern of plantation ownership in the "green triangle" of southeastern South Australia and southwestern Victoria is presented in, for example, Gould (1987) and previous annual reports of the South Australian Woods and Forest Department. State-owned plantations in the region managed by the Woods and Forests Department amount to approximately 80 000 ha and are comprised of a few large, more or less contiguous blocks of land. On 16 February 1983, some 21 000 ha of exotic pine plantations were burnt over in South Australia alone, most very severely, by eight fires that covered a gross area of around 120 000 ha. In contrast, private forest industry in the region, with a comparable estate of around 70 000 ha, but comprised of many smaller parcels scattered across the region more as a result of circumstances rather than by any strategic design, suffered only minor (40 ha) wildfire losses (Nethercott 1990).

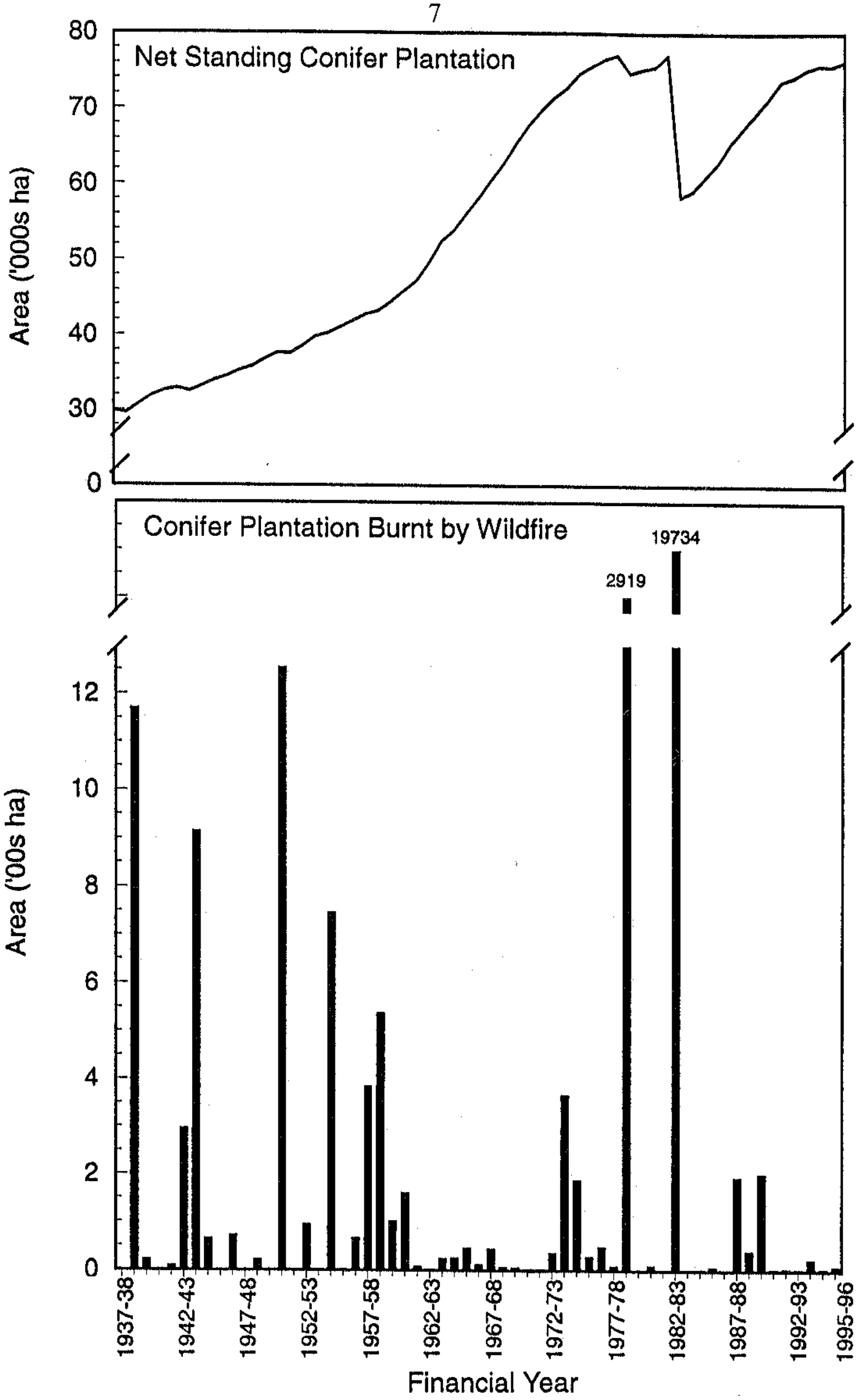

Figure 1.4: Total plantation area and area burnt by wildfire in state-owned exotic conifer plantations of South Australia during the 1937-38 to 1995-96 fire seasons (compiled from annual reports of the Woods and Forests Department of South Australia).

Pine Commission 1988). Most of the exotic pines planted are susceptible to fire damage of one sort or another, but especially radiata pine even for relatively low-intensity fires (Nicholls and Cheney 1974). Even though the other major pine species are far more fire resistant than radiata pine and can withstand considerable crown scorch (McCormick 1976) and even some crown fuel consumption, there will be a reduction in growth for several years. Crown fires are especially destructive, more often than not leading to outright tree deaths regardless of the species. The occurrence of large high-intensity wildfires can severely affect the economic well-being of the organization (and the local communities dependent on them) that have invested considerable sums of money and time in the planting and tending of these areas (Woods 1965). Young plantations are easily killed by wildfire and offer few if any post-fire salvage opportunities (Bankes et al. 1986). The costs of clean-up and replanting in these situations can be considerable (Geddes 1981). Most large plantation owners have come to accept the fact that a certain percentage of their estate (say less than 0.1% per annum over the long run) will succumb to wildfire (Douglas and Thomas 1962); this percentage is generally based on the capacity of the timber using industry to utilize the fire-killed timber before degrade sets in (French et al. 1969; Keirle and Johnstone 1970; Wright and Gorse 1970). Small and moderate sized fires have little impact on timber supplies as any loss can be redistributed over time by various means available to the owner (Cheney 1985b). Major conflagrations, however, can greatly disrupt long-term wood supplies. Following the 1983 Ash Wednesday Fires in southeastern South Australia, a massive salvage operation of the older merchantable fire-killed timber was required in order to minimize the economic consequences in the following years (Bankes 1984; Cole 1984; Thomas 1986).

The safeguarding of exotic pine plantations from wildfires has been a major concern of the forest industry in Australasia almost from day one (Gill 1963; Anon. 1978; Church 1981). Many advances in fire control technology and management have occurred over the intervening years (McArthur 1967b; Douglas 1976; Hawkes 1979; Luke and McArthur 1978; Cooper 1980; Telford 1988; Geddes 1995; Raymond 1995), including the construction of lookout towers for fire detection (Douglas 1967b), equipment development (Rankin 1939; Hill 1959; Douglas 1969), fuel and fire breaks (Childs 1961; Jolly and Guild 1974), suppression strategies and tactics (Douglas 1974b; Pratt and Thomas 1988), and various presuppression measures including fuel hazard reduction burning inside (Hewett 1965; McArthur 1966a; Peet 1967; McCormick 1969a; 1969b; 1971b; Fearnside 1970; Ashcroft 1971; Bukelis 1971; Billing 1979, 1980a; Mair 1992) and outside the plantation (Rowell and Cheney 1979) as well as other forms of fuels management (Gregor 1972; Burrows 1980b, 1981; Norman 1985). Systems for rating fire danger or assessing potential fire behaviour have been developed as an aid to determining the state of readiness and resource requirements for initial attack dispatch (e.g., Douglas 1973). Sadly, many innovations in exotic pine plantation fire control management have come about as the result of wildfire disasters (Pederick 1983), including firefighter fatalities associated with the establishment and/or protection of exotic pine plantations in all three countries (McArthur et al. 1966; Fiji Pine Commission 1991, p. 8; Millman 1993).

1.3 The State of Fire Behaviour Prediction in Australasian Pine Plantations

One of the earliest published accounts pertaining to the quantitative evaluation of potential fire behaviour in Australasian exotic pine plantations is that prepared by J.M. Fielding of the

Australian Commonwealth Forestry Bureau in 1941 based on fuel moisture stock readings and personal estimates obtained from foresters in the southeastern region of South Australia during the 1940-41 fire season (Table 1.2). Many of the state forest services in Australia as well as the Commonwealth Government have undertaken to develop guides for predicting fire behavior for use in prescribed burning and to a lesser extent for wildfire management (Douglas 1957; Luke 1962; McArthur 1958, 1966a, 1971; Peet et al. 1968, 1971; Cheney 1975, 1978; Thomson 1978, 1979; Byrne and Just 1982; Dawson 1982b; Woodman and Rawson 1982; Hunt and Simpson 1985; Sneeuwjagt and Peet 1985; Watts and Bridges 1989); *see* also Hoare's (1989) summary. Some fire effects work has also been undertaken at the same time (e.g., Gilmour 1965; Vines 1968; Springett 1971, 1976a, 1976b; Attakorah 1974; McCormick 1976; Woodman and Billing 1979; Billing 1981; Hunt and Simpson 1985). The guides specifically developed for prescribed burning have been based on the results of low- to moderate-intensity experimental fires conducted outdoors in real fuel complexes; laboratory studies of fire behavior in pine litter fuel beds have been virtually non-existent -- Ward's (1971) study is the only known exception. Concurrent with this effort has been the preparation of several case studies of high-intensity wildfires (e.g., Douglas 1967a, 1974a, 1974b; McArthur 1965; McArthur et al. 1966; Van Loon 1967; Ollerenshaw and Douglas 1971; Geddes and Pfeiffer 1981; McArthur et al. 1982; Billing 1980b, 1983; Keeves and Douglas 1983; Watson et al. 1983; Underwood et al. 1985; Hamwood 1992a); Dawson (1982a) attempted a compilation of all published and unpublished information in the early 80s.

Two empirically-based forest fire danger/fire behaviour prediction systems are currently in widespread use in Australia, one specifically for Western Australia (Burrows and Sneeuwjagt 1991) and the other commonly used throughout the southeastern states of Australia (Cheney 1991a). The basic index from the McArthur (1967a, 1973) Forest Fire Danger Meter or its derivatives (Noble et al. 1980; Crane 1982) provides for the prediction of wildfire behaviour in terms of forward rate of spread, flame height, and spotting distance in a dry *Eucalyptus* spp. forest with fine fuel quantities of 12.5 t/ha on level to gently undulating terrain although spread predictions can be adjusted for slope steepness and fuel quantities significantly different from the standard (Cheney 1968; McArthur 1984). Both the Keetch-Byram Drought Index (**KBDI**) (McArthur 1966b; Keetch and Byram 1968; Peet 1969; van Didden 1971) and the Mount Soil Dryness Index (**MSDI**) (Mount 1972; Burrows 1987) are used in conjunction with the McArthur meter; New Zealand also used the **KBDI** throughout most of the 70s (Valentine 1972) while Fiji utilized the **KBDI** throughout the 70s and 80s (McArthur 1971). Both the English (800 1/100 in.) and SI (200 mm) scales of the **KBDI** (*cf.* Alexander 1990, 1992a) are used in Australia whereas with the **MSDI**, the SI 200 mm unit (Mount 1972) scale and a 2000 point scale (Burrows 1987) are both used in the country Mount (1991).[2]

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[2] In December 1991 the author compiled the following summary for the six states and two territories of Australian with respect to current useage of these two drought indexes by the forest services and other fire management organizations including the Bureau of Meteorology ("+" means in use and "-" denotes not the use):

Index (unit scale)	ACT	NSW	NT	QLD	SA	TAS	VIC	WA
KBDI (800 1/100 in.)	-	-	-	+	-	-	-	-
KBDI (200 mm)	+	+	-	-	+	-	+	-
MSDI (200 mm)	-	+	-	-	+	+	-	-
MSDI (200 mm x 10)	-	+	-	-	-	-	-	+

In the above tabulation ACT = Australian Capital Territory, NSW = New South Wales, NT = Northern Territory, QLD = Queensland, SA = South Australia, TAS = Tasmania, VIC = Victoria, and WA = Western Australia.

Table 1.2: Fire hazard classification scheme devised by J.M. Fielding for radiata pine plantations in south-eastern South Australia (from Foley 1947).

FIRE HAZARD SCALE.
(Mt. Burr, South Australia.)
DAILY FIRE DANGER CLASSIFICATION—NEW CLASSIFICATION, JANUARY, 1941.
South-east of South Australia.

The danger to be recorded is the maximum danger occurring during the day.

The descriptions below are based on the manner a fire would burn in the following Monterey Pine Stands.

(*a*) *High Quality.*—Stocking over 600 per acre. Height 40 ft. to 45 ft. Green level about 10 ft. All undergrowth completely suppressed. Only needle litter on the floor.

(*b*) *Low Quality.*—Stocking about 600 per acre. Height about 30 ft. Green level 0 to 3 ft. Dense bracken and undegrowth occurring throughout, and much of it dead.

Danger.	Fire Description.		Weather.	Moisture Pine Rods.
	(*a*) High Quality.	(*b*) Low Quality.		
0. Nil	Fire will not burn	Fire will not burn		18·0 +
1. Very low	Needle litter burns slowly	Litter and some undergrowth burns	Cool winds—W., S.W., S., S.E., E., cool gentle N.E., N., or N.W.	13·2–18·0
2. Low	Litter burns readily and a few dead needles on limbs burn	Litter, most undergrowth, and nearly all dead needles burn. A few green needles burn	Wind ditto	9·8–13·2
3. Low medium	Most dead needles on limbs burn. Green needles almost untouched	All undergrowth burns clean, Most of green needles burn	Winds ditto, but warmer	7·9–9·8
4. Medium	Practically all green crowns partly burn	Practically all green crowns completely burn	Winds ditto, but warmer	6·6–7·9
5. High medium	Many green crowns completely destroyed	Whole plantation swept, crowns and all	Warm, dry winds, N.E., E., N.W., or W. Maximum temperature over 77	5·3–6·6
6. High	"Crown fire"—all crowns burn rapidly	Plantation swept at considerable speed	Winds ditto; always fairly strong. Maximum temperature over 83	4.0–5.3
7. Very high	"Blow up" day	"Blow up" day	Wind ditto; practically always strong. Maximum temperature over 90	< 4·0

Table 1.3: Dispatchers guide for fires starting in radiata pine plantations of southern New South Wales, Australia, according McArthur (1973) forest fire danger classes (from Luke 1962).

	Degree of Fire Danger					
	Extreme (Upper limit)	Extreme (Lower limit)	Very High	High	Moderate	Low
Probable extent of fire danger in days during a 4-month period for various types of fire season.						
Mild season (4 in 10)	—	—	11	22	28	60
Moderate season (4 in 10)	—	2	14	35	45	25
Severe season (2 in 10)	2	5	24	35	29	25
Probable maximum rate of spread of fire.						
Forward spread in chains per hour	130	75	35	15	8	4
Perimeter in chains per hour	295	175	80	40	27	14
Area, in acres, one hour after start	700	250	60	15	6	2
Minimum suggested requirements for earliest possible attack.						
Men	50	30	12	6	4	2
Tankers	4	3	2	1	—	—
Bulldozers	2	2	1	—	—	—
Expected period, in hours, to bring fire under control	5	2 to 4	1 to 2	½	½	½

N.B. It is not considered necessary here to supply full details of the method of fire danger assessment. However, Extreme danger (upper limit) involves the following conditions: Temperature over 100° F.; Relative humidity below 15°; Fuel moisture content 2-3%; Wind speed in excess 25 m.p.h. in the open and of 5 m.p.h. in a pine plantation stand. Under such conditions fires in cured grasslands may travel at speeds up to 10 m.p.h. and in open eucalypt forest up to 6 m.p.h. Crowning is a common phenomenon under such conditions, and spot fires may commence several miles in advance of a main fire head. It is possible that six such days will be experienced during a 10-year period in many parts of South-Eastern Australia.

Cheney (1971, 1973) has indicated that "Experiments in Australia have shown that there is little difference between the behaviour of eucalypt and pine fires except in the very high to extreme category when spotting becomes an important factor in the spread of eucalypt fires". There is collaborative evidence for this statement (McArthur 1965; Cheney 1968). As a result, Cheney (1975. 1985b) and his co-workers (Loane and Gould 1986; Gould 1987) have continued to base their estimates of head fire rate of spread in radiata pine plantations in particular on predictions from the McArthur. This fire behaviour guideline is deemed to be most relevant to intermediate and middle-aged plantations which have been pruned and thinned exhibiting surface fuel loads of 10-15 t/ha. Wildfire behaviour characteristics in exotic pine plantations have been related to the McArthur (1973) forest fire danger index (Tables 1.3-1.6, although none of the guidelines specify when the onset of crowning can be expected although this is done for the native forest type in a tabulation on the reverse side of the McArthur (1973) meter. Inspite of some shortcomings with the basic relationships embedded in the McArthur (1973) meter. It continues to be widely used in Australian fire control operations and as a research tool in a wide variety of applications (e.g., Shugart and Noble 1981; Gill et al. 1991; Beer and Williams 1995).

The "Forest Fire Behaviour Tables for Western Australia" (Sneeuwjagt and Peet 1985) were designed to predict head fire rate of spread primarily for use in prescribed burning operations, but are considered sufficiently robust enough to be employed for general fire danger rating and wildfire spread prediction; the tables were recently converted to equation form to facilitate the development of a computerized decision support system (Beck 1995a). Five native hardwood and two pine plantation (pinaster or maritime and radiata) fuel types are currently recognized. The "Red Book", as it is known locally, has enjoyed remarkable success as a fire behaviour guide even under severe burning conditions (Burrows 1984a; Underwood et al. 1985), especially in those commercial forest types where most of the experimental fires used to develop the tables were conducted (Burrows and Sneeuwjagt 1991). Most underpredictions have occurred in fuel types which are very susceptible to crowning, and are not well represented in the existing empirical data base (Burrows, Ward and Robinson 1988; McCaw et al. 1988, 1992) although gross over predictions have also been documented (Smith 1992).

The only other fire danger index of note used in Australia in the Fine Fuel Flammability Index (FFFI) devised by Williams and Dexter (1976); the FFFI is used primarily in Victoria and to a lesser extent in New South Wales (e.g., Watts and Bridges 1989). Fire potential in radiata pine plantation fuel complexes has in turn been linked to various FFFI levels (Table 1.7). Various techniques for direct estimation of pine litter moisture content have been developed over the years (e.g., Dexter and Williams 1976; Anon. 1984; Norman 1986; Burrows 1991) in lieu of forest fire danger indexes like the FFFI or the Western Australian Red Book tabular approach (Sneeuwagt and Peet 1985) which are based on weather observations (Williams 1979), including fuel moisture sticks or "hazard rods" comprised of radiata pine dowels (e.g., Foley 1947; Douglas 1957; Hatch 1969; Valentine 1971; Williams 1977a; Evon 1991). A limited number of basic dead fuel moisture studies have also been undertaken (e.g., King and Linton 1963; Williams 1977a; Ashcroft 1967; Byrne 1980; Woodman 1982a; Pook 1993; Pook and Gill 1993).

The Fiji Pine Commission (and now Fiji Pine Limited) utilized a fire danger rating/fire behaviour prediction system developed by McArthur (1971) based on experimental fires and

Table 1.4: Fire behaviour characteristics in various radiata pine plantation fuel complexes under severe fire weather conditions according to Douglas (1964).

Flame Height	Spotting potential	Rate of forward spread (Average bad conditions FFDI = 50)
(a) Juvenile Plantations		
Almost always tree height and often greater.	Low in very young plantings unless slash from previous crop is present; at or near canopy formation much higher.	Depends on fuel quantity; in very young plantations, with little or no auxiliary vegetation, low; following second spring, usually much auxiliary vegetation, and R.O.S. high, probably 200-500 chains per hour.
(b) From canopy formation to age of first thinning.		
Usually tree height or greater. When pruned, the slash usually has not compacted enough to create a large enough air barrier between ground and crown. Fire runs up unpruned stems because of needles caught in "elbow" between branch and trunk.	Moderately high.	Dense fuel type with little chance for wind entry at ground level; of order of 20-80 chains per hour with higher values where crown fires are throwing spots well ahead.
(c) Middle aged stands.		
Ground fires with flames 10-20′ only are possible in pruned stands where slash is not heavy and is well compacted.	Low	20-40 chains per hour.
Crown fires occur frequently in unpruned stands and where thinning slash is high and widespread.	High	60-80 chains per hour.
(d) Old well-thinned stands at or near final crop stage.		
Ground fires are usually maintained with flame heights 10-20′. However, patchy crown fire development occurs where heavy ground fuels or patches of regrowth are able to lift the flame height close enough to the green level.	Moderate, reduced by the filtering effect of the crowns.	Varies quite widely, say 30-70 chains per hour, with higher rates where intermittent crowning occurs, or where stockings are low enough to allow greater ingress of wind.
(e) Slash after clear-felling.		
Fire intensity and flame height vary with quantity and condition of slash. Old slash with needles fallen from limbs burns less fiercely.	Very high with marked tendency for whirlwind development.	High, may exceed 80-120 chains per hour.

Table 1.5: Fire behaviour characteristics and associated suppression implications for *Pinus* spp. plantations exceeding 12 m in height with fine surface and ground fuel loads of 10 t/ha according to McArthur's (1973) forest fire danger classes (from Cheney 1975).

Fire Danger Index	5		10		20		30		40		50	
Fire Danger Classification	Low		Moderate		High		Very High		Very High		Extreme	
Stand condition: Pruned (P) Unpruned (UP)	P	UP	P	UP	P	UP	P	UP	P	UP	P	UP
Rate of spread (m/h)	60	120	120	240	230	460	340	680	450	900	670	1400
Shape factor L:W	2:1	2:1	2.5:1	2.5:1	2.5:1	2.5:1	3:1	3:1	3:1	3:1	3:1	3:1
Perimeter multiplier (xL.)	2.42	2.42	2.30	2.30	2.30	2.30	2.21	2.21	2.21	2.21	2.21	2.21
Rate of perimeter increase (m/h)	145	290	280	550	530	1060	750	1500	1000	2000	1500	3000
Area of fire @ 2h. (ha)	0.6	1.8	1.8	7.2	6.6	26	14.5	48	21	85	47	205
Area of fire @ 6h. (ha)	5	20	16	65	60	240	108	435	190	763	422	1850
Production rate of held fire-line (m/man-hour)	220	80	180	60	125	30	105	20	90	15	70	10
Number of men required for initial attack	2	5	2	12	6	48*	10	100*	15	180*	30	400*

* Initial attack will probably fail; figure calculated to compare difficulty of suppression

Table 1.6: Head fire rate of spread in exotic pine plantations in south-eastern Queensland, Australia, relation to McArthur's (1973) Forest Fire Danger Index (FFDI) and plantation age (from Anon. 1988a).

Rate of Spread Exotic Plantation – Metres Per Hour
Fire Danger Index

Age	2	5	10	15	20	25	30	40	50	60
1	40	100	200	320	420	520	640	840	1060	1260
2	80	200	400	640	840	1050	1280	1680	2120	2520
3	120	300	600	960	1260	1600	1980	2520	3200	3800
4	100	240	500	800	1040	1300	1600	2100	2640	3140
5	80	180	400	640	820	1040	1280	1680	2100	2880
6	60	140	300	480	620	780	960	1260	1600	1880
7	40	100	200	320	420	520	640	840	1060	1260

Table 1.7: Guidelines for interpreting the Fine Fuel Flammability Index (FFFI) in radiata pine plantations and eucalypt forest fuels in Victoria, Australia (after Anon. 1981).

FFFI	Ease of ignition in fine fuels and miscellaneous comments
>20	Fuels non-flammable. Surface and profile fuel moisture contents very high.
15-20	Fuels very difficult to ignite. Burning very difficult to sustain. Surface and profile fuel moisture contents high.
1	Conifer fuels difficult to ignite. Eucalypt fuels very difficult to ignite. Burning difficult to sustain. Surface and profile fuel moisture contents moderately high. Suitable conditions for burning elevated slash with low risk of igniting ground fuels.
7.5-10	Conifer fuels easy to ignite. Eucalypt fuels moderately easy to ignite. Burning is sustained. Surface fuels drying and profile fuel moisture content moderately high. Fires are usually of a moderate to low intensity during the day depending on wind velocity and fuel quantities. Suitable range for carrying out low intensity prescribed burning operations when other parameters, particularly wind, are suitable.
4.5-7.5	Conifer fuels very easy to ignite burning readily sustained. Eucalypt fuels easy to ignite, burning readily sustained. Surface fuels moderately dry and profile fuel moisture content falling. Moderate to high intensity fires can develop.
2.5-4.5	Fuels very easy to ignite. Burning readily sustained during both day and night. Surface fuels dry, profile fuel moisture content low. High intensity fires can develop.
<2.5	Fuels highly susceptible to ignition sources. Burning very readily sustained during both day and night. Surface and profile fuel moisture contents very low. Fires burning under these conditions will be erratic and exhibit extreme fire behaviour. They will be very difficult to control and are likely to be uncontrollable under windy unstable conditions.

Table 1.8: Semi-theoretical comparison of fire behaviour in pruned vs. unpruned exotic pine plantations under <u>high fire danger conditions</u> as patterned after McArthur's (1965) analysis (from Alexander 1992b).

Fire description and characteristics	Stand A (pruned to 5 m)	Stand B (unpruned)
Type of fire	Surface	Crown
Forward spread rate (m/h)	300	600
Fuel consumed (t/ha)	18	28
Head fire intensity (kW/m)	2700	8400
Flame height (m)	2	12
Fire area @ 1 hr (ha)	4.86	19.44
Fire perimeter @ 1 hr (km)	0.83[a]	1.65[a]
Spotting distance (m)	<200[b]	up to 2000[b]

[a] Theoretically, approximately 9% and 45% of the total perimeter would have fire intensities exceeding 2000 kW/m (Catchpole et al. 1992) thereby precluding direct attack by conventional means (Alexander 1992d).

[b] After Douglas (1974b).

documented wildfires in New South Wales slash pine plantations. The emphasis of the decision aids was on prescribed underburning but McArthur (1971, Fig. 8) did provide the basis for predicting forward rates of spread of wildfires up to around 1800 m/h as a function of litter moisture content and wind speed. These guidelines were used up to 1988 when the decision was made to adopt the Canadian Forest Fire Weather Index System (Van Wagner 1987) as a result of a recommendation by New Zealand fire control authorities following the disastrous 1987 fire season in Fiji (Alexander 1989a).

New Zealand adopted the Canadian Forest Fire Weather Index (FWI) System as the basis for a national fire danger rating system (Valentine 1978) beginning in 1980, thereby abandoning the use of a modified fire danger meter originally developed in the southeastern U.S.A. that had been in use for over 30 years. New Zealand has subsequently adopted the overall research philosphy of Canada's forest fire danger rating system (Alexander 1991c). A forest fire danger classification scheme has recently been drawn up (Alexander 1994a, 1994b; Fogarty 1996) based in part on the FWI System and Canadian Forest Fire Behavior Prediction System (Forestry Canada Fire Danger Group 1992), both major subsystems of the Canadian Forest Fire Danger Rating System (Stocks et al. 1989). Early indications are that it does an acceptable job of assessing fire potential in exotic pine plantations (Pearce and Alexander 1994; Fogarty 1994).

1.4 Crown Fire Prediction: A Critical Knowledge Gap

In Australia at least, which has had a relatively active forest and rural fire behaviour research programme for many decades now[3], the greatest deficiency in the systems developed for assessing fire danger or predicting fire behaviour in exotic pine plantations is the inability to specify the point at which certain combinations of fuel, weather and topographic conditions lead to the formation of crown fires, even though the projected forward spread rates would logically imply crowning. And yet, given that a good portion of commercial exotic pine plantations are to close human habitation, continual monitoring and evaluating the probability of a crown fire would obviously be an asset. This kind of information is also needed in order to minimize the risk to firefighter safety and thereby avert fatality situations such as occurred on the 1958 Wandilo Fire in South Australia (McArthur et al. 1966). Presumably, this knowledge is required as well for initial attack planning and dispatching decision in order to keep losses to a minimum because after the onset of crowning, a fire typically doubles or even triples its forward spread rate and for a given period of time, the area burned will be at least 4-9 times greater (Alexander 1985a) than had it remained as a surface fire (Table 1.8); this fact has important implications for certain silvicultural practices such as pruning and thinning regimes since young, unpruned

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[3] A limited amount of research on exotic pine plantation fire behaviour was carried out in New Zealand (Alexander 1991c) and Fiji (Heuch 1990) during the early and mid 1970s. Presently, Fiji does not have any fire research capability. New Zealand only recently resumed its efforts following a 15-year hiatus (Alexander 1992-93). In April 1992, I began a one-year secondment as a Visiting Fire Research Scientist at the New Zealand Forest Research Institute (NZFRI) in Rotorua, under the terms of an international assignment agreement between the Government of Canada and NZFRI. This opportunity enabled me to more thoroughly complete my indoctrination concerning Australasian exotic pine plantation fire and forest management issues whilst participating in a whole host of related fire research and technology transfer activities (e.g., Alexander 1992d, 1993, 1994a, 1994b; Alexander and Pearce 1992a, 1992b, 1993; Alexander et al. 1993; NRFA and NZFRI 1993; Pearce and Alexander 1994, 1995a, 1995b; Pearce et al. 1994, 1995). As a result of my efforts, I was made the first Honorary Member of the Forest and Rural Fire Association of New Zealand (FRFANZ) in 1993.

and unthinned exotic pine plantations are especially prone to crowning (McArthur 1965; Cheney 1975). The transition from a surface fire to a crown fire is deemed to be critical from a fire control perspective, because crowning generally represents a level of fire behaviour that normally precludes any direction suppression action by most conventional means, at least at the head of the fire. Furthermore, crowning increases the probability of breaching firebreaks and other barriers to surface burning by direct flame contact, radiative heat transfer and/or spotting.

Being able to predict the likelihood of a crown fire is also needed for gauging the effectiveness of fuel management activities or the implications of proposed changes in silvicultural practices (e.g., to dispense with pruning or to go to wider initial spacings). For example, Douglas (1964) first advanced the concept, based on wildfire case histories, that old well-thinned plantation stands can be made, or become, "crown-fire-free" in all, or almost all, fire weather situations. However, Cheney (1991b) has recently pointed out that several forest authorities in Australia are currently endeavouring to create areas in commercial pine plantations designated as crown-fire-free zones without any idea of how effective they would be under a given set of burning conditions, a concern that was also raised at the 11th meeting of the Australian Forestry Council Research Working Group (RWG) No. 6-Fire Management Research held at Victor Harbour, South Australia, July 3-4, 1990.

Australian forest fire researchers and fire managers have been actively engaged in investigating exotic pine plantation fire behaviour off and on for a couple of decades now. Considerable time and effort has been expended in conducting experimental fires of low to moderate intensity for the purposes of formulating models or guides for use in understory fuel reduction burning within plantations. Coupled with this activity has been the preparation of wildfire case studies where crowning was frequently involved, as opportunities presented themselves. The lack of work on identifying the limiting conditions for crown fire development in exotic pine plantations is seen as simply a reflection of the general reluctance of forest owners to provide sites or "sacrifice areas" (Underwood 1985) for conducting experimental fires over a broad range of fire behaviour that would include high-intensity crown fires. This is in contrast to the high-intensity experimental fires that have been undertaken in both native forests, shrublands and grasslands (McArthur 1966c; 1967a; Burrows et al. 1991; McCaw 1995; Cheney et al. 1992, 1993; Marsden-Smedley 1993; Burrows 1994; Marsden-Smedley and Catchpole 1995). Nor is this situation likely to be easily remedied in the foreseeable future.

Despite significant progress globally in understanding and predicting forest fire behaviour in general over the past 70 years, the development of a purely physical model that would predict both the initiation and spread of crown fires remains continuing research challenge. Thus, a universally accepted model that could be utilized in Australasian exotic pine plantation fuel types simply does not exist. Furthermore, the applicability of Van Wagner's (1977a, 1989, 1993) models of crown fire initiation and spread to Australian exotic pine plantations has not been rigorously evaluated; in fact some evidence exists to suggest that the crown fire initiation model may not be valid, at least under certain circumstances (e.g., Smith 1992). Adoption of an overseas system for crown fire prediction (e.g., Forestry Canada Fire Danger Group 1992) would require extensive field verification and undoubtedly changes in current management practices (i.e., fire weather data collection and fire danger rating calculations) thereby necessitating the need for a major program of technology transfer and training.

1.5 Thesis Objective, Approach to the Problem and Research Philosophy

There are three aspects to the problem of predicting the likelihood of a crown fire occurring, its intensity and the general class or type: (*i*) initiation of crown combustion, (*ii*) continued propagation or propensity for flame movement through the crown fuel layer and the (*iii*) final spread rate and intensity after crowning. The central focus of this thesis is on the development of a quantitative model that can be used for determining the threshold conditions for the initiation of crown fires in exotic pine plantations of Australasia on the basis of fire, fuel, weather and topographic characteristics. The geographical emphasis of the work is Australia, and to lesser extent New Zealand and Fiji.

Weber's (1990) suggestion that for many specific problems in fire behaviour research "... the most effective method of solution is a combination of mathematical modelling, physical insight and relevant experiments" has been adopted for this investigation. This acknowledges the fact that fire behaviour model development is both an art form and a science (Van Wagner 1985). As Thomas (1971) stated many years ago, "... a judicious mixture of theory and empiricism allows idealized model experiments to represent the main features governing..." free-burning wildland fires. The author's background and experience in fire suppression with the USDA Forest Service (Alexander 1974) and fire research with the Canadian Forest Service (Alexander and Quintilio 1990) in observing wildfires, operational prescribed fires and experimental fires was considered as asset in this overall undertaking.

During the first year's candidacy, the author travelled and met with fire managers and fire researchers in all of the Australian states as well as Fiji and New Zealand beginning in the last quarter of 1989. The purpose of these field reconnaissances was two-fold: (*i*) to obtain a first hand feel for the variation in fuel complexes and the associated forest management practices within the region and (*ii*) to establish a network of contacts. All relevant past research dealing with exotic pine plantations was thoroughly reviewed. In this regard, the bibliography compiled by Gill et al. (1991) was particularily useful in the early stages of the research process. Due consideration was given to both enhancing and extending the existing knowledge base on exotic pine plantation fire behaviour in Australasia. Various short-term studies were initiated in order to fill some of the more glaring information and data gaps, many of which will be reported on separately.

While on professional development/educational leave from the Canadian Forest Service to pursue a Ph.D. degree at the Australian National University (ANU), the author occupied a Visiting Fire Researcher position in the Bushfire Research Unit of the Commonwealth Scientific and Industrial Research Organisation's (CSIRO) Division of Forestry and Forest Products laboratory in Canberra, Australian Capital Territory (ACT). This enabled the author to participate in and initiate fire behavior field studies that provided the inspiration for many of the elements reported on in this thesis. This included participation in the CSIRO Bushfire Research Unit's experimental burning project in regrowth eucalypt forests near Eden, New South Wales (Cheney et al. 1992; Gould 1993; Gould et al. 1997) in April 1990 which provided valuable in initiating a study of convection column temperatures above low- to moderate-intensity surface fires in a ponderosa pine (*Pinus ponderosa*) plantation in the Kowen Forest, ACT, in cooperation with the Unit and ACT Forests during 1990-92 (Alexander 1991d). A second experimental burning project was undertaken in 1990-91 in cooperation with the Western

Australia Department of Conservation and Land Management (McCaw 1990)[4]. This study was carried out in maritime pine plantation trial plots located in the Iffley Block of southwestern Western Australia and was specifically designed to examine the factors influencing the initiation and spread of crown fires under dry summertime conditions (Alexander, McCaw, Smith and Neal 1991). The author was also unfortunate enough to be able to undertake post-mortem investigations of three major exotic pine plantation wildfires that took place in the Western Australia (January 1990), Queensland (September 1991 and Victoria (November 1991) during the author's sojourn in Australia. While these efforts produced quantitative data and provided opportunities for gaining additional insights into mechanisms involved in the development and behaviour of crown fires, it became abundantly evident from the review of literature on crown fires (Alexander, Stocks, Lawson and McAlpine 1991) that there was not an adequate, workable theoretical framework by which to analyse field observations and data. Thus, the emphasis of the thesis centered on the fundamental structure of a model for predicting the onset of crowning in the idealized forest fuel complex afforded by exotic pine plantations.

The essential qualities of what constitutes a Ph.D. thesis were explored in this author's mid-term review of progress required of Ph.D. candidates by ANU (Alexander 1991d, p. 1-2). This is a thesis in the forestry and wildland fire sciences rather than mathematics, physics or engineering. Therefore, due consideration has been given to developing a model(s) whose technical basis can readily be comprehended and applied by most experienced and knowledgeable foresters or plantation fire managers. In this sense, a deliberate effort has been made to appropriately blend the human side of forest resource management with the quantitative models exploited by computer technology (Garland 1988) while at the same time carrying out the necessary fundamental fire behaviour research that forms the basis for the operational products that are readily desired by field practitioners (Cohen 1990). In this regard, Williams and Rothermel's (1992) comments are very apropos:

> *The best chance for success in fire behavior prediction requires a mix of fire experience with analytical modeling methods. But in situations where conditions are beyond the limits or outside the assumptions of the models, fire predictions must rely even more on intuitive judgements. Such judgements could be more easily made if managers know general patterns of fire behavior through a full range of burning conditions.*

Thus, the ultimate aim of the research project associated with this thesis was not the construction of a completely physically-based model for predicting all aspects of crown fire behaviour *per se*, but rather to develop simple but objective criteria that can be used in assessing the potential for the onset and sustain spread of crown fires in order to design better fire protection strategies and/or evaluate the impacts of different silvicultural regimes, as opposed to "near" real-time fire prediction (Table 1.9).

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[4] A film on this study entitled **Videotape Documentation of the High-Intensity Fire Behaviour Experiments in *Pinus pinaster*, Iffley Block, Western Australia, March 1991** (PAL, 2 hours & 5 minutes) was completed and copies distributed to those organizations that contributed financially to the rental costs associated with the helicopter used to film the experimental fires and thereby document certain fire behaviour characteristics. A copy of the video has also been deposited with the National Film Lending Collection at the National Library of Australia, Canberra, Australian Capital Territory.

Table 1.9: The scope of quantitative wildland fire behaviour prediction (adapted from Rothermel 1974, 1980).

Fire situation	Intended use	Resolution		Relative usefulness/value	Ease of prediction accuracy	Impact of inaccurate prediction
		Time frame	Area			
Possible	Training	Long-term	N/A	Moderate	Extremely to Very Easy	Minor or minimal
	Long-range planning (e.g., preparedness system development)	Yearly/Seasonal	State/Island Province Territory	Good	Easy to Moderately Easy	Significant
Potential	Short-term planning (e.g., daily fire assessment)	Daily/Weekly	Forest/ District	Very good	Moderately Difficult to Difficult	Serious
Actual	Near-real-time (e.g., automated dispatch, project fires, escaped fire situation analysis)	Minutes to hours	Stand or site-specific	Excellent	Very to Extremely Difficult	Critical

1.6 Organization of the Thesis

Chapter 2, constitutes a unique state-of-the-art summary of existing knowledge, theories and models concerning crown fire dynamics in conifer forests; to a certain extent this is, with respect to the Australasian scene, accomplished in Sections 1.3 and 1.4 of Chapter 1. The value of this document has been the critique of the strengths and weaknesses of previous observations and studies in guiding the specific approach used for model development, testing and application to be reported on in the subsequent chapter.

In Chapter 3, a model for predicting the onset or initiation of crowning founded on simple physical reasoning and based on existing or newly developed relationships and data reported in the literature is systematically outlined. Model predictions are compared against available data from several experimental and operational prescribed fires as well as an intensively studied wildfire. Finally, a synopsis of the major findings of this thesis with respect to its value as a significant and original contribution to knowledge or application of knowledge is given. Particular attention has been paid to thoroughly documenting all relevant data and related information in the text of this chapter or as an appendix. Thus, any investigator should presumably be able to reach the same results and conclusions as the author (a basic tenet of the scientific method).

In the concluding chapter, suggestions of how the research results reported on here might be "operationalized" in fire and forest management activities or used to support other fire research efforts is made and a list of outstanding research issues that should be addressed in order to the enhance model's performance are outlined. Chapter 4 closes with some thoughts on the more general applicability of the research reported on in this thesis.

1.7 Nomenclature and Units of Measure

The symbols and abbreviations used in this thesis (Table 1.10) are a blend of simplicity and the most commonly accepted nomenclature and terminology as reviewed in numerous sources. Original symbols have been retained where ever possible. All fuel moisture contents cited in this thesis are expressed on an oven-dry weight basis. The International System (SI) of units is followed where possible.

Note that prior to Australia's adoption of SI unit practice in the early 70s, fuel load and fuel consumption data was sometimes expressed in tons (long) per acre rather than in pounds per square foot or pounds per acre where a "long " ton is 2240 pounds as opposed to a "short" ton of 2000 pounds (McArthur and Cheney 1972) which is more commonly used, for example, in the U.S.A. and to a lesser extent in Canada, especially since the mid 70s (Van Wagner 1978). This fact should be borne in mind when examining or using fuels data contained in older Australasian fire research and fire management literature (e.g., McArthur 1965, 1971; McArthur and Cheney 1966; McArthur et al. 1966; Van Loon 1967; Cheney 1968, 1973; Gilmour and Cheney 1968; Packham 1970; Peet and McCormick 1971; Van Loon and Love 1973; Just 1972). The multiplication factor for converting tons (long)/acre to tonnes/hectare is 2.5107 rather than 2.2417 which is used for the conversion of tons (short)/acre to tonnes hectare (Van Wagner 1978).

Table 1.10a: List of symbols, quantities and units.

Symbol or abbreviation	Quantity or definition	Units or value
a	Coefficient term in Equation 2.15	1.0
$\mathbf{A}$	Coefficient term in Equations 3.28 & 3.45	dimensionless
$\boldsymbol{A}$	Flame angle[a]	degrees (°)
$\boldsymbol{A_p}$	Fire plume angle[a]	degrees (°)
$\boldsymbol{A_T}$	Flame tilt angle[b]	degrees (°)
b	Coefficient term in Equation 2.16	0.001
$\mathbf{b}$	Slope associated with $\Delta T.Z$ (*see* Table 3.3)	dimensionless
$\boldsymbol{b}$	Buoyancy term (*see* Equations 3.6, 3.7 & 3.10)	0.025574
$\mathbf{B}$	Coefficient term in Equations 3.28 & 3.45	dimensionless
BA	Stand basal area	m^2/ha
$\mathbf{c}$	Coefficient term in Equation 3.9	variable
$\boldsymbol{c_p}$	Specific heat of air at constant pressure (= 1003.9)	J/kg·K
$\mathbf{C}$	Proportionality constant in Equation 3.5	dimensionless
$\boldsymbol{C}$	Criterion for initial crown combustion (*see* Equations 2.6 & 2.8)	dimensionless
CD	Crown depth	m
$\boldsymbol{C_R}$	Combustion rate	kW/m^2
$\mathbf{d}$	Fuel particle diameter	cm
$\boldsymbol{d}$	Crown bulk density	kg/m^3
DF	Drought Factor (as per McArthur 1973)	10.0 (max.)
$\boldsymbol{D}$	Horizontal flame depth	m
DBHOB	Diameter-at-breast-height outside bark	cm
FFDI	Forest Fire Danger Index (McArthur 1973)	dimensionless
$\boldsymbol{g}$	Acceleration due to gravity (= 9.8)	m/sec/sec
$\boldsymbol{h}$	Heat of ignition	kJ/kg
$\boldsymbol{h_s}$	Crown scorch height	m
$\boldsymbol{h_F}$	Flame height	m
$\boldsymbol{H}$	Low heat of combustion	kJ/kg
HFC	Height of fuel consumption	m
HSF	Height to scorched foliage	m
$\boldsymbol{I}$	Intensity of line heat source	kW/m^2
$\boldsymbol{I_B}$	Byram's fire intensity (*see* Equation 2.1)	kW/m
$\boldsymbol{I_o}$	Critical surface fire intensity for initial crown combustion	kW/m
$\boldsymbol{I_s}$	Surface fire intensity (as per Byram 1959a)	kW/m
$\boldsymbol{k}$	Proportionality constant in Equations 3.16 & 3.20	dimensionless
$\boldsymbol{k_1}$	Proportionality constant in Equations 3.17, 3.21, 3.26 & 3.27	dimensionless
$\boldsymbol{k_2}$	Proportionality constant in Equations 3.29 & 3.34	dimensionless
$\boldsymbol{k_3}$	Proportionality constant in Equations 3.32 & 3.35	dimensionless
$\boldsymbol{K}$	Proportionality constant in Equation 3.10	dimensionless
KBDI	Keetch-Byram Drought Index	0.01 in. *or* mm
$\boldsymbol{L}$	Flame length	m
$\mathbf{m}$	Fuel load	kg/m^2
$\mathbf{m_F}$	Available crown fuel load	kg/m^2

[a] As measured between the flame front or fire plume and the unburned fuelbed.

[b] As measured between the flame front and the vertical.

Table 1.10b: concluded.

Symbol or abbreviation	Quantity or variable definition	Units or value
m	Crown foliar moisture content	%
MSDI	Mount Soil Dryness Index	mm
N	Time since last rain (McArthur 1973)	days
N_c	Byram's convection number	dimensionless
p	Power term in Equation 3.9	variable
P	Amount of last rain or precipitation	mm
P_f	Power of the fire	kW/m^2
P_w	Power of the wind	kW/m^2
r	Rate of fire spread in Equations 2.1 & 3.1	m/sec
R	Head fire rate of spread	m/h
R_o	Critical minimum spread for active crown fire	m/h
R_θ	Head fire rate of spread on a slope	m/h
RH	Relative humidity	%
S	Maximum spotting distance (as per McArthur 1973)	km
S_o	Critical mass flow rate for solid crown flame	kg/m^2-h
SH	Stand height	m
t_i	Time to ignition	sec
t_d	Duration of exposure	sec *or* min
t_r	Flame front residence time	sec
t_R	Particle residence time	sec
T_a	Ambient air temperature	°C
T_c	Convection column temperature	°C
T_{ic}	Initial crown temperature	°C
T_L	Lethal temperature for crown foliage	°C
T_o	Ambient air temperature	°K
ΔT	Temperature increase above ambient conditions	°C
u	Wind speed	m/sec
U	Wind speed at height Z	km/h
U_s	Effective within stand wind speed	km/h
$U_{1.2}$	Wind speed measured at a height of 1.2 m above ground	km/h
U_{10}	International standard 10-m open wind speed	km/h
v	Wind speed at height Z	m/sec
TH	Tree height	m
W	Total available fuel load (as per McArthur 1973)	t/ha
w	Fuel weight consumed per unit area	kg/m^2
W_F	Foliage dry weight	kg
z	Live crown base height	m
z_θ	Effective live crown base height on a slope	m
Z	Height above a fire	m
Z	Height above ground	m
σ	Surface-area-to-volume ratio	cm^2/cm^3
θ	Slope steepness	degrees (°)
ρ	Air density at height Z	kg/m^3

CHAPTER 2:

CROWN FIRE BEHAVIOUR IN CONIFER FORESTS: A SYNTHESIS OF EXISTING KNOWLEDGE[1]

2.1 Basic Descriptors of Wildland Fire Behaviour

Fire behaviour is defined as "The manner in which fuel ignites, flame develops, and fire spreads and exhibits other related phenomena as determined by the interaction of fuels, weather, and topography" (*cf.* Merrill and Alexander 1987). The most fundamental principle in understanding the dynamics of crown fire initiation and spread is Byram's (1959a) concept of a free-burning fire's intensity. He defined fire intensity as the rate of heat energy release per unit time per unit length of fire front, regardless of its depth or width. In the United States this definition of fire intensity is most commonly referred to as "Byram's fireline intensity". In Canada the preferred term is "frontal fire intensity" (Alexander 1982; Merrill and Alexander 1987); one of the reasons for making this distinction is to differentiate between line-fire intensity and Rothermel's (1972) reaction intensity or the area-fire intensity which is simply the product of frontal fire intensity divided by the flame depth (Alexander 1982).

Byram's (1959a) fire intensity cannot be measured directly *per se*, but rather it must be computed by the following formula:

$$I_B = Hwr \tag{2.1}$$

where, in compatible SI units (Van Wagner 1978), I_B is Byram's fire intensity expressed in kilowatts per metre (kW/m), H is the net low heat of combustion in kilojoules per kilogram (kJ/kg), w is the quantity of fuel consumed during the active combustion phase in kilograms per square metre (kg/m^2), and r is the linear rate of fire spread in metres per second (m/sec). For an in-depth discussion on the various attributes of fire intensity, one is encouraged to consult Alexander (1982). Fire intensity can vary more than 1000-fold, or from about 10 kW/m, considered the threshold for self-sustaining surface fire spread, to at least 100 000 kW/m for major conflagrations (Byram 1959a). For many practical purposes, H can be considered a constant. Thus, most of the potential variation in I_B is largely due to r and, to a lesser extent, w.

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[1] This chapter is based to a large extent on information distilled from review documents prepared during the author's Ph.D. candidacy as well as a previously published review paper (Alexander 1988) with the emphasis being placed on practical concepts. The first one, entitled **Crown Fire Initiation and Spread: Experience in Canadian Forests and Relevance to Australian Exotic Pine Plantations**, constituted an invited presentation made at the Plantation Fire Management: Opportunities for Research Workshop held in conjunction with the 11th meeting of the Australian Forestry Council's Research Working Group (RWG) No. 6 - Fire Management Research, July 3-4, 1990, Victor Harbour, South Australia (Alexander 1990b). The second involved a chapter on the physical aspects of crown fires in conifer forests co-authored with several of the author's colleagues in the Canadian Forest Service (Alexander, Stocks, Lawson and McAlpine 1991). Unfortunately the book was never published largely because of the unfavourable reviews of the book as a whole and the enormous task required for a re-write. However, one of the reviewers of the proposed chapter on crown fire initiation and spread remarked that "If the rest of the book was at this level, it would be a significant contribution".

Fire intensity is directly related to flame size. An increase in flame size as fire intensity (Fig. 2.1) increases can be attributed to the simply fact that additional fuel becomes available for combustion (McArthur 1967a). In many eucalypt forest types, the bark on the trees provides a "ladder" (Fig. 2.2) to effectively lift the surface flames into the crown fuel layer (Wilson 1992a, 1992b). Although elevated fuel in shrub and crown fuel layers generally do not make up a large proportion of the total available fuel load, they do have a dramatic effect on extending the vertical structure of the flame front (Cheney et al. 1992; Wilson 1992a, 1992b, 1993; Wouters 1993; Buckley 1994).

Several authors, including Byram (1959a) have empirically related fire intensity to flame length or height in a variety of artificial fuelbeds and natural fuel complexes (e.g., Albini 1981a; Johnson 1982; Burrows 1984a, 1994; Tassios and Packham 1984; Simard et al. 1989; Weise and Biging 1996); certain derived relationships have purposely not been included in Figure 2.1 in order to reduce the amount of clutter (e.g., Botelho et al. 1994 for maritime pine (*Pinus pinaster*) stands and Burrows 1994, Equations 7-7 and 7-8, based on small-scale laboratory fires in mixed *Eucalyptus* spp. litter fuelbeds). Flame length is considered to represent the distance between the tip of the flame and the midpoint of the flame depth, whereas flame height refers to the average maximum extension of the flames (Merrill and Alexander 1987). Wind and/or slope causes flames to incline from the vertical and to increase in length; flame length and height are essentially the same in the absence of wind and/or slope. A schematic diagram illustrating these and other aspects of flame size geometry is presented in Figure 2.3; other versions do exist (e.g., Nelson 1980, 1986; Rothermel and Deeming 1980; Cheney 1981; Ryan 1981; Burrows 1984b). Flame depth is the width of the zone within which continuous flaming occurs behind the leading edge of the fire front. Flame angle refers to the angle formed between the flame at the fire front and the ground surface whereas the flame tilt angle is taken from the vertical.

A considerable degree of variation in these relationships shown in Figure 2.1, which are deemed to be applicable only to surface fires, evidently exists as a result of the experimental range in fire intensity sampled, the manner in which the data was collected (e.g., visual estimates of flame size versus photographic documentation), any assumptions made concerning the calculation of I_B by Equation 2.1 (e.g., the way in which w are derived and/or the value of H used) and how an investigator interprets the measurement of flame length because there is in reality no recognized international standard. Byram's (1959a, Equation 3.4) flame length - I_B relation is the most widely known and as a result is widely applied for deriving estimates of intensity for surface fires (e.g., McNab 1977). The SI unit version of his original equation is as follows (from Alexander 1982)[2]:

$$L = 0.0775\, I_B^{0.46} \tag{2.2}$$

where L is the flame length (m). Nelson and Adkins' (1986) L-I_B relation is gradually becoming used for the same purpose (e.g., Finney and Martin 1993). Their equation is as follows:

$$L = 0.0475\, I_B^{0.493} \tag{2.3}$$

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[2] Note that the conversion of Byram's (1959a) original equation from English to SI units has been incorrectly done by several authors (e.g., Wilson 1980; Chandler et al. 1983; Barney et al. 1984; Windisch 1987).

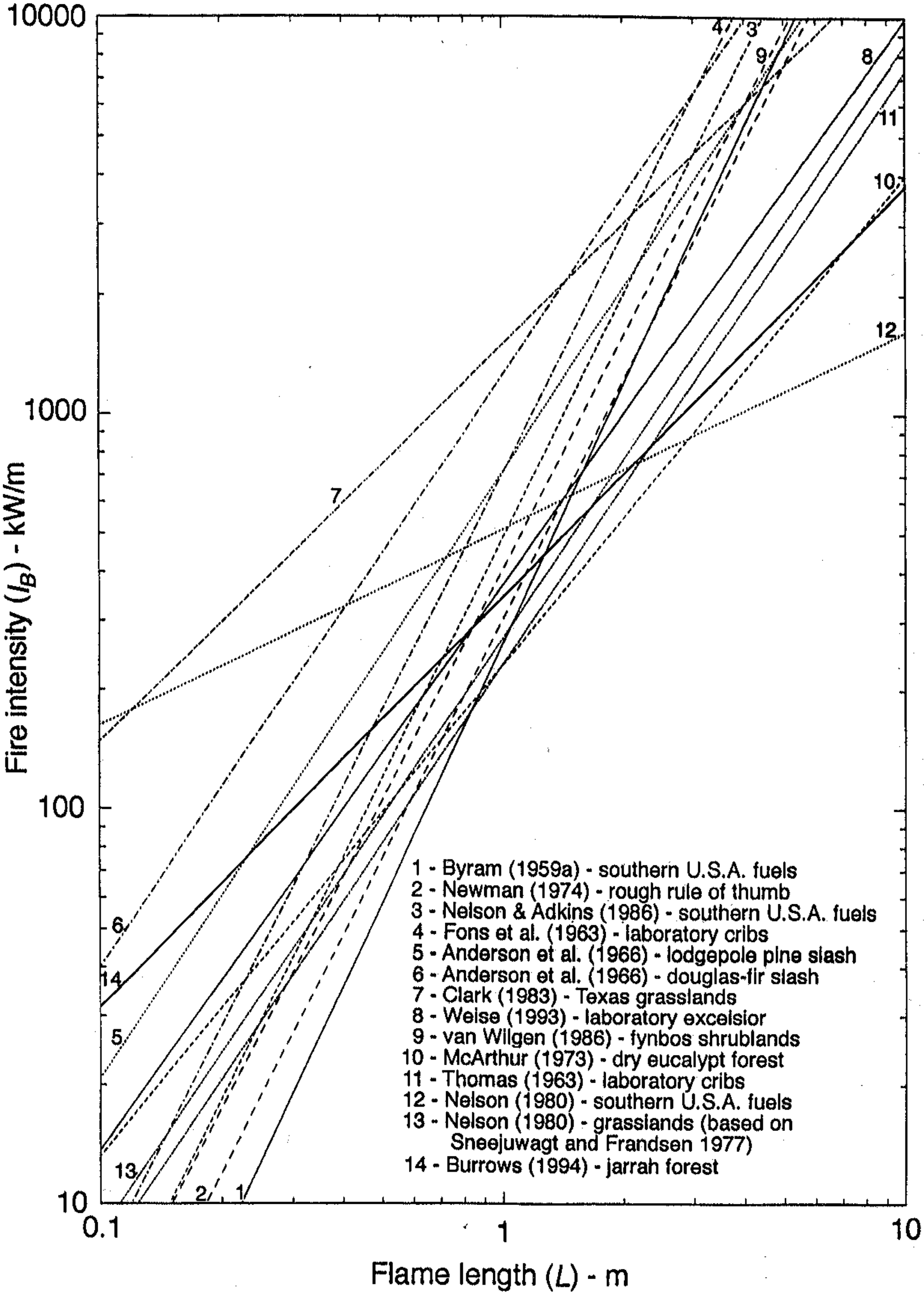

Figure 2.1: Summary of the empirical surface fire intensity - flame size relationships reported in the literature.

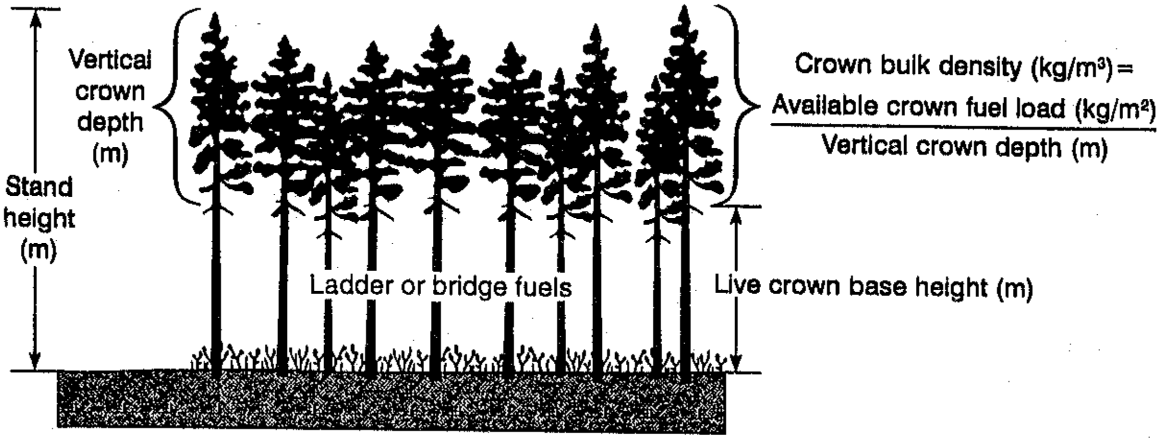

Figure 2.2: Two of the three crown fuel properties, namely live crown base height and crown bulk density, as identified in Van Wagner's (1977a) theory for the start and spread of crown fires in coniferous forest stands.

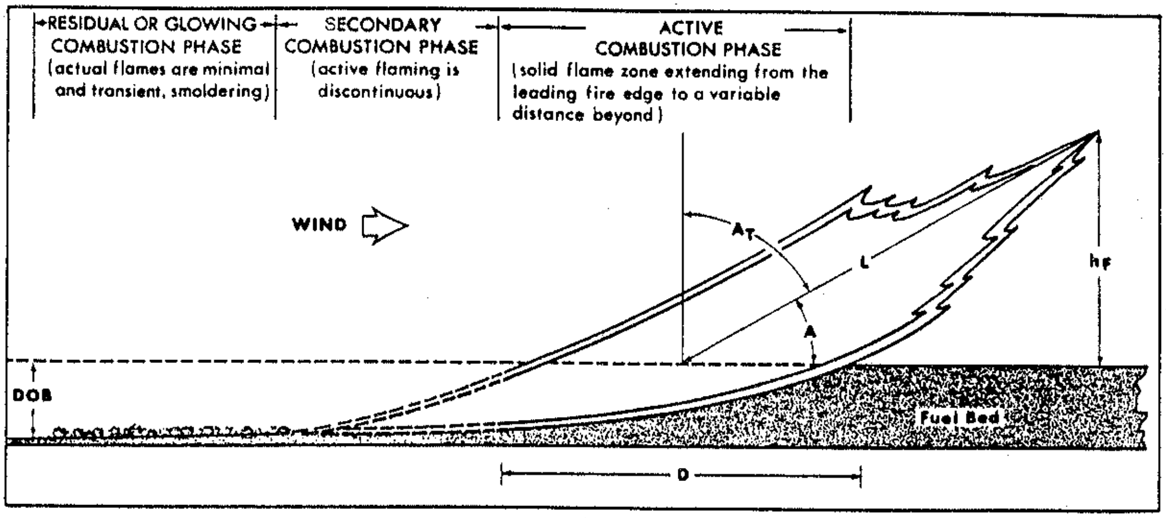

Figure 2.3: Crown section of stylized surface head fire on level terrain illustrating the energy or heat-release stages during and following the passage of the flame front, flame length (L), flame height (h_f), flame angle (A), flame tilt angle (A_T) and flame depth (D) (from Alexander 1982).

Nelson and Adkins (1986, Equation 6) related I_B to flame height and wind speed. The transposition of their equation gives the following result:

$$h_F = \frac{I_B}{385\ u} \tag{2.4}$$

where h_F is flame height (m) and u is wind speed (m/sec). Dr. R.M. Nelson, Jr. derived a relationship between I_B versus h_F and rate of fire spread (*see* Simard et al. 1989, Equation 6), which when transposed provides an alternate means of estimating h_F :

$$h_F = \frac{I_B - 47}{15\ 444\ r} \tag{2.5}$$

where r is rate of fire spread (m/sec) as defined earlier in Equation 2.1.

The differences noticeable in Figure 2.1 may also be attributed to fuelbed structure alluded to earlier on. In this regard, Methven (1973) made the following observations concerning two experimental fires carried out at the Petawawa Forest Experiment Station, Ontario, Canada, in a red pine (*Pinus resinosa*) and eastern white pine (*P. strobus*) stand exhibiting nearly identical I_B values (i.e., 76 kW/m versus 78 kW/m):

> *The calculated intensities, however, reflect only the average fire conditions and in fact the first fire resulted in some overstory damage due to localized but fairly widespread peaks of intensity. These were due to a clumped distribution of balsam fir saplings which resulted in live branches close to the ground and a foliage bulk density great enough to carry fire upwards. Wherever these concentrations of fire occurred, therefore, flame heights were raised from less than 30 cm to over 3 meters with a much increased energy output per unit ground area and scorching of overstory crowns. The increase in intensity* [i.e., flame size] *was not so much a product of the increased fuel loading which amounted to only 0.04 gm* cm^{-2}*, but to the rate of combustion of this fuel, which, due to its arrangement or bulk density, burned much more rapidly than an equivalent quantity of ground fuel.*

Methven (1973) noted that the higher fuel consumption of first fire (0.589 kg/m^2 versus 0.465 kg/m^2) was balanced by the faster rate of spread of the second fire as a result of lower relative humidity, drier litter fuels and greater in-stand wind speed.

Cheney (1990a) has noted that "... flame characteristics associated with a specific fire intensity are only applicable to fuel types with the same fuel structure characteristics". He illustrated the significance of this fact by contrasting the physical characteristics of a forest fire with a grass fire in Australia, each exhibiting a head fire intensity of 7500 kW/m:

> *A grass fire ... will travel at 5 km* h^{-1} *in an average fuel of around 3 t* ha^{-1} *and will have flame length of up to 4 m. This fire can be fought directly and there is a 90 percent probability that the head fire will be stopped by a 5 m wide fire fuelbreak ...*

> *A fire ... in a dry eucalypt forest has very different characteristics. Burning in a 15 t ha^{-1} forest fuel, the fire will travel at around 1 km h^{-1} and have flames which extend up through the crowns to a height of perhaps 10 m above the tree tops and more than 30 m above the ground from the surface fire. The fire will be throwing firebrands up to 1 km ahead of the fire and have extensive short-distance spotting and will be unstoppable by any means unless there is a change in some factor influencing fire behaviour.*

Cheney (1990a) concluded that "Bryam's fireline intensity is useful to quantify certain flame characteristics ... but should not be used to compare fires in fuel types which are structurally very different". Thus, suggestions such as Hirsch's (1996b), that Wilson's (1988b) relationship between fire intensity and the probability of grass fire breaching a firebreak of a given width be applied to black spruce (*Picea mariana*) stands of western and northern Canada represented by Fuel Type C-2 in the Canadian Forest Fire Behavior Prediction System (Forestry Canada Fire Danger Group 1992; De Groot 1993) cannot be readily justified.

2.2 The Nature and Characteristics of Crown Fires

As eluded to earlier on, calculated wildland fire intensities can easily range over at least four orders of magnitude, from less than 100 kW/m to more than 100 000 kW/m (Van Wagner 1983; Cheney 1991c). Incomplete crowning or partial consumption of the ladder and crown fuel layers gradually begins to occur at fire intensities of 2000-4000 kW/m (Byram 1959a; Kiil 1976; Burrows, Ward and Robinson 1988) and lethal crown scorch is virtually complete, although this obviously varies according to stand structure (Hough and Albini 1978). Depending on the forest cover or fuel type characteristics, fire intensities in excess of 4000 kW/m are generally associated with fully developed crown fires (Alexander, Stocks, Lawson and McAlpine 1991).

Crowning forest fires typically advance as a single flame front, with intensities up to at least 10 000 kW/m. Wildfires spreading at fire intensities of around 30 000 kW/m or greater represent a level of severity exhibiting various aspects of extreme fire behaviour, including long-range spotting up to distances of a kilometre or more (DeCoste et al. 1968; Sando and Haines 1972), which depending on their density and the size of the fire, could in turn result in the formation of pseudo-flame fronts ahead of the main fire perimeter (McArthur 1968; Wade and Ward 1973). In rare instances, spotting up to nearly 20 km may occur (Anderson 1968a) under certain environmental conditions and perhaps even further in some forest types (Luke and McArthur 1978). In these instances, the derived spread rates result in extraordinarily high fire intensity values when computed using Equation 2.1 (e.g., Kiil and Grigel 1969).

Rate of spread contributes the greatest range to the final fire intensity, varying for forest fires from perhaps 1.5 to 14 000 m/h (Keeves and Douglas 1983; Wade 1983), while fuel consumption varies about 10-fold from 1 to 10 kg/m^2 (Van Wagner 1983), and from 2 to 20 kg/m^2, for example, in the U.S.A. Pacific Northwest (Fahnestock and Agee 1983). To become large, a fire must spread quickly at high intensity, killing the trees (Van Wagner 1983). Surface fires spreading beneath the canopies of most conifer forests seldom exceed ≈ 360 m/h without the onset of crowning (Kiil 1976). Once the initial crowning takes place, this results in the flame defoliation of the overstory canopy which allows the ambient winds to penetrate into the forest stand, increasing the surface fire intensity and thereby reinforcing or sustaining the crown fire spread; Van Wagner (1973a) considered continuous crowning begins to take place when forward spread rates reach 900-1800 m/h, depending on the fuel type. It is the increased spread rate after crowning that results in greatly increased fire intensity and area burned (Alexander 1985a), whereas the additional fuel consumed due to the crown involvement is relatively small (Wendell 1960; Methven 1973). As Van Wagner and Methven (1978) note, "Crown fires may consume the foliage and perhaps the fine twigs, but this is only a few percent of total live biomass". The amount of crown foliage and fine twigs typically consumed in crown fires may range from 0.5 to 1.0 kg/m^2, whereas total fuel consumption typically ranges from 2 to 3 kg/m^2 (*cf.* Forestry Canada Fire Danger Group 1992) -- i.e., an increase in fuel consumption of one-quarter to one-third as a result of crowning. Spread rates may increase two to six times once a fire crowns (McArthur 1965; Van Wagner 1965a; Rothermel 1983; Rothermel and Mutch 1986; Burrows, Ward and Robinson 1988). Maximum sustained spread rates of crown fires in conifer forests are generally on the order of 5000 m/h (Anon. 1958; Byram 1959b; Chandler et al. 1963) although higher velocities have been reported (Johansen and Cooper 1965; Kiil and Grigel 1969; Anderson 1983; Keeves and Douglas 1983).

Surprising as it may seem, in crowning forest fires the crown fuel layer is actually subjected to being immersed in flames for a shorter period of time that the surface fuels. Surface fires in conifer forests with moderately deep forest floor layers typically produce flame front residence times (Fons et al. 1962) of 25 seconds to perhaps one minute (McArthur and Cheney 1966; Van Wagner 1968; Lawson 1972; Kiil 1975; Nelson and Adkins 1988). In contrast, grass fires typically have flame front residence times of 10-15 seconds Sneeuwjagt and Frandsen 1977; Cheney 1990) whereas in logging slash fires would generally have residence times on the order of 1.5-2 minutes (Anderson et al. 1966; Rothermel and Anderson 1966, p. 34; Brown 1972). Despain et al. (1996a, 1996b) determined that the duration of flaming combustion in the crowns of lodgepole pine (*Pinus contorta*) forests average 24.5+9.6 seconds with a range of 5-48 seconds based on analysis of videotape footage taken of individual torching trees and stands "crowning out" during the 1988 fires in Yellowstone National Park, U.S.A. (Davis and Mutch 1989); they found no significant difference between single trees and stands of trees in the time that crowns remained burning. Earlier on, Ashton (1986) found that the flame duration in burning crowns of *Eucalyptus obliqua* forests varied only slightly (10-12 seconds) based on a similar analysis of news film footage of the 1983 Ash Wednesday fires in southeastern Australia (Rawson et al. 1983). Alexander (1996) has speculated that the ratio between the flame front residence times at the ground surface versus the aboveground or in the "aerial" zone of a crown fire is roughly 3:1.

2.3 Types of Crown Fires

A crown fire is "A fire that advances through the crown fuel layer..." (Merrill and Alexander 1987). Hawley and Stickel (1948) are believed to be the first to recognize two basic types of crown fires, namely "running crown fire" and "dependent crown fire", terms commonly attributed to Brown and Davis (1973) by most authors:

> *The former type* [i.e., the running crown fire] *progresses independently through the crowns of the trees. It spreads with great rapidity, though probably no faster than a*

> *quick-running grass and brush fire. It is closely followed by a surface fire. The dependent crown fire accompanies a surface fire. The burning material on the ground furnishes the volume of heat which ignites the crowns and maintains the crown fire.*

The terms "intermittent crown fire" and "intermittent crowning" apparently followed later on (e.g., Douglas 1957, 1964).

Although they may appear to spread independently as alluded to above, crown fires advance through the crown fuel layer normally in direct conjunction with a surface fire. Van Wagner (1977a) proposed that crown fires in conifer forests could be classified according to their degree of dependence on the surface phase and the criteria could be described by several semi-mathematical statements. The three classes of crown fire are (after Merrill and Alexander 1987; Alexander 1988):

> Passive crown fire -- a fire in which trees "torch" individually but rate of spread is controlled by the surface fire; basically not that different from a high-intensity surface fire; synonymous with intermittent crown fire.
>
> Active crown fire -- a fire that advances with a well-defined wall of flame extending from the ground surface to above the crown fuel layer (i.e., the surface and crown phases must travel together as a linked unit); most crown fires are of the active class; roughly synonymous with dependent crown fire.
>
> Independent crown fire -- a fire that advances in the crown fuel layer only, running ahead and some what independent of the surface phase (i.e., the surface fire of course lags some distance behind the leading edge of the crowning phase); roughly synonymous with running crown fire.

High-intensity wildfires do in fact exhibit all three classes of crowning in time and space. The class of crown fire to be expected in a conifer forest on any given day, according to Van Wagner (1977a), depends on three simple properties of the crown fuel layer and two basic fire behavior characteristics:

- initial surface fire intensity
- foliar moisture content
- live crown base height
- crown bulk density
- rate of fire spread

The first three quantities determine whether a surface fire will ignite coniferous foliage. The last two determine whether or not a continuous flame front can be sustained within the crown fuel layer. A dichotomous key to a forest fire classification scheme incorporating Van Wagner's (1977a) three classes of crown fire and the corresponding theory has been prepared by Alexander (1988).

Crown fires have been described by a whole host of adjectives. For example, Harper (1944) made mention of "mild", "light", medium, "heavy", "severe" and "very severe" crown fires in describing the immediate postburn visual evidence following crowing although he offered no quantitative basis for these qualitative terms. In the Canadian Forest Fire Behavior Prediction (FBP) System (Forestry Canada Fire Danger Group 1992; Hirsch 1996a; Taylor et al. 1996), the degree of crowning is specified by the crown fraction burned (CFB). The "... CFB is a measure of the degree of potential crown fuel consumption expressed as a proportion of the total number of tree crowns and as such constitutes an indication of the probable type of fire activity to be experienced over a burned area for fuel types that are susceptible to crowning" (Poulin et al. 1994). CFB values will range from 0.0 (i.e., a surface fire with no crown fuel involvement) to 1.0 (i.e., 100% crown fuel involvement associated with a fully-developed crown fire). The following broad categories are currently recognized:

CFB	**Type of Fire**
<0.1	Surface Fire
0.1 - 0.89	Intermittent Crown Fire
≥0.9	Continuous Crown Fire

The above classification assumes that if less than 10% of the trees are touching, a surface fire will prevail. There is obviously a wide range in the criteria for intermittent crown fires thereby necessitating the need for also specifying the CFB value associated with this type of crown fire activity.

2.4 Predicting Crown Fire Phenomena: Theories and Models

2.4.1 Criteria for the Initiation of Crowning

Various attempts have been made in the past to develop a generic model for crown fire initiation based purely on heat transfer principles (e.g., Molchanov 1957; Izbicki and Keane 1989; Grishin 1992, 1996; Clark et al. 1996a, 1996b), often with limited or unproven success. Van Wagner's (1977a) efforts constitute one outstanding exception. According to Van Wagner (1977a) the onset of crown combustion in a conifer forest stand is expected to occur when the surface fire intensity (I_s) attains or exceeds the critical surface intensity for crown combustion (I_o) value. In other words, if $I_s \geq I_o$, crowning can occur or if $I_s < I_o$, a surface fire will result. Ladder or bridge fuels (Fig. 2.2) must presumably be present in sufficient quantity to intensify the surface burning as well as to extend the height of flames (Muraro 1962, 1971; Lawson 1972, 1973; Wilson 1992b). The equation used to calculate I_o is as follows:

$$I_o = (Czh)^{1.5} \tag{2.6}$$

where I_o is the critical surface fire intensity for initial crown combustion (kW/m), C is the criterion for initial crown combustion (dimensionless), z is the live crown base height (m) (*see* Fig. 2.2) and h is the heat of ignition (kJ/kg). Van Wagner (1977a) assumed "... that the vertical spread of fire into the crowns is for practical purposes independent of crown bulk density."

The quantity h in Equation 2.6 represents the heat energy required to raise the crown foliage to ignition temperature (from Van Wagner 1977a):

$$h = 460 + 26\,m \tag{2.7}$$

where ***m*** is the foliar moisture content (%) (Fig. 2.4). The coefficient of 26 in Equation 2.7 was later changed by Van Wagner (1989, 1993) to 25.9 although he gave no explanation for this minor correction. Other relations for ***h*** have been proposed (e.g., Fons 1946; Byram et al. 1952; Anderson 1969; Frandsen 1973; Rothermel 1972), principally with dead forest fuels in mind as opposed to live conifer needles (e.g., Cohen 1989; Cohen et al. 1990 -- *see* Fig. 2.4). Van Wagner (1977a) did acknowledge that "The additional dependence of I_o on ignition energy, ***h***, remains an assumption since data are too few to demonstrate it." Equation 2.7 takes into account the total energy required to heat moist fuel to boiling point temperature of water (100°C), evaporate the free water, and finally heat the dry fuel to ignition temperature. In formulating Equation 2.7, the initial fuel temperature was assumed to be equal to an ambient air temperature of 20°C (*cf.* Van Wagner 1967c, 1968). The effect of a variable initial fuel/ambient air temperature level on the resultant ***h*** value is illustrated in Figure 2.4.

Equations 2.6 and 2.7 collectively define the amount of heat energy required initiate combustion of coniferous foliage. A graphical representation of their combined effect is presented in Figure 2.5. Note that the minimum or critical surface fire intensity requirements for ignition of coniferous tree crowns increases with both ***m*** and ***z***. Because fire intensity and flame size are related it is possible to infer a critical or minimum flame length for initial crown combustion using Equations 2.2 and 2.6 (Fig. 2.6). According to Figure 2.6, the flames of a surface fire do not have to necessarily reach into the tree crowns to initiate crowning (recall that flame height and flame length are only equal in the case of no wind, no slope). Rossotti (1993) indicated that "... leaves from the forest canopy may ignite if they are no more distance than one and a half times the flame height", although she offered no basis for this pronouncement.

Van Wagner (1977a) considered the quantity ***C*** in Equation 2.6 "... is best regarded as an empirical constant of complex dimensions whose value is to be found from field observations". Van Wagner (1977a) derived a value of 0.010 for ***C*** using the following transformation of Equation 2.6:

$$C = I_o/(zh)^{1.5} \tag{2.8}$$

The data associated with three experimental crown fires carried out in an eastern Canadian red pine plantation (Table 2.1) were used in this derivation where $z \approx 6$ m and the mean stand height (**SH**) was ≈ 12-15 m and the stand density was ≈ 3160 trees/ha (Van Wagner 1964, 1968, 1977a). The average depth and load of the forest floor layer were 6.4 cm and 28 t/ha, respectively; understory vegetation was noticeably lacking (Van Wagner 1968). A nominal value of 100% was chosen for ***m*** and the I_B just prior to crowning was set at 2500 kW/m although it was admitted that "This estimate of behaviour at the moment of crowning is necessarily rough, since the transition took place within less than a minute" (Van Wagner 1968).

A very limited amount of testing of Van Wagner's (1977a) crown fire initiation model has been undertaken to date (Alexander 1988; Van Wagner 1993). And although the results have been encouraging enough to result in its operational implementation (e.g., Anon. 1992b; Forestry Canada Fire Danger Group 1992), there appear to be many instances were the model fails.

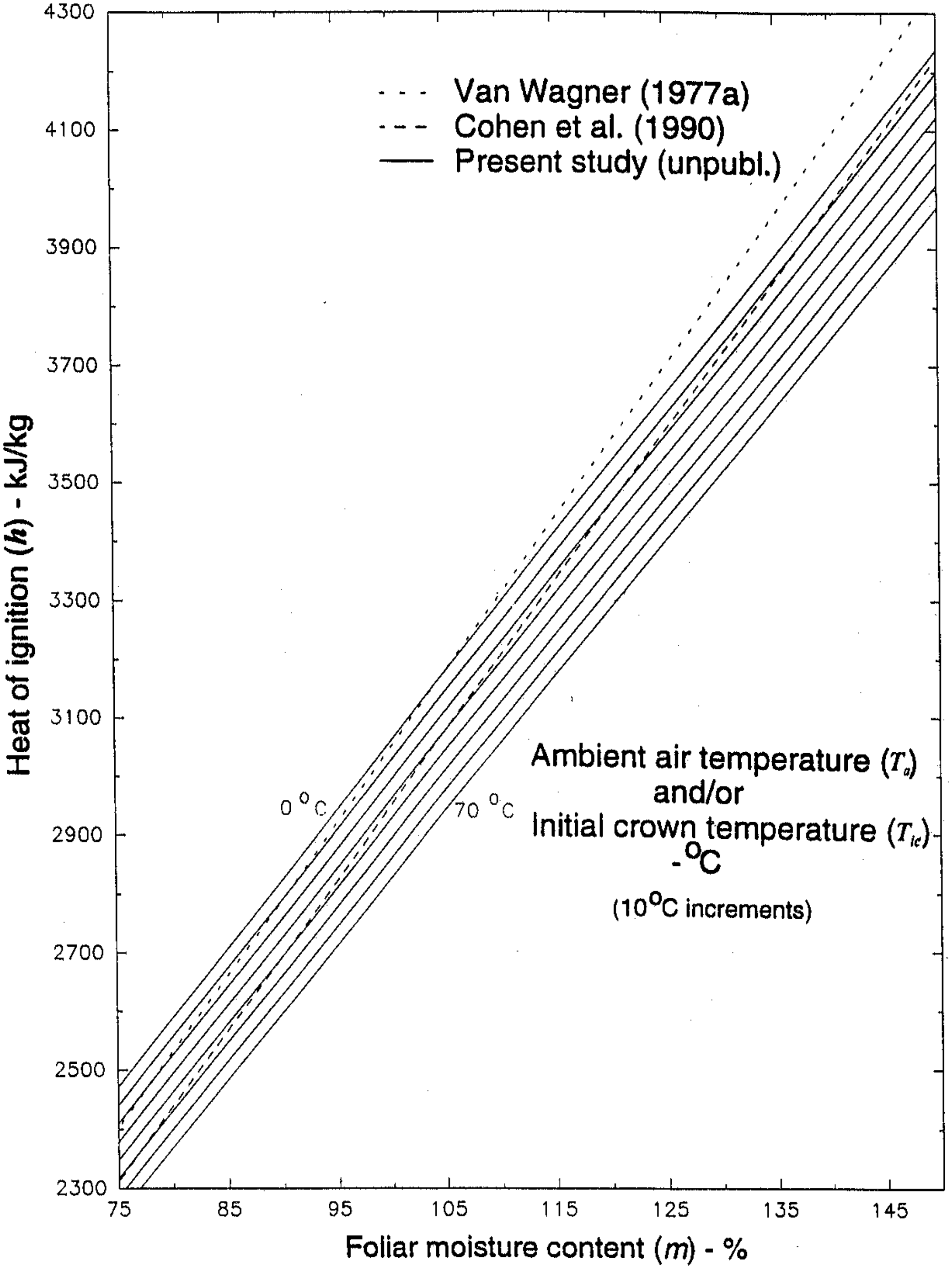

Figure 2.4: Heat of ignition for coniferous needle foliage as a function of foliar moisture content according to various sources.

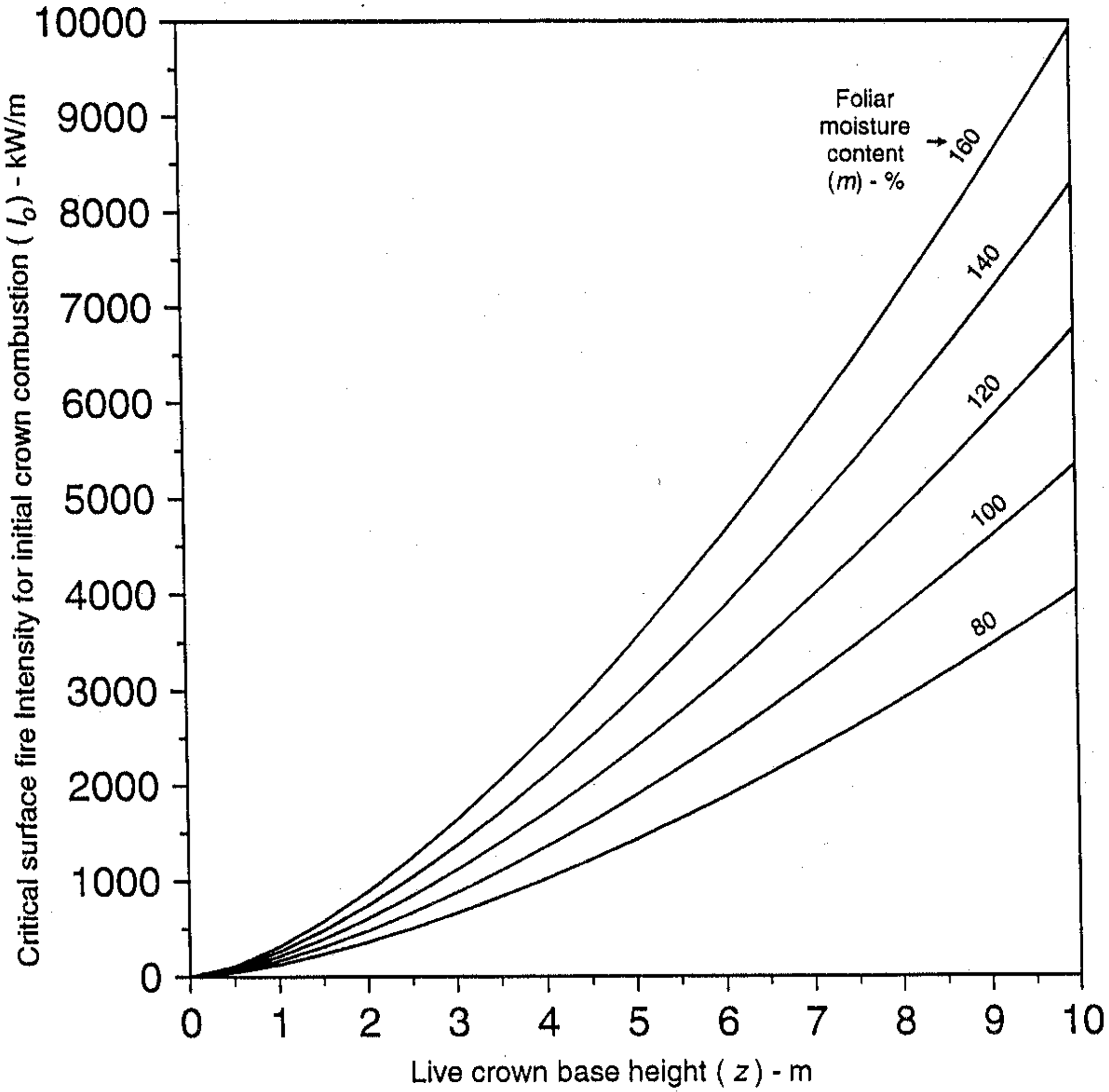

Figure 2.5: Critical surface fire intensity for initial crown combustion in coniferous forest stands as a function of live crown base height and foliar moisture content according to Van Wagner (1977a).

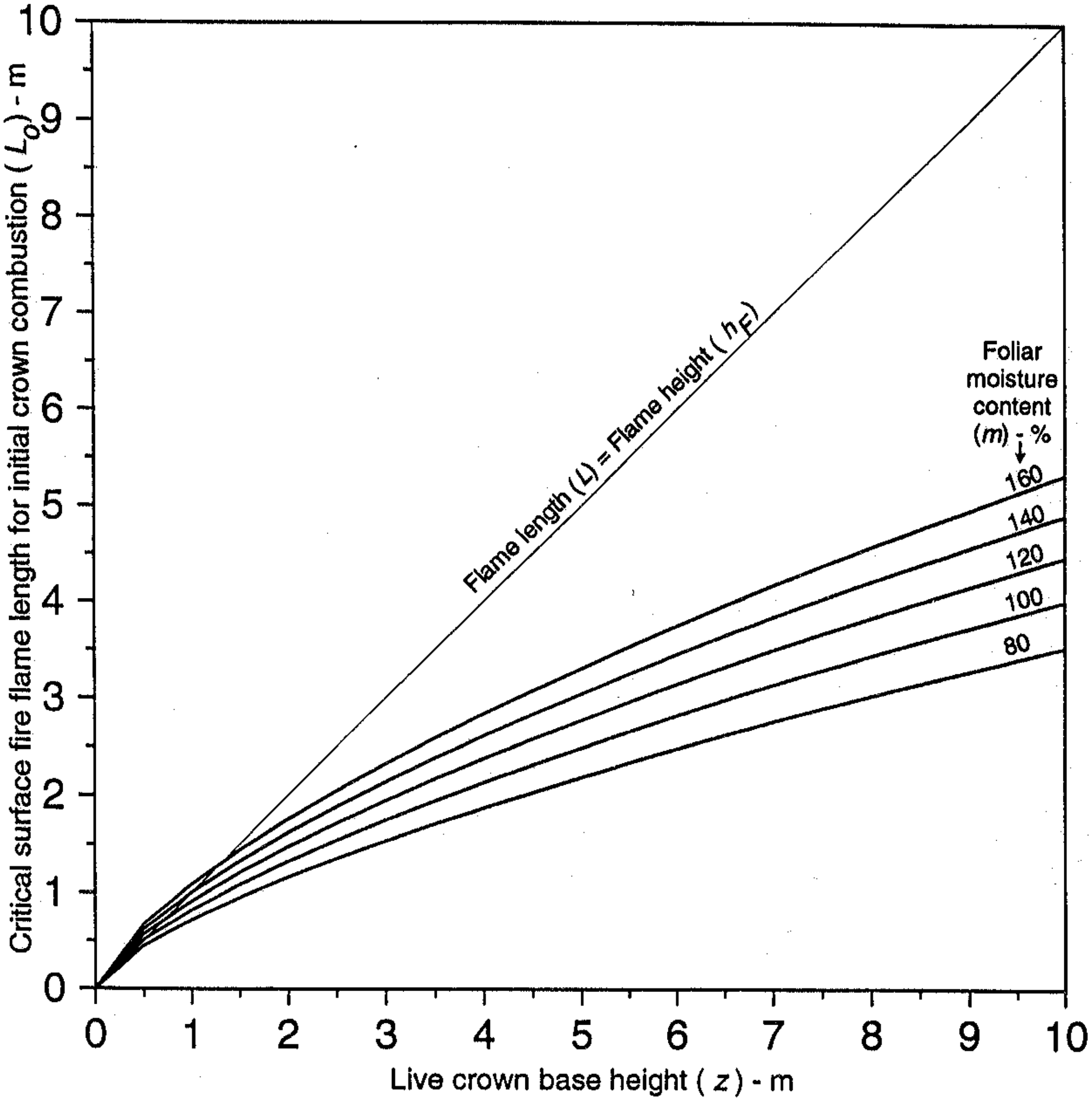

Figure 2.6: Critical surface fire flame length for initial crown combustion in coniferous forest stands as a function of live crown base height and foliar moisture content according to Van Wagner (1977a) based on Byram's (1959a) flame length-fire intensity relationship. The line of exact agreement between flame length and flame height is noted for reference purposes.

Table 2.1: Summary of the burning conditions and associated fire behaviour characteristics for the three experimental crown fires carried out in red pine plantation stands utilized by Van Wagner (1977a) in the development of his theories on the start and spread of crowning forest fires (adapted from Van Wagner 1964, 1968, 1977a; Alexander 1991b).

Item	Experimental fire		
	R1	C4	C6
Date of burning	8 June 1962	14 July 1966	31 May 1967
Ambient air temperature (°C)	24.4	22.8	18.9
Relative humidity (%)	26	32	25
10-m open wind speed (km/h)	15	23	19
Days since rain	9 (3.0)[a]	5 (1.0)[a]	5 (0.8)[a]
Duff moisture content (%)	54	24	66
Litter moisture content (%)	10	12	12
Foliar moisture content (%)	100	135	95
Keetch-Byram Drought Index (mm)	41.2	63.5	7.7
McArthur (1973) Drought Factor	7.7	9.1	5.5
McArthur (1973) Forest Fire Danger Index	12.7	13.0	8.6
Fine Fuel Moisture Code (FFMC)[b]	92.2	90.8	91.9
Duff Moisture Code (DMC)[b]	64	89	41
Drought Code (DC)[b]	190	352	86
Initial Spread Index (ISI)[b]	12.5	15.0	14.8
Buildup Index (BUI)[b]	70	109	41
Fire Weather Index (FWI)[b]	31	43	27
Forest floor consumption (t/ha)	22.0	19.1	13.2
Head fire rate of spread (m/h)	648	1008	1656
Head fire intensity (kW/m)	7300	21 100	22 500
Head fire flame length (m)	15.0	21.0	-
Head fire flame height (m)	14.8	19.8	30.5
Head fire flame depth (m)	8.0	14.0	-
Head fire residence time (sec)	45	50	-

[a] The amount (mm) on the last day it rained is noted in parentheses.

[b] These fire danger indexes constitute the three fuel moisture codes and three fire behaviour indexes comprising the six standard components of the Canadian Forest Fire Weather Index System (Van Wagner 1987).

The 2894-ha Burnt Fire that occurred in northern Arizona, U.S.A., November 1-4, 1973, provides a case in point. Dieterich (1979) provides an excellent summary of this wildfire and Rietveld (1976) provides some additional details on stand structure and fire impacts. The predominant fuel type in the area was variable stocked stands of ponderosa pine (*Pinus ponderosa*), some of which had been partially cut and precommercially thinned during the 10-year period prior to the fire (Rietveld 1976). The major run of the 1973 Burnt Fire occurred on November 2 under the influence of strong surface winds but cool ambient air conditions as evident by the following tabulation where T_a is the ambient air temperature (°C), U_{10} is the 10-m open wind speed (km/h) where the 6.1-m (20-ft) open winds reported by Dieterich (1979) were increased by 15% to approximate 10-m open wind speeds as per Turner and Lawson (1978, p. 27, Appendix 6) and R is the head fire rate of spread (m/h) (after Dieterich 1979):

	Daytime conditions		**Night**
	"High"	**"Extreme"**	**conditions**
T_a (°C):	10.0	10.0	1.7
U_{10} (km/h):	56	74	37
R (m/h):	805	1811	402
w (kg/m^2):	0.56	0.56	0.45
I_B (kW/m):	2325	5251	934

Dieterich's (1979, p. 1) Figure 1, an excellent color photo taken in September 1974, shows a stand with an average crown scorch height (h_s) of ≈ 7.6 m that was burnt through early on during the morning of November 2; green tops are very evident in the photograph. Dieterich (1979) summed up the damage or impact[3] resulting from the Burnt Fire as follows:

> *Damage from this fast-spreading fire was extremely variable ranging from complete destruction of crown material in patches of saplings and pole timber and an occasional mature tree, to large areas where the only evidence of fire was a blackened litter layer and slight scorch on the lowest portions of the crowns.*

The "crowned-out" areas within the fire perimeter no doubt occurred when spread rates approached ≈ 2000 m/h for short periods of time (Dieterich 1979). Dieterich (1979) notes that much of the ponderosa pine "... was open-grown, and tree crowns extended to within 4-5 feet [1.22-1.52 m] of the ground." Assuming that $z = 1.37$ m (Dieterich 1979) and that $m = 120\%$ according to foliar moisture content measurements made by Sackett (1980) late in the fall in the same general area as the Burnt Fire, $h = 3580$ kJ/kg and in turn $I_o = 343$ kW/m. It's obviously

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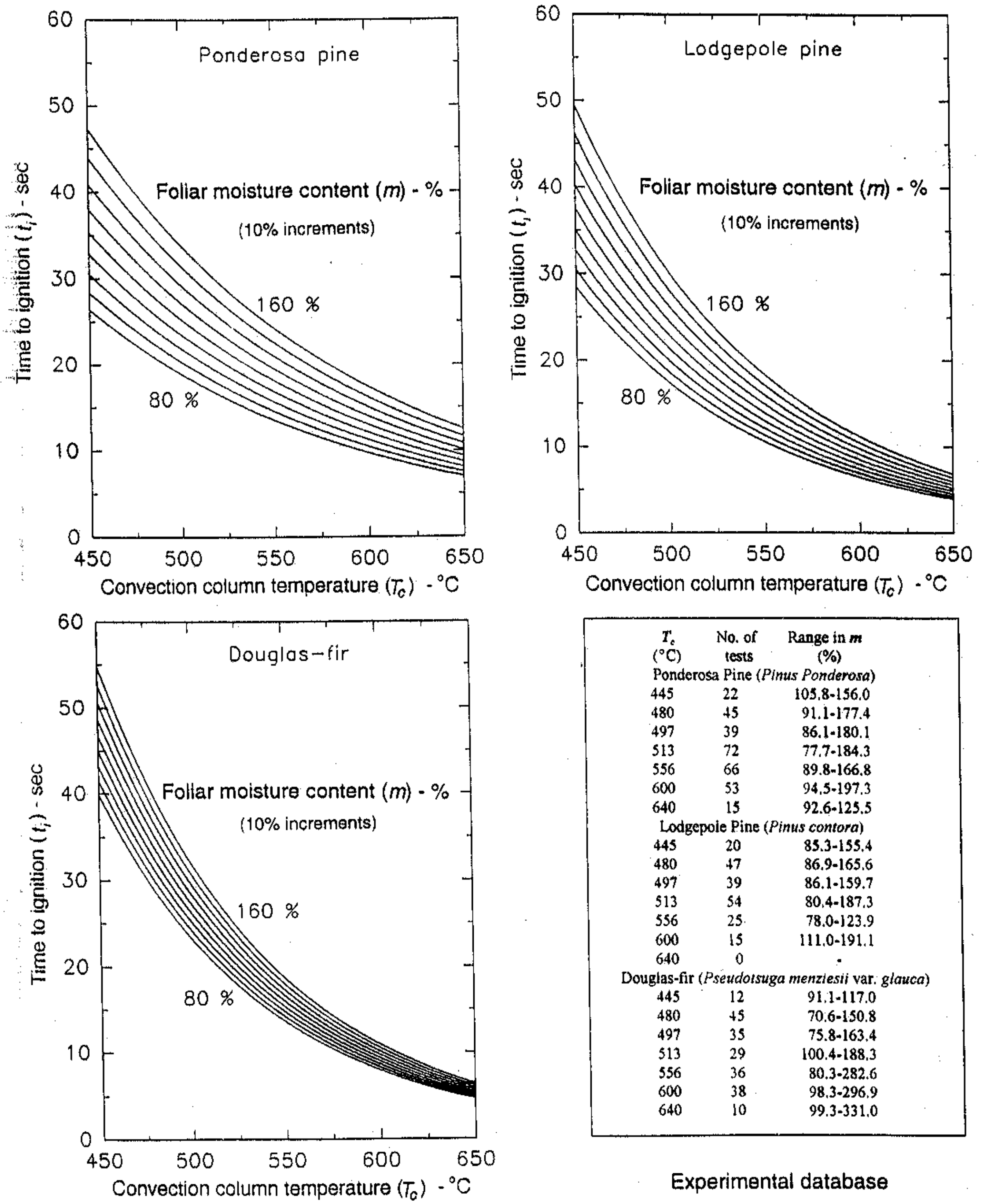
[3] It's worth noting that for the three situations given in the above tabulation, Dieterich (1979) computed theoretical crown scorch heights (h_s) of 8, 14 and 5 ft. (2.4, 4.3 and 1.5 m), respectively. Dieterich (1979) presumably based these computations on the basis of the English unit version of Van Wagner's (1973b) equation for predicting h_s from I_B, T_a and wind speed as presented in Albini (1976a) and assumed that the wind speed in Van Wagner's (1973b) equation was the 6.1 m open wind speed standard that is commonly used for fire danger rating and fire behaviour prediction purposes in the U.S.A (Crosby and Chandler 1966; Finklin and Fischer 1990). In actual fact, Van Wagner (1973b) measured the wind speed within the stand at a height of 1.2 m above ground (*cf.* Van Wagner 1963b, 1968). If we assume a wind adjustment coefficient or factor of 0.3 (*cf.* Rothermel 1983) then the in-stand wind speeds at 1.2 m ($U_{1.2}$) would be approximately 14.5, 19.3, and 9.7 km/h, respectively. Thus, the correct computed crown scorch heights should have been about 11.2, 19.1, and 5.6 m (37, 63 and 18 ft), respectively (*see* Equation 3.25 in Chapter 3).

evident from the above tabulation that in this case Van Wagner's (1977a) model represented by Equation 2.6 grossly overestimated the potential for crown fire initiation.

Xanthopoulos (1990) has endeavoured to develop a model that would allow for the quantitative prediction of crown fire initiation. Overviews of the study have been published (Xanthopoulos and Wakimoto 1991; Xanthopoulos 1992). The model is based on the results of two separate experiments. The first involved examining the effect of moisture content on the ignitability of live needle foliage (Xanthopoulos and Wakimoto 1993) by exposing branchlets near a pilot flame at various simulated convection column temperatures (using a device specifically designed for the experiment) between 350 to 640 °C and then recording the time to ignition, if it occurred; the boundary between the upper limit of discontinuous flaming and the buoyant plume is considered to be ≃ 320 °C and flame tip temperature is generally regarded as lying between 500-600 °C although intermittent flaming could extend to as high as 800 °C (Drysdale 1985). The experiment was repeated at monthly intervals over the course of a year thereby taking advantage of as much possible natural seasonal variation in foliar moisture content (*cf.* Philpot and Mutch 1971) as opposed to artificially inducing a desired level (e.g., Van Wagner 1961, 1967b, 1967c; Quintilio 1977; Fuglem and Murphy 1979). Three conifer species were examined and regression equations relating time to ignition to foliar moisture content and convection column temperature were developed (Fig. 2.7 a-c). Simulated convection column temperatures (T_c) were carried out at nine different levels: 350, 400, 445, 480, 497, 513, 556, 600 and 640 °C (Fig. 2.7d). Data from the trials carried out at 350 °C and 400 °C were not included in the development of the regression equations because at 350 °C practically all the tests failed to produce an ignition, while at 400 °C, only about 30% of the tests resulted in successful ignitions. The results of this component of the Xanthopoulos' (1990) overall study are discussed further in the next chapter (*see* Section 3.2.1).

The second experiment undertaken by Xanthopoulos (1990) consisted of 65 experimental fires carried out in the wind tunnel at the USDA Forest Service's Intermountain Fire Sciences Laboratory (IFSL) facility located in Missoula, Montana, U.S.A. (Beaufait 1965; Rothermel and Anderson 1966; Rothermel 1972; Wilson 1982). Four different wind speeds were examined (u = 0.0, 0.447, 1.341 and 2.235 m/sec). The maximum I_B achieved was ≃ 380 kW/m. Time-temperature profiles were obtained from thermocouples placed at four different heights above (0.5, 0.9, 1.3 and 1.7 m) and at four locations along the fuelbeds (0.91 x 3.5 m or 0.91 x 6.15 m) comprised of ponderosa pine and western white pine (*Pinus monticola*) needle litter, excelsior shavings or square wooden sticks of three different thicknesses (0.32, 0.64 and 1.27 cm). A series of multiple regression equations were derived from the resulting data in order to predict time-temperature profiles at any height above a moving fire. The independent variables were Rothermel's (1972) reaction intensity and wind coefficient, fuel load, height above fuelbed and wind speed. Xanthopoulos (1990) developed his crown fire initiation model on the basis of a calculated "ignition score" obtained by intergrating the results of the two sets of regression equations. A threshold value above which crown fire ignition is expected to occur was determined experimentally by exposing tree branches or small trees to an additional set of fires carried out in the IFSL wind tunnel and outdoors in a simulated field setting (3.5 x 3.5 m plots), obtaining time-temperature profiles at the effective crown base height and then calculating a corresponding ignition score.



T_c (°C)	No. of tests	Range in *m* (%)
Ponderosa Pine (*Pinus Ponderosa*)		
445	22	105.8-156.0
480	45	91.1-177.4
497	39	86.1-180.1
513	72	77.7-184.3
556	66	89.8-166.8
600	53	94.5-197.3
640	15	92.6-125.5
Lodgepole Pine (*Pinus contora*)		
445	20	85.3-155.4
480	47	86.9-165.6
497	39	86.1-159.7
513	54	80.4-187.3
556	25	78.0-123.9
600	15	111.0-191.1
640	0	-
Douglas-fir (*Pseudotsuga menziesii* var. *glauca*)		
445	12	91.1-117.0
480	45	70.6-150.8
497	35	75.8-163.4
513	29	100.4-188.3
556	36	80.3-282.6
600	38	98.3-296.9
640	10	99.3-331.0

Experimental database

Figure 2.7: Time to ignition for needle foliage as a function of convection column temperature and foliar moisture content for three coniferous tree species according to Xanthopoulos (1990).

By his own admission, Xanthopoulos (1990) acknowledged that his "... model has a number of deficiencies ... the major one being a lack of extensive testing in real crown fires." Perhaps a more important reservation is whether thermocouple data collected from experimental fires carried out in the IFSL wind tunnel can be used in the development of models or regression equations for predicting time-temperature profiles that would in turn be applied to read-world situations such as their use in assessing crown fire initiation or in estimating $\boldsymbol{h_s}$. Xanthopoulos (1990) has made a very concerted effort to develop a crown fire initiation model. However, consider the following limitations:

1) The constraining influence of the limited ceiling found in most wind tunnels which would not allow convection to develop as freely as in an open environment (*see* Fleeter et al. 1984; Weise 1994). The ceiling height would also limit the height to which thermocouples could be positioned above the spreading flame front.

2) Even though natural fuel materials were used, the artificially prepared fuelbeds do not necessarily simulate very well the natural gradients in moisture content, decomposition and bulk density that would be found in real-world situations inspite of the uniformity that is achieved in redistributing the fuels from the field to the lab (Schuette 1965; Deeming and Elliott 1971). It's been this author's experience from having seen slides and viewing video footage of fires conducted in the wind tunnel facility at IFSL that a considerable amount of flaming/glowing combustion is taking place long after the head of the fire has reached the end of the fuelbed. Surely this must be affecting the resulting time-temperature profiles. Admittedly, additional heat is released following passage of the flame front in field fires but it would not appear to be anywhere near the extent observed in some of the IFSL fire/fuel situations.

3) The level of fire intensity attainable or permittable (i.e., what would be considered "safe") in the wind tunnel is not necessarily viewed as a limitation to the use of laboratory fires. However, several authors have observed relatively constant flame dimensions almost irregardless of the environmental conditions (e.g., Nelson and Adkins 1986; McAlpine 1988).

4) Furthermore, surely in many cases the thermocouples at 0.5 m and perhaps occasionally at 0.9 m were bathed directly by the flame front and undoubtedly flickers of flame would have become detached from the main flaming front and momentarily affect the next highest thermocouple. The very fact that the time-temperature profile regression equations are therefore based on thermocouple data involving both direct flame contact and convectively heated air would seem to invalid their use with the foliar ignitability regression equations.

The above comments are not meant to suggest any particular bias towards the relative value of laboratory fires. Indeed, inspite of some limitations (e.g., Anderson 1968b), good use has been made of this approach in studying certain aspects or characteristics of wildland fire behaviour such as the mechanical effects of slope steepness on rate of fire spread (e.g., Van Wagner 1968, 1977b, 1988), fire plume angles (e.g., Fendell et al. 1990; Carrier et al. 1991) and firewhirls (Haines and Updike 1971; USDA Forest Service 1991), although it is not viewed as a panacea for investigating all free-burning wildland fire phenomenon. The ability to produce a steady wind velocity in the tunnel environment is obviously a great advantage in being able to model the idealized situation but there are very real physical limitations of such facilities (*see* for example, Section 2.4.5).

2.4.2 Criteria for Continuous Crown Fire Spread

Assuming a surface fire is of sufficient intensity and duration or persistence to initiate crown combustion, the question still remains as to whether a continuous flame front will develop within the crown zone, both vertically and horizontally. Several authors have made subjective estimates about the minimum crown fuel load required to sustain vertical fire spread in coniferous tree crowns (e.g., Muraro 1971; Sando and Wick 1972; Williams 1977a) whereas Martin and Sapsis (1987) have attempted by experimental means to quantitative the amount of fuel required to support combustion vertically. Others have speculated, without regard for the foliage weight of the individual trees, about the minimum distance between tree crowns (e.g., Schmidt and Wakimoto 1988) or the maximum crown closure (e.g., Fahnestock 1970) in order to reduce the likelihood of lateral fire spread from crown to crown ahead of the surface fire. However, to be meaningful, crown fuel characteristics must eventually be related to some aspect of fire behaviour and its variation (which in turn be predicted from a knowledge of environmental conditions -- i.e., fuel moisture, wind, slope, etc.). Ideally, such a relationship should involve both the vertical and horizontal aspects of the crown fuel layer. Perhaps the best objective basis for judging this is the concept of a minimal sustained rate of fire spread (after crown combustion) in relation to crown bulk density as developed by Van Wagner (1977a).

Obviously certain conifer stands are more prone or susceptible to sustained crowning simply because of their crown fuel characteristics (i.e., in addition to a low *z*, fine fuel such as needles and small twigs are in sufficient quantity to support continuous horizontal fire spread in the tree crowns). Van Wagner (1977a) theorized that the bulk density of the crown fuel layer must have a lower limit below which active crowning (Fig. 2.8) would not be possible and suggested the following relationship:

$$\boldsymbol{R_o} = \frac{\boldsymbol{S_o}}{\boldsymbol{d}} \tag{2.9}$$

where $\boldsymbol{R_o}$ is the critical minimum spread rate for an active crown fire (m/h), $\boldsymbol{S_o}$ is the critical mass flow rate for solid crown flame (kg/m^2-h) and $\boldsymbol{d}$ is the crown bulk density (kg/m^3) (Fig. 2.2). The computation of $\boldsymbol{d}$ is as follows:

$$\boldsymbol{d} = \frac{\mathbf{m_F}}{\mathbf{CD}} \tag{2.10}$$

where $\mathbf{m_F}$ is the available crown fuel load (kg/m^2) and **CD** is the vertical crown depth (m). As illustrated in Figure 2.9, $\boldsymbol{d}$ is not necessarily constant with height in the crown space although it's often useful to think of it as such for practical purposes. It's worth noting that Roussopoulos (1978b) used the vertical needle foliage distribution in forest stands to determine *z*. He defined *z* as the height separating the lower 5% of $\mathbf{m_F}$ from the upper 95%. In

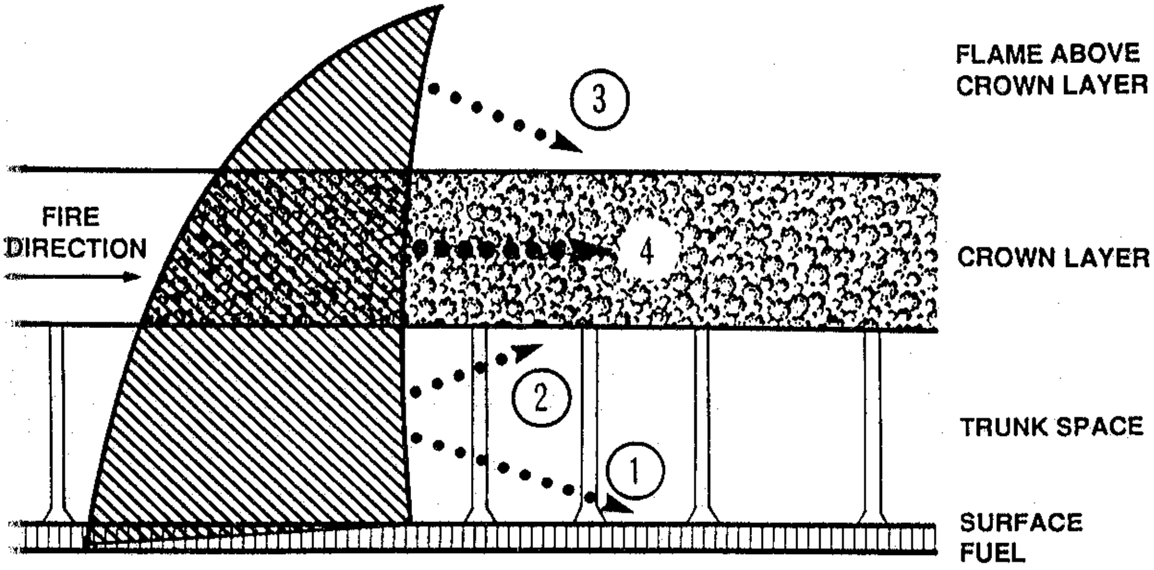


Figure 2.8: Schematic diagram illustrating the four components of forward radiated heat transfer in an active crown fire spreading through an idealized coniferous forest stand: trunk space radiates to (1) surface and (2) crown fuels; flame above the canopy radiates to (3) crown fuels; and flame within the crown fuel layer radiates (4) throughout the layer (after Van Wagner 1968).

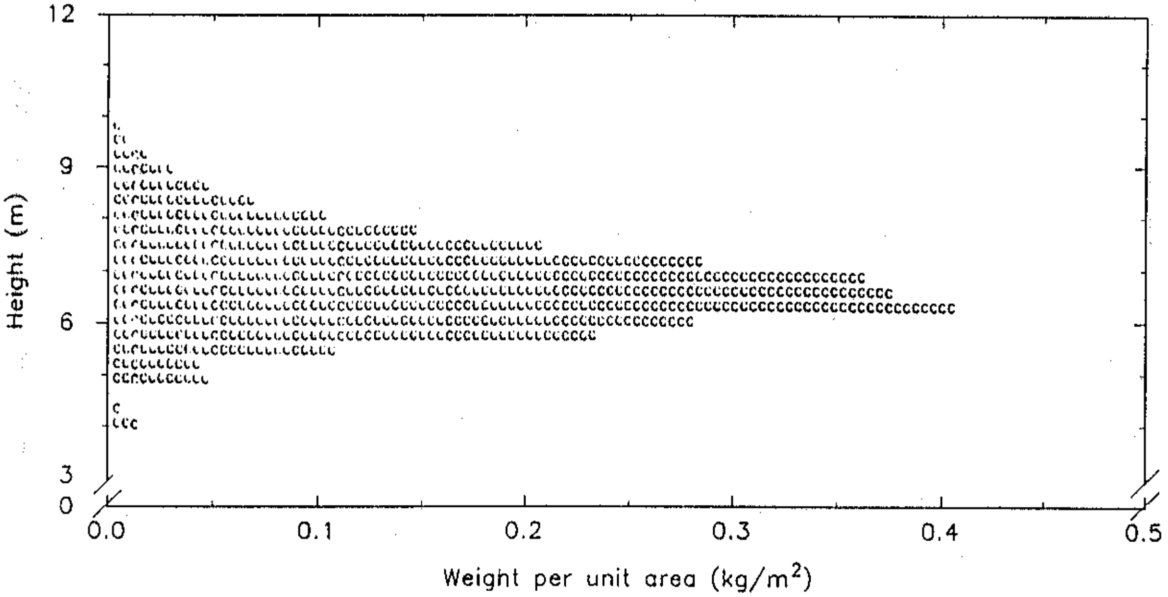
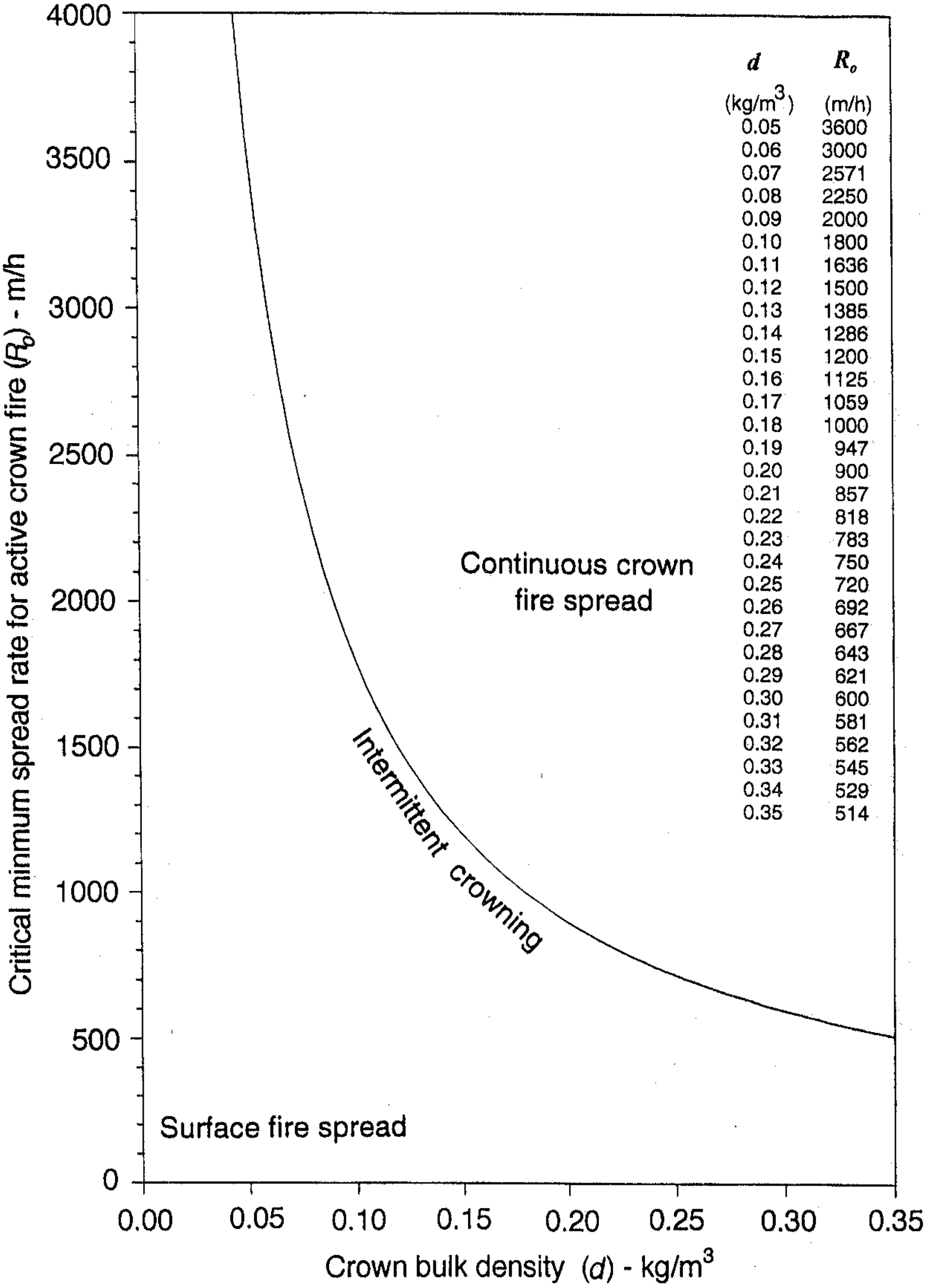


Figure 2.9: Variation in fuel load with height above ground in an unthinned 32-year- old red pine plantation, Lake States region, U.S.A. (adapted from Sando and Wick 1972).

forest mensuration terms, **CD** is equivalent to a stand's live crown length -- i.e., stand height **SH** substracted from its z. Albini (1993) viewed the R_o criterion as a "lean flammability limit" whereas Agee (1996) termed it a "crown bulk density threshold". Currently the best available estimate of S_o for conifer forest stands is 180 kg/m^2-h (Van Wagner 1977a) based on the experimental fires carried out by Van Wagner (1964, 1968) in red pine plantations (Table 2.1); Van Wagner (1993, Equation 2) mistakenly indicated that S_o = 0.05 (kg/m^2-sec) when he should have in fact indicated that S_o = 3.0 (kg/m^2- min) if one is specifyng that R_o is in m/min (*cf.* Alexander 1988, Equation 6). In contrast, Thomas (1967) determined that S_o = 216-288 kg/m^2-h for laboratory crib fuelbeds. Two things should be borned in mind in applying Equation 2.9 with the resultant value of S_o derived by Van Wagner (1977a). Firstly, the number of experimental crown fires that contributed to the derivation of S_o = 180 kg/m^2-h is exceedingly small (i.e., $n = 3$). Secondly, no allowance has been made for any foliar moisture content effect, although, m nominally equals 100%. Finally, the range in S_o reported on by Thomas (1967) for very uniform fuelbeds (with much lower moisture contents) would suggest a certain degree of uncertainty that could equally be applied to Van Wagner's (1977a) derivation of S_o for the crown fuel layer of a conifer forest stand. A graphical representation of Equation 2.9 is presented in Figure 2.10; sample interpretation: assuming $I_s \geq I_o$, an active crown fire would not be possible in a conifer stand with a d of 0.25 kg/m^3 unless the rate of spread after crowning exceeded 720 m/h. Note that the minimum spread rate required for crowning increases as the bulk density of the crown fuel layer decreases (or in other words, the crowns get progressively wider apart). Once a fire crowns, active crowning will continue provided the rate of spread is fast enough (i.e., $R \geq R_o$) to maintain a continuous flame front in the trunk space and crown fuel layer and thereby transfer enough heat to the unburned tree crowns in order to maintain continuous ignition and flaming combustion (Fig. 2.8). Some authors have misinterpreted R_o to mean the surface fire rate of spread instead of the crown fire rate of spread (e.g., Keyes 1996).

Agree (1996a, 1996b) has rightly noted that there has been very limited testing of Van Wagner's (1977a) criteria for continuous active crowning represented by Equation 2.9 and the value derived for S_o. Van Wagner (1977a) found that his criteria compared favourably against the observed type of fire activity and spread rate of a high-intensity wildfire that occurred in a jack pine (*Pinus banksiana*) forest near Chalk River, Ontario, Canada (Van Wagner 1965a), where R_o = 1620 m/h and the estimate of the actual R = 1476 m/h. Ten of the 12 experimental fires carried out in an immature jack pine stand in north-central Ontario, Canada, as described by Stocks (1987b) where d would nominally equal ≈ 0.23 kg/m^3, "... exhibited crown fire behavior, generally moving as a continuous, forward-tilted flame front with flame heights reaching 20 m or twice the average stand height ..." (Stocks 1987b) with spread rates that generally (there were two exceptions) exceeded 800 m/h, which also compares favourably with Van Wagner's (1977a) criteria. Alexander, Stocks and Lawson (1991) found from experimental fires carried out in black spruce (*Picea mariana*)-lichen woodland stands in the Northwest Territories, Canada, where d = 0.20 kg/m^3, that continuous crowning occurred when R ≈ 960 m/h when theoretically it should at least exceed 900 m/h. Agee (1996a, 1996b) examined the incidence of crown fire activity (or lack thereof) in seven stands (six of which were thinned-unthinned comparisons) burnt during the 1994 fires in the Wenatchee region of north-central Washington, U.S.A., where estimates of d (varying from 0.035-0.15 kg/m^3) were made after-the-fact. On the basis of this limited empirical test, he concluded that the critical threshold of d was ≈ 0.10 kg/m^3 for the burning conditions that prevailed at the time, suggesting crown fire



d (kg/m^3)	R_o (m/h)
0.05	3600
0.06	3000
0.07	2571
0.08	2250
0.09	2000
0.10	1800
0.11	1636
0.12	1500
0.13	1385
0.14	1286
0.15	1200
0.16	1125
0.17	1059
0.18	1000
0.19	947
0.20	900
0.21	857
0.22	818
0.23	783
0.24	750
0.25	720
0.26	692
0.27	667
0.28	643
0.29	621
0.30	600
0.31	581
0.32	562
0.33	545
0.34	529
0.35	514

Figure 2.10: Theoretical relation between the critical minimum spread rate for active crown fire and crown bulk density in coniferous forest stands according to Van Wagner (1977a).

spread rates on the order of at least 1800 m/h which does tend to agree with the available wildfire documentation but only in a rough sort of way.

Fires in certain conifer forest fuel types such as sand pine (*Pinus clausa*) forests in Florida, U.S.A., appear to spread by active crowning or they don't spread at all (Johansen and Cooper 1965; Hough 1973; Doren et al. 1987; Custer and Thorsen 1996). Pinyon-juniper woodlands in the western U.S.A. constitute another example (Hester 1952). Bruner and Klebenow (1979) found from an analysis of 30 prescribed fires in *Pinus monophylla - Juniper osteosperma* stands in Nevada that the following simple rule of thumb could be used to predict whether a successful burn was possible or not: score = maximum wind speed (mi/h) + air temperature (°F) + vegetation cover (%). At a score of 110 or less, burning conditions were such that fires would not carry. A score of 110 to 125 indicated that fires would carry but continual retorching was necessary whereas a score of 125-130 indicated that conditions were optimal for a self-sustaining fire following ignition. A score higher than 130 indicated conditions were too hazardous for prescribed burning. The authors acknowledge that there appeared to be a very narrow separation between conditions necessary for successful prescribed burning and those that would result in an uncontrollable high-intensity wildfire that would escape the confines of the prescribed burn unit. Similar observations of wind speed or spread rate thresholds have been noted in certain shrublands and grassland fuel types (Lindenmuth and Davis 1973; Davis and Dieterich 1976; Burrows et al. 1991; McCaw 1995).

Development of a truly independent crown fire on flat topography most certainly must require very strong winds. This is necessary in order to achieve the direct flame contact and forward radiation heat transfer through the crown foliage, that is required to continue the propagation in a horizontal dimension, more or less independent of the surface fire energy output rate. Slope steepness can no doubt compensate for reduced wind flow; for example, a 30° slope can result in about a ≃ 7 to 8.5 fold increase in rate of fire spread (McArthur 1962; Rothermel 1972; Van Wagner 1977b; Cheney 1981; Weise 1993), and at least a corresponding increase in fire intensity compared to the same fuel and weather conditions on level terrain (Fig. 2.11). Sustained independent crown fire runs are undoubtedly a very rare event, if in fact they occur at all, given the natural variation in wind velocity, fuels and terrain. The time lapse photography taken of the 1979 Ship Island Fire in central Idaho, U.S.A. (Anon. 1993b) offers an excellent example of what appears to be a independent crown fire run on a steep slope. Incidents of crown fires spreading over top of small to moderate sized snowdrifts in conifer forest stands on steep slopes during the spring have admittedly been reported on from time to time (e.g., Huff 1988a, 1988b). It's unlikely that the crown phase can advance ahead of the surface fire by more than abut 150 m (Kurbatsky 1969) and generally considerably less. However, these represent short bursts of limited duration. The concept of the crowning phase of a forest fire racing ahead of the surface phase by several hundred metres or even kilometres for hours on end is a myth which has been perpetuated in drawings and text by not only the media but to a certain extent in the popular, technical and scientific literature as well (e.g., Cottrell 1989).

2.4.3 Spread Rate After Crowning

Assuming the initiation of a crown fire has occurred, the next fire behaviour parameter of critical importance is the crown fire spread rate. Once crowning, a fire's forward rate of spread is most strongly dependent on wind velocity, and predicting the highly variable spread rate of

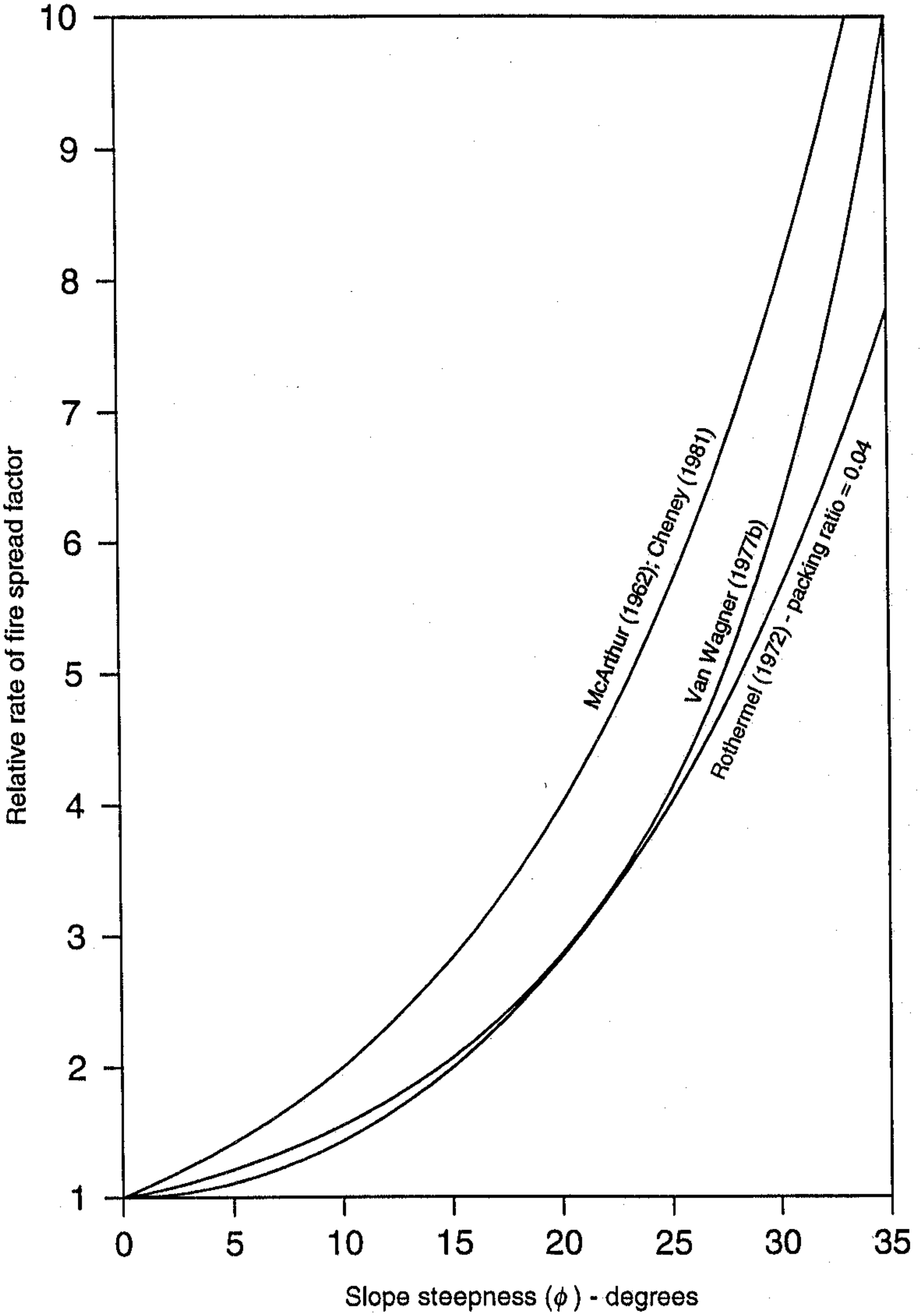


Figure 2.11: The effect of slope steepness on uphill rate of spread of free-burning wildland fires in the absence of wind according to Australian (McArthur 1962; Cheney 1981), Canadian (Van Wagner 1977b) and American (Rothermel 1972) authorities.

a crowning fire then becomes of critical importance. Kerr and others (1971) considered that "In the foreseeable future there is little prospect of predicting the behavior of a fast spreading crown fire in timber over any extended period of time". Much progress has been made in the last 25 years or so.

Alexander, Stocks, Lawson and McAlpine (1991) plotted $\boldsymbol{U_{10}}$ against the spread rates associated with crown fires used in the development of the Canadian FBP System (Forestry Canada Fire Danger Group 1992) as obtained through numerous experimental burning projects and wildfire monitoring in various conifer forest fuel types. The 80 or so observations included $\boldsymbol{R}$ values up to 6400 m/h with associated $\boldsymbol{U_{10}}$ levels of almost 50 km/h. Although the resultant scattergram showed a remarkably high degree of agreement between the two variables there was considerable scatter, no doubt due to differences in fuel complex characteristics (e.g., black spruce versus jack or lodgepole pine) and in both dead and live fuel moisture levels. Nevertheless, a simple linear regression equation explained 68% of the variation in the data. Similar strong correlations have been noted for crown fires in shrublands and other conifer forests (Konev 1984; McCaw 1995) as well as dry, fully cured grasslands (Cheney et al. 1993).

Thomas (1971) considered that the rate of fire spread for very homogeneous wildland fuel complexes (e.g., shrubfields, conifer forest stands) could be predicted from the bulk density of the fuel consumed and the wind speed $\boldsymbol{u}$ (m/sec) on the basis of the following simple formula (where $\boldsymbol{d}$ as used here is assumed to equate to the bulk density of the fuel consumed):

$$\boldsymbol{r} = \frac{0.07\,(1 + \boldsymbol{u})}{\boldsymbol{d}} \tag{2.11}$$

An earlier version of this model (Thomas 1970a) allowed for variable fuel moisture content but the final one (Thomas 1970b, 1971), represented by Equation 2.11, assumed a live fuel moisture content (equivalent to $\boldsymbol{m}$ as used here) of 100%. While some testing of Thomas' (1971) model has been undertaken for shrubland and grassland fuel complexes (Catchpole 1987; Marsden-Smedley and Catchpole 1995), its relevance to crown fires in conifer forest stands has not been examined to date.

Nelson and Adkins (1988) derived the following equation from an analysis of surface fires carried out in a wide variety of fuelbeds, both in a wind tunnel and outdoors in the field (after Nelson and Adkins 1988, Equation 14):

$$\boldsymbol{r} = \frac{0.39\,\boldsymbol{w}^{0.25}\boldsymbol{u}^{1.51}}{\boldsymbol{t_r}} \tag{2.12}$$

where $\boldsymbol{t_r}$ (sec) constitutes the flame front residence time as defined by Fons et al. (1962) as the horizontal flame depth $\boldsymbol{D}$ (Fig. 2.2) divided by the fire's rate of advance $\boldsymbol{r}$. In applying this model, one would need to provide estimates of both $\boldsymbol{w}$ and $\boldsymbol{t_r}$. Nelson and Adkins (1988) considered that their rate of fire spread model represented by Equation 2.12 could be applied to crown fires although no supporting proof for this claim was offered.

Fuel moisture content has long been recognized as being a major factor controlling the ignition and spread of wildland fires (Hawley 1926). Any mathematical model for predicting fire spread must therefore account for this influence. The effect of $\boldsymbol{m}$ on crown fire initiation has already been discussed in Section 2.4.1. Many investigators have reported on the significance of $\boldsymbol{m}$ in relation to various fire properties by burning small, live conifer or "Christmas" trees in a laboratory setting (e.g., Van Wagner 1961, 1967b, 1967c; Quintilio 1977; Fuglem and

Murphy 1979). For example, Van Wagner (1967c) observed, over a range in ***m*** of 68 to 124% that there was an approximately 30-fold increase in thermal radiation received at a distance of ≃ 0.9 m away from ≃ 1.5-m tall white spruce (*Picea glauca*) trees that were burnt by igniting balls of crushed newspaper around the base of each tree. Although its been easy to demonstrate the effect of fine deal fuel moisture on the horizontal rate of fire spread in natural fuels in the laboratory (e.g., Anderson and Rothermel 1965; Rothermel and Anderson 1966; Van Wagner 1968; Anderson 1969), this has so far proven near impossible with live fuels exhibiting very high moisture contents. Thus, there is at present no proven theory by which to base an ***m*** effect on crown fire ***R***. Van Wagner (1974, 1989, 1993) has deduced a hypothetical relative foliar moisture effect (FME) on the basis of simple heat transfer theory (*cf.* Thomas et al. 1964), normalized to a level of 97%, which is currently used to adjust the crown fire ***R*** for differences in ***m*** in the conifer plantation fuel type of the Canadian FBP System (Forestry Canada Fire Danger Group 1992). This function is presented in Figure 2.12. Also presented in Figure 2.12 is the FME function embedded in the rate of fire spread model developed for oak chaparral (predominately *Quercus turbinella*) shrublands in Arizona, U.S.A., by Lindenmuth and Davis (1973) on the basis of 32 experimental fires where the average ***m*** was 84.4 and ranged from 71.4-142.4. The difference in these two functions is quite striking and suggests that the present FME in the FBP System is probably much to strong an effect.

Catchpole and de Mestre (1986) rightly pointed out that there are two basic aspects to the physical modelling of fire spread in wildland fuels:

> *The first is the actual combustion of the fuel -- rate of consumption of fuel, height and thickness of flame produced, etc. The second is the process of transfer of heat from the combustion zone to the fuel ahead of this zone, to raise it to ignition temperature. A model cannot be genuinely predictive physical model unless it models both of these processes.*

The development of such a truly physical model to predict the spread rate of crown fires propagation has proven a complex and difficult process, but significant progress has been made in recent years in tackling this issue. The most promising result has come about as a result of the fundamental work of Albini (1985, 1986) who developed a radiation-driven model that finds the temperature of the fuel particles ahead of a steady-state line fire. This model was tested (Albini and Stocks 1986) against the observed spread rates on nine experimental crown fires conducted in an immature jack pine stand in north-central Ontario (Stocks 1987b). Flame height, flame tilt angle, the radiometric temperature of the crown layer burning zone, and the intensity of radiation from the idealized flame sheet were considered the critical variables in this radiation-driven model. By estimating the first two variables using a phenomenological model and scaling principles (Baughman and Albini 1980; Albini 1981a), and by assuming values for the last two parameters, this model exercise (Albini and Stocks 1986) predicted crown fire spread rates with reasonable accuracy; note that ***m*** was considered a constant (i.e., 100%) for present purposes. The fact that this model performed satisfactorily at greatly different scales (it was also tested on small-scale laboratory fires -- Albini 1986) is a strong indication that the formulation is robust. Further work is required, however, in order to better estimate the four critical variables listed above, before a closed predictive model of crown fire spread rates is achieved. American and Canadian fire researchers are continuing to cooperate in addressing this issue (Albini 1996; Call and Albini 1996; Stocks and Alexander 1996).

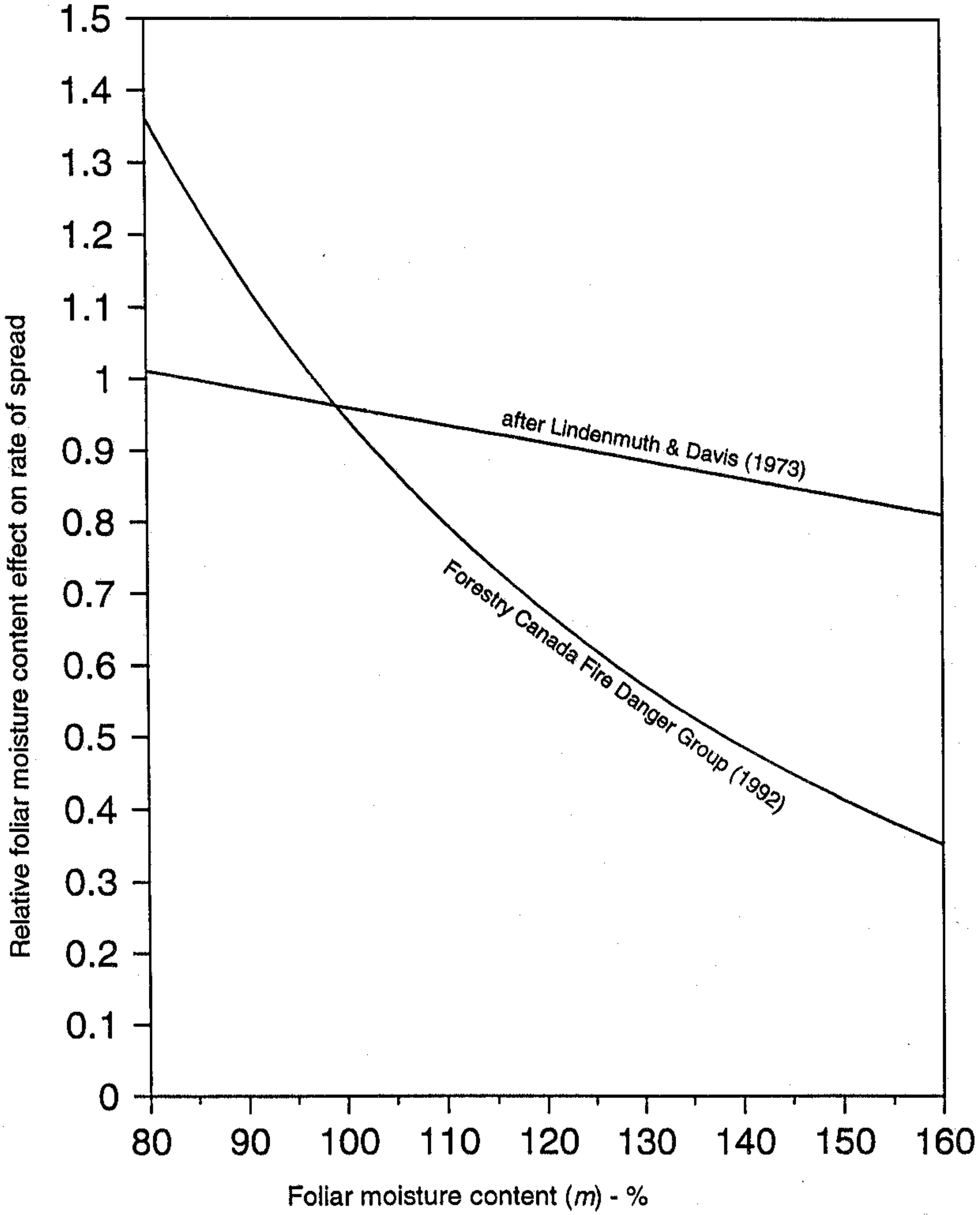


Figure 2.12: Relative effect of foliar moisture content on rate of fire spread in a conifer forest stand and a shrubfield.

2.4.4 Fire Intensities and Flame Sizes

As mentioned in Section 2.3, within the context of the Canadian FBP System, the crown fraction burned or CFB refers to the proportion of trees involved in the crowning phase of the fire and thereby defines, for a given preburn crown fuel load, the contribution of the crown fuel layer to $\boldsymbol{w}$ in Equation 2.1 when calculating $\boldsymbol{I_B}$ values for crown fires. Presumably, the CFB or degree of crown fuel involvement depends on the amount by which the actual rate of fire spread exceeds the spread rate associated with $\boldsymbol{I_o}$. In the FBP System, an exponential function was configured such that when this difference reached 600 m/h, CFB would equal 0.9. While the resulting formulation (Forestry Canada Fire Danger Group 1992, Equation 58) provides for a smooth transition, unfortunately CFB theoretically never equals 1.0, even at exceedingly high spread rates. A very simple alternative is to consider that full-fledged crown fire development (i.e., CFB = 1.0) takes place when the crown fire spread is twice the surface fire spread rate just prior to crowning and in the absence of any detailed empirical data, a linear relationship is assumed. This suggestion is predicated on the fact that a forest fire, as a minimum, typically doubles its spread rate following crowning (*cf.* McArthur 1965). A comparison of the current FBP System computational process with this alternative method is presented in Figure 2.13.

In crown fires, more so than with surface fire, the resulting "wall of flame" forms an effective barrier against the prevailing winds due to the great buoyancy established above the flaming front. As a result, the flames appear to stand vertical or nearly so (Van Wagner 1968), except under very strong winds (Van Wagner 1977a). Gill and Knight (1991) note that there are several possible measures of flame height, namely peak flame height, average height of a number of peaks minimum flame height and the average flame height. Typically when flame heights of crown fires are quoted in the literature, most observers don't make any such distinction. Very often extremes or peak values are cited. Byram (1959a) indicates that efforts to objectively and quantitatively measure flame sizes on crown fires is complicated by the fact that "... the sudden ignition of unburned gases in the convection column can result in flames flashes which momentarily extend several hundred feet [≈ 100-200 m] into the convection column aloft" (e.g., Barrows 1961); Sutton (1984), for example, has photographically documented one such flame flash that extended for at least 192 m above the ground over a radiata pine (*Pinus radiata*) plantation in southeastern South Australia during the infamous Ash Wednesday fires in 1983 (Keeves and Douglas 1983). Such flashes can easily result in overestimates of average flame heights "... which usually range from 50 to 150 feet [≈ 15-45 m] on high-intensity fires" according to Byram (1959a). Flame heights associated with crown fires have been quoted as varying from two to three to as high as four times (these instances are undoubtedly "peaks") the mean **SH** for wildfires and experimental fires with intensities of ≈ 5000 - 40 000 kW/m in conifer forests with **SH** values of ≈ 10-20 m (e.g., Geddes and Pfeiffer 1981; Rothermel and Mutch 1986; Stocks 1987b; Alexander 1991a), which is generally in line with Byram's (1959a) claim.

Byram (1959a) acknowledged that his empirically derived relationship (Adkins 1987; Nelson 1991) represented by Equation 2.2 would under predict $\boldsymbol{L}$ "... for high-intensity crown fires because much of the fuel is a considerable distance above the ground". He suggested, on the basis of personal visual estimates (Nelson 1991), that "... this can be corrected for by adding one-half of the mean canopy height [equivalent to **SH** used here] to ..." the value of $\boldsymbol{L}$ obtained by Equation 2.2. Byram (1959a) provided an example indicating that if Equation 2.2 "... gave

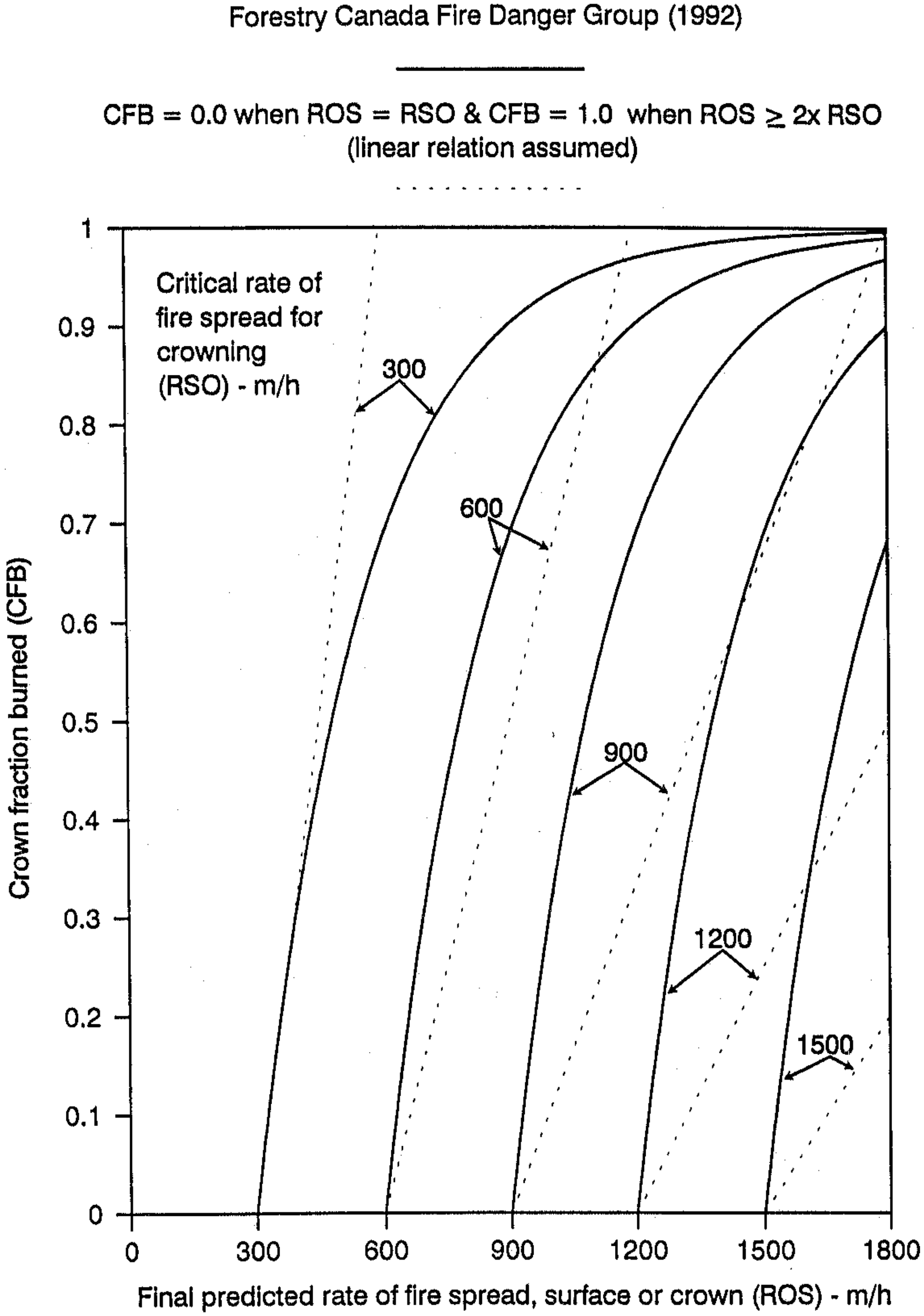


Figure 2.13: Proportion of crown fuel involvement as a function of head fire rate of spread for crowning forest fires.

an estimated value ... of 40 feet [≃ 12 m] and the mean canopy height is 60 feet [≃ 18 m], then the corrected estimate is 70 feet [≃ 21 m]", thereby implying that the flames would only extend about three metres above the tree tops of a conifer forest stand. An **L** value of ≃ 12 m would constitute an I_B of nearly 60 000 kW/m. On the basis of this example, Byram's (1959a) "model" for crown fire flame lengths would not appear to be realistic. Rothermel (1991a) has suggested that the L-I_B formulation of Thomas (1963) should provide a reasonable approximation of flame lengths for intensities typically experienced by crown fires (from Rothermel 1991b):

$$L = 0.0266\, I_B^{2/3} \tag{2.13}$$

According to Rothermel (1991a), C.E. Wan Wagner agreed that Thomas' (1963) relation represented by Equation 2.13 should represent crown fire flame lengths better than Byram's (1959a) model but also indicated that it may underestimate flame lengths for "... low-intensity crown fires". The following tabulation offers a comparison of the two approaches for predicting the flame lengths of crowning forest fires:

I_B level (kW/m)	Byram (1959a) surface fire **L** (m)	Byram (1959a) **SH** = 10 m crown fire **L** (m)	Byram (1959a) **SH** = 20 m crown fire **L** (m)	Thomas (1963) crown fire **L** (m)
4000	3.5	8.5	13.5	6.7
10 000	5.4	10.4	15.4	12.3
30 000	8.9	13.9	18.9	25.7
100 000	15.5	20.5	25.5	57.3

This tabulation coupled with documentation available for experimental crown fires (Table 2.2) supports the above suspicion that Byram's (1959a) crown fire flame length model would consistently result in underestimates except perhaps at the lower intensity levels (say less than 5000 kW/m) in short to moderately tall conifer forest stands. Thomas' (1963) relation as an alternative means of predicting crown fire flame lengths as advocated by Rothermel (1991a) appears to produce reasonable values over a fairly wide range of intensities (Table 2.2) although there are obviously some inconsistencies in predictions at intensities above 10 000 kW/m. This could very well be due to differences in stand structure (i.e., **SH** and z) and the fact that wind speed is not considered in Equation 2.13. For example, the wind speed that prevailed during the red pine plantation experimental crown fire C4 (Van Wagner 1968) was slightly less than the C6 experimental crown fire in the same fuel complex. The reservation expressed by C.E. VanWagner (*in* Rothermel 1991a) concerning the use of Equation 2.13 for crown fire flame lengths would appear to be unfounded on the basis of the available documentation (Table 2.2).

Albini and Stocks (1986) used the following relation, based on a flame structure model originally advanced by Albini (1981a), to calculate flame heights for the experimental crown fires reported on by Stocks (1987b) in an immature jack pine stand in north-central Ontario, Canada, in their testing of a physical model for predicting crown fire spread rates referred to in Section 2.4.3 (after Albini and Stocks 1986):

$$h_F = \frac{0.00618\, I_B}{u} \tag{2.14}$$

Table 2.2: A comparison of observed flame lengths from published accounts of experimental crown fires in various Canadian forest fuel types with predictions from two existing models.

Source of information	Experimental fire number or identification	Fuel complex	z (m)	U_{10} (km/h)	Actual I_B (kW/m)	Observed L (m)	**SH** (m)	Byram (1959a)		Thomas (1963) L (m)
								Surface L (m)	Crown L (m)	
Van Wagner (1968)	R1	Red pine plantation	5.8	15	7300	15	12.2	4.6	10.7	10.0
Van Wagner (1968)	C4	Red pine plantation	7.0	23	21 100	21	15.0	7.6	15.1	20.2
Van Wagner (1968)	C6	Red pine plantation	7.0	19	22 500	30	15.0	7.8	15.3	21.2
Kiil (1975)	-	Black spruce forest	1.5	19	4180	5	4.4	3.6	5.8	6.9
Newstead and Alexander (1983)	Tenogum	Black spruce forest	1.9	6	3680	5+	5.4	3.4	6.1	6.3
Newstead and Alexander (1983)	Water	Black spruce forest	1.4	6	4230	5+	4.6	3.6	5.9	7.0
Albini and Stocks (1986)	13	Jack pine forest	4.0	15	15 790	17	10.0	6.6	11.6	16.7
Stocks (1987b)	11b	Jack pine forest	4.0	21	40 900	20	10.0	10.2	15.2	31.6

where h_F in this case represents the flame extension above the fuelbed or in other words above ***SH***. Furthermore, ***u*** in this case is taken to be the mean wind speed over the flame height. In their calculations of I_B using Equation 2.1, Albini and Stocks (1986) set H = 22 000 kJ/kg and used the observed crown fire spread rate for ***r***. However, for ***w***, only the crown fuel consumed was considered. The coefficient 0.00618 in Equation 2.14 is "... a dimensional constant that depends weakly upon fuel characteristics" (Albini and Stocks 1986) and was derived in part from estimates made of flame tilt angle and flame height taken from still photographs of experimental fire 13 (*see* Stocks 1987, p. 85, Fig. 4). The model form represented by Equation 2.14 for predicting crown fire flame heights is presumably self-consistent so long as the flames are not too short (i.e., half the **CD**). One needs to utilize a fluid mechanical model such as Grishin's (1992) to have a completely consistent description of flame height from the ground surface to up above the tree crowns as I_B increases. A proven L-I_B model specifically for crown fires is needed to support models dealing with other characteristics of crown fire behaviour (e.g., Venkatesh and Saito 1992).

2.4.5 Elliptical Fire Shapes

Although the perimeter or outline of a free-burning fire originating from a single ignition source may be very irregular, the overall shape can quite often be represented by a simple, smooth ellipse provided the prevailing wind is more or less unidirectional, although other similar shapes have been suggested; for reviews on this subject refer to Anderson (1983) and Alexander (1985a). The most fundamental property of an elliptical shaped fire is its length-to-breadth ratio (L/B) (McArthur 1966c; Cheney 1981; Alexander 1985a) which is synonymous with length-to-width ratio (Anderson 1983; Andrews 1986a; Rothermel 1991a). L/B is generally regarded as a function of wind speed (Fig. 2.14). The higher the wind speed the more narrow and elongated the fire shape (Alexander et al. 1988). An estimate of fire size (i.e., area burned and perimeter length) and growth rate can in turn be made on the basis of the L/B coupled with the fire's overall linear spread.

In presenting the relationships depicted in Figure 2.14, the American models of Anderson (1983), Andrews (1986a), Rothermel (1991a) and Finney (1998), which use 6.1-m (20-ft) open winds (Crosby and Chandler 1966; Finklin and Fischer 1990) instead of the international standard 10-m open winds as an input were adjusted by increasing the wind speeds by 15% as per Turner and Lawson (1978, p. 27, Appendix 6) in order to be compatible with the Canadian (Alexander 1985a, Equation 35; Forestry Canada Fire Danger Group 1992) and Australian (McArthur 1966c; Cheney 1981) L/B models. In the Canadian models, a single function is deemed applicable for both surface and crown fires in conifer forests where U_{10} is inputed directly as is the case with the Australian model for grasslands. In contrast, the American models require the 6.1-m (20-ft) open winds be adjusted to a "mid-flame height" (Albini and Baughman 1979; Baughman and Albini 1980) by a wind adjustment coefficient or factor. In the case of crown fires, this has been taken to be 40% (Rothermel 1991b) or alternatively one half (Rothermel 1991a; Finney 1996) of the 6.1-m (20-ft) wind speed while others have chosen not to apply a reduction (e.g., Simard et al. 1983) as has been done here (Fig. 2.14) and elsewhere (Alexander 1985a, p. 294, Fig. 7b) in the absence of any definitive guidelines. The Canadian and Australian models are empirically based (i.e., they were derived from observation of experimental and wild fires, both surface and crown in the former case)

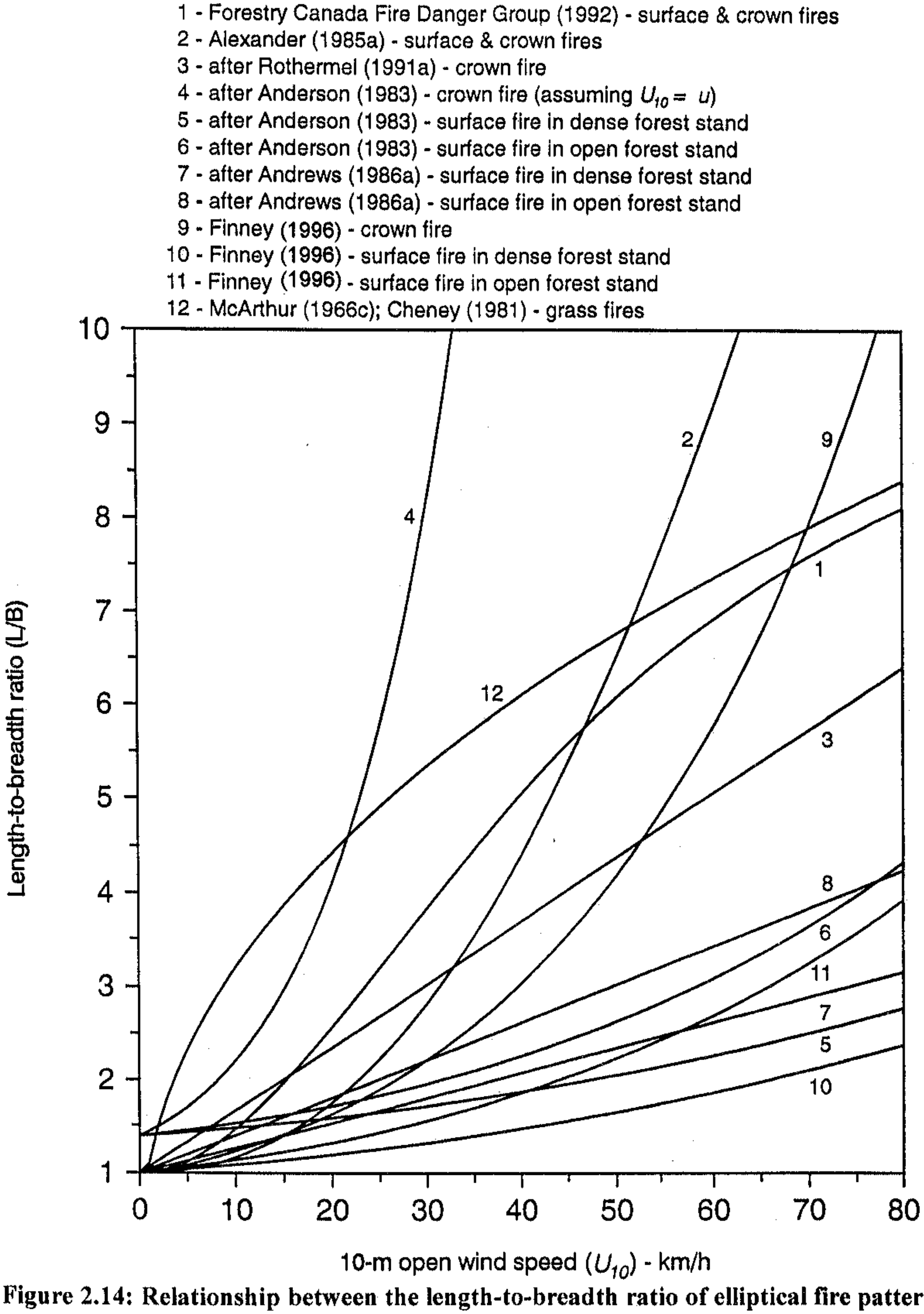


Figure 2.14: Relationship between the length-to-breadth ratio of elliptical fire patterns in forests and grasslands versus wind speed, as determined for the international standard height and exposure of 10-m in the open on level terrain, according to various Canadian (Alexander 1985a; Forestry Canada Fire Danger Group 1992), American (Anderson 1983; Andrews 1986a; Rothermel 1991a; Finney 1996) models and Australian (McArthur 1966c; Cheney 1981).

whereas the American models are to one extent or another based on the series of small-scale experimental fires conducted in a wind tunnel by Fons (1940a).

A cursory examination of the predictions from any of the American models with the observational data on L/B for crown fires compiled by Alexander (1985a) suggests that they are not robust enough over a practical range in wind speeds (say from 15-50 km/h) to produce realistic estimates. Even the model predictions for surface fires in grasslands in comparison to the Australian data and model (McArthur 1966c; Cheney 1981) are wholly inadequate (*see* Alexander 1985a, p. 294, Figs. 7a and 7b). Rothermel (1991a) acknowledged that Anderson's (1983) model "... does not reduce to a circle at zero windspeed and produces elongated fires at high wind speeds" as illustrated for example by Alexander (1985a, p. 294, Fig. 7b). The latter issue has already been mentioned above. Anderson's (1983) model does indeed produce an anomalous result at zero wind, namely L/B ≈ 1.4, when logically one would expect a circular fire or L/B = 1.0. Andrews (1986a) and Rothermel (1991a) have corrected this deficiency by simply producing equations which avoid this y-intercept problem, although no details of the derivations are given, whereas Finney (1996) has simply subtracted ≈ 0.4 from the resultant value so as to achieve an L/B = 1.0 at zero wind which in turn depresses the overall relationship (Fig. 2.14). Following ignition, a surface fire first burns out from its source in a circular pattern and then begins to assume an elliptical shape (Curry and Fons 1938; Alexander, Stocks and Lawson 1991). McAlpine (1988, 1989) has clearly shown that the L/B of point source fires carried out in wind tunnels with relatively narrow fuelbeds (generally less than a metre wide) similar to that used by Fons (1940a) will not have stabilized or reached an equilibrium state by the time the flanks of the fire reach the edges of the fuelbed, thereby questioning the reasonableness of the American models. In evaluating his model against the shape of several documented wildfires that exhibited extensive crowning, Anderson (1983) ended up selecting wind reduction coefficients or factors so that the predicted L/B from his model would match the observed L/B. Of course this approach assumes that the basic underlaying model is valid which given the preceding discussion does not appear to be the case.

2.4.6 Atmospheric Conditions Aloft and Extreme Fire Behaviour

Extreme fire behaviour is generally defined as a level of fire behaviour that (from Merrill and Alexander 1987):

> ... *often precludes any fire suppression action. It usually involves one or more of the following characteristics: high rate of spread and frontal fire intensity, crowning, prolific spotting, presence of large fire whirls, and a well-established convection column. Fires exhibiting such phenomena often behave in an erratic, sometimes dangerous, manner.*

Various meso- and synoptic-scale atmospheric conditions where there is an obvious direct connection to extreme fire behaviour include the strong surface winds associated with frontal passages (Brotak 1977; Brotak and Reifsnyder 1977) and downdrafts from thunderstorms (Cramer 1954; Krumm 1959; Schroeder and Buck 1970; Haines 1988a). Less discernible processes include large-scale subsidence (Krumm 1959; Schroeder and Buck 1970), the presence of a jet stream over a fire area (Schaefer 1957; Dieterich 1976; Flannigan and

Harrington 1987), atmospheric instability or turbulence (Byram and Nelson 1951; Reifsnyder 1954; Davis 1969; Haines and Upike 1971; Goens 1978; Haines 1988b) and the wind speed and direction profiles in the lower atmosphere (Byram 1954, 1955, 1959b; Anon. 1957a; Taylor 1962; Kerr et al. 1971; Steiner 1976; Baughman 1981).

A number of wildland firefighter fatality incidents in the U.S.A. in the 30s, 40s and 50s (Wilson 1977a) drew attention to the so called "blowup fire" (Arnold and Buck 1954; Byram 1954; Colson 1956; Anon. 1957b), most notably the 1949 Mann Gulch Fire in Montana (Maclean 1992; Rothermel 1993). Byram (1954) regarded a blowup fire as one "... which suddenly, and often unexpectedly, multiplies its rate of energy output many times". He also considered blowup fires to exhibit intensities that seemed "... far out of proportion to apparent burning conditions", a distinction which generally has been forgotten over the years for as Rothermel (1991b) points out, the term "blowup" or blowup fire "... has become so commonly used for any fire that suddenly increases in rate of spread or intensity that the unique character of these fires..." has been somewhat forgotten over the years (e.g., Bates 1962; Argow 1967; Burrows 1984b; Goens 1990).

G.M. Byram was a pioneer in analyzing the possible contributions that atmospheric conditions aloft played in extreme fire behavior situations (USDA Forest Service 1991; Nelson 1996a; *see* also the annual reports of the USDA Forest Service's Southeastern Forest Experiment Station during the 1950s). Beginning in about 1950 or so, he began studying the mechanisms involved in the development and nature of high-intensity wildfires by combining what he termed the "case study method" (Byram 1954, 1960) with related analytical work on the subject. Byram (1959a) eventually proposed a theory for discerning the occurrence of wind-driven, high-intensity crown fires from blowup fires on the basis of the ratio of the rate at which the heat or thermal energy produced by the fire itself is converted into turbulent or kinetic energy of motion in the fire's convection column, termed the "power of the fire" (P_f), compared with the rate of energy flow in the wind field or in other words the "power of the wind" (P_w). To make these comparisons required the derivation of two energy criterion equations that determine the conditions under which a fire will either "blow up" and become a free-convection phenomenon controlled by its own thermal energy and perhaps thereby result in erratic, unpredictable fire behaviour (i.e., $P_f > P_w$), or exhibit the features of forced convection in which the energy flow in the wind field dictates the ensuring fire behaviour and is presumably predictable (i.e., $P_f < P_w$). Byram eventually referred to the dimensionless ratio P_f/P_w as the "energy rate number" (Byram 1960; Wendell et al 1962) and a little later on as the convection number or N_c (Byram et al. 1964). Butler and Reynolds (1996) have chosen to express Byram's N_c concept as P_w/P_f rather than P_f/P_w but offered no explanation for this change in convention.

The relevant equations associated with Byram's energy criterion concept for a neturally stable atmosphere are as follows (after Nelson 1993a, 1993b):

$$P_f = gI_B\, a/c_p T_o \tag{2.15}$$

$$P_w = \rho\, (v - r)^3\, b/2 \tag{2.16}$$

$$N_c = P_f/P_w \tag{2.17}$$

where P_f is the rate at which thermal energy is converted into kinetic energy in the convection at height Z above the fire (kW/m^2), P_w is the rate of energy flow in the wind field at height Z above a fire (kW/m^2), g is the acceleration of gravity (= 9.8 m/sec^2), I_B is the head fire intensity as defined by Byram (1959a) (kW/m), c_p is the specific heat of air at constant pressure (= 1003.9 J/kg·K), T_o is the free-air temperature at the elevation of the fire (°K), ρ is the air density at height Z above a fire (m/sec), r is the head fire rate of spread (m/sec), v is the wind speed at height Z (m/sec), and a (= 1.0) and b (= 0.001) are simply factors for converting from force to mass times acceleration and from force to energy per unit length (Nelson 1993a); note that $(v - r)$ represents the wind speed relative to the speed of the fire front rather than a fixed point on the ground. Though ρ decreases slightly with increasing Z, it is held constant here for computational purposes because the change in ρ in the first couple of thousand metres elevation is very small (List 1951). Rothermel (1991a) used a constant value for ρ (1.09 kg/m^3), however, a value of 1.11 kg/m^3 seems more appropriate (*cf.* Nelson 1993a), at least for Z up to ≈ 2500 m MSL. Given this and the fact that g and c_p are constants, then only T_o, I_B, v and r are needed operationally. Note that when $v = 0$ (i.e., calm on no wind condition), $N_c = \infty$ (Byram et al. 1964), although even for a "calm" wind condition, U_{10} is regarded as <1 km/h or < 0.2 m/sec (List 1951, p. 119, Table 36) so perhaps $v = 0.0$ occurring in the field is really a fallacy, although it could obviously exist in the laboratory (Byram et al. 1964; Martin et al. 1991; Weise 1993; Weise and Biging 1996).

Although there may be some value in knowing both P_f and P_w, for normal computational purposes, Equations 2.15 and 2.16 could simply be combined and allowing for conventional units of measurement in fire management operations, the result is that Equation 2.17 can be expressed simply as:

$$N_c = 19.6\, I_B/1.114329\, (T_a + 273.16)\, [(U/3.6) - (R/3600)]^3 \qquad (2.18)$$

where, T_a is the ambient air temperature at the elevation of the fire (°C), U is the wind speed (km/h) at height Z and R is the head fire rate of spread (m/h).

According to Byram's (1959b) theory, when P_f/P_w or N_c exceeds unity, rate of spread as well as fire intensity and other fire behaviour characteristics are presumably judged to be independent of surface winds speed and fire behaviour would in turn become dependent on the winds aloft (Chandler et al. 1963). Byram (1959b) claimed from his case study analyses of wildfires that had occurred throughout the U.S.A. between about 1939 and 1957, that "blowups" were most likely to occur when P_f/P_w or N_c was equal to or greater than a value of 1.0 for at least ≈ 300 m (≈100 ft) above the fire, in which case the fire dominates the wind field and a pronounced convection column forms. In this way, the vertical wind speed profile determines how P_f/P_w or N_c varies with height in the lower atmosphere. Speeds ordinarily increase with height for several hundred metres above the earth's surface. The most favourable condition for the situation that Byram (1959b) found was conducive to blowup fire occurrences is the presence of a "low-level jet wind" (i.e., there is initially a zone of increasing wind speed with height near the earth's surface and then a zone of decreasing velocity above the "jet" point of maximum wind speed which generally occurs at about 500 m above ground level). Theoretically, when $N_c < 1.0$ for a considerable difference above a fire, the fire is completely dominated by the wind field. Byram (1959b) considered that possibly one of the most erratic fire behaviour situations is in the transition zone where P_f and P_w are nearly equal.

Byram (1959b) considered that blowup fires or high-intensity free-convection fires dominated by their own energy would produce "... dynamic convection columns..." that exhibit very distinct motion or movement of hot gases upwards into the convective plume's central core. For this reason, blowup fires are often characterized by the development of a strong, well-established convection column or plume towering above the spreading fire rather than leaning over in the direction of the wind as is the case with wind-driven or wind-dominated fires which may not actually form true convection columns under very high velocity winds but rather just smoke plumes. It's generally been surmised that the spectacular spread and behaviour of blowup fires in view of the associated burning conditions was a result of the momentum feedback from the vertical velocity in the fire's convection column which causes turbulent indraft winds and thereby promotes rapid combustion leading to increased fire intensities, a process that presumably reinforces itself (*see* Gaylor 1974, p. 132, Fig. 3.53). Rothermel (1991a, 1991b) considered that the increased convective and radiant heat transfer in such instances was responsible for the exceptional rates of fire spread, in light of the prevailing wind speeds. However, the higher than normally expected spread rates could also be due to high-density, medium-range spotting and firewhirls (Byram et al. 1964; Berlad and Lee 1968; Lee 1972; Cheney 1981, 1983). Rothmel (1991a, 1991b, 1995) choose to enunciate the importance of crown fires with well-defined convection columns by referring to them as "plume dominated" in contrast to crown fires that are driven by the force of strong winds (*see* also Davis and Mutch 1995, pp. 227 and 228, Figs. 9-16 and 9-17). Other authors have used the term "convectively driven" (e.g., Byram 1966) or "convection dominated" (e.g., Cheney and Bary 1969). Plume-dominated fires presumably can cause strong downdraft winds (Rothermel 1991a) and induce lightning and thereby start new fires (Gill 1974).

Rothermel (1991a, 1991b, 1995) has used Byram's (1959b) ratio of $\boldsymbol{P_f}$ to $\boldsymbol{P_w}$ (only level terrain situations can currently be considered) as a means of judging whether crown fires are likely to be wind-driven versus plume-dominated or "blowups" based on the wind speed measured, forecasted or estimated at the 6.1-m (20 ft) open standard as used in the American fire danger rating and fire behaviour prediction systems. (Deeming et al. 1977; Rothermel 1983; Finklin and Fischer 1990) for $\boldsymbol{U}$ in Equation 2.18 rather than considering significance of wind speeds at other heights above the ground and in turn $\boldsymbol{N_c}$ or $\boldsymbol{P_f/P_w}$ as Byram (1959b) had found from his wildfire case study analyses. This would appear to be a major point of departure in the operational implementation of Byram's (1959b) findings concerning his energy criterion for wildland fires. For example, by Rothermel's (1991a, 1991b, 1995) criteria where only one calculation of $\boldsymbol{P_w}$ is considered at $\boldsymbol{Z} = 6.1$ m (or 10 m when $\boldsymbol{U_{10}}$ is equated to $\boldsymbol{U}$), all ten of the experimental crown fires that occurred in an immature jack pine stand in north-central Ontario, Canada, as described by Stocks (1987b) would be regarded as plume-dominated because in all cases $\boldsymbol{N_c}$ was greater than unity (*see*, for example, Call 1997, p. 29, Table 1). The fact that Stocks (1987b, p. 84, Fig. 3) showed that the spread rates of these experimental fires as well as several high-intensity wildfires in similar jack pine fuel complexes exhibited such a consistent pattern when plotted together against a function of wind speed and fine dead fuel moisture, would suggest that Rothermel's (1991a, 1991b, 1995) criteria for plume-dominated or blowup fires is not discriminating enough.

Byram's $\boldsymbol{P_f/P_w}$ concept or $\boldsymbol{N_c}$ has been used in the analysis of several relatively well-documented wildfires (e.g., Wade and Ward 1973; Simard et al. 1983; Aronovitch 1989). In simplistic terms, $\boldsymbol{N_c}$ can be regarded as a "... method of comparing the rate the fire is doing work by thermal convection ... [i.e., $\boldsymbol{P_f}$] with the work the winds are performing to overcome work by thermal convection ... [i.e., $\boldsymbol{P_f}$] with the work the winds are performing to overcome the thrust of the convection column ... [i.e., $\boldsymbol{P_w}$]" (Wade and Ward 1973). The use of $\boldsymbol{N_c}$ might possibly help to explain why certain strong wind-driven, high-intensity fires exhibit little or no crowning activity (e.g., Luke and McArthur 1978; Dieterich 1979; Buckley 1990, 1992; NFPA 1992; Smith 1992) while others do (e.g., Schaefer 1957; Prior 1958; Keeves and Douglas 1983; McCaw et al. 1992). For example, during the multiple fire situation on 16 October 1991 in the Spokane region of eastern Washington (NFPA 1992) where 10-m open winds were averaging in excess of ≈ 50 km/h (Alexander and Pearce 1992a) it was noted that "Unlike other severe wildland fires ... crowning was limited. The high velocity of the winds did not allow the thermal columns from the fires to reach the crowns. Fast-moving ground [surface] fires were more typical ...". Cheney (1981) has also pointed out that the "...amount of crown fire activity appears to be reduced..." when winds are strong. Luke and McArthur (1978) explain further:

> *Although rate of spread are greatly increased with increasing wind speed, flame heights are correspondingly reduced. This partly explains why crown fires do not always occur when wind speeds and rates of spread are high. This was documented in the southern Tasmanian fires of 7 February 1967 when very few forest fires crowned. Average wind velocities of 80 km/h were recorded in the open on that day, equivalent to wind speeds of 16-18 km/h close to ground level in low quality dry sclerophyll eucalypt forest and around 13 km/h in a tall eucalypt forest. At high wind speeds the flame angle became very acute and from observation it appears that any fires in the crowns were immediately blown out by the very strong at treetop height. Flame flashes occurred but only occasionlly consumed whole tree crowns.*

The lack of crowning in such cases could possibly be due to a decrease in the flame front residence resulting from fuel conditions (i.e., the amount, variation in bulk density with depth and moisture status/gradient) as well as the inclination of the convection column or fire plume.

Nearly 50 years has elapsed since G.M. Byram began his classic pioneering studies regarding the possible causal connections between atmospheric conditions aloft and extreme fire behaviour. Much has been written since, yet inspite of considerable observational and statistical evidence (e.g., Rothermel and Gorski 1987; Brotak 1991; Werth and Ochoa 1993) which has not always been conclusive (e.g., Potter 1996) linking temperature, moisture and wind characteristics in the lower couple of thousand metres of the atmosphere to large, high-intensity fire occurrences, there still remains doubt as to validity of the concept and/or the actual physical processes involved. Van Wagner (1985) makes the following statements concerning the blowup fire issue:

> *When a fire becomes very intense, there is no wonder that its principal manifestation is a huge convection column. Consider that every kilogram of fuel requires 5 m^3 of air to supply its basic oxygen need, and produces upwards of 0.5 kg of water vapor in the process. Furthermore, several times this amount of air may be entrained by the time the combustion products leave the flame zone. All this gas is then heated to flame temperature and thereby endowed with tremendous buoyancy. But is this immense superstructure to be dealt with as cause or effect? Does the main control of fire behavior still reside in the high temperature region*

> *of fuel and flame, or has some distinct discontinuity of process taken over? Can a forest fire become a true mass fire so that all air inflow is centripetal? If so, how does it spread? Does it matter whether the convection column breaks through to a towering mushroom, or blows out at a pronounced angle (except for spotting potential)? If certain features of the atmosphere-in-depth have been identified as associated with extreme fire behavior, are these features also well correlated with weather near the ground? This last questions sums up the problem as it relates to everyday fire danger rating systems, Do we or do we not need an additional atmospheric variable, as well as the standard surface weather observations, to account for the extreme end of the intensity range? It seems to me that the definitive answers to all these questions are still waiting in the wings.*

Admittedly, Byram's N_c theory and criteria for blowup fires has been successfully validated independently by others in a couple of cases, mostly notably by Wade and Ward (1973).Still other investigators have found the relationship between the variation in N_c with height and observed fire behaviour to be inconclusive (e.g., Ward and Nelson 1972) and a number of uncertainties still exist with respect to various assumptions underlying Byram's theory (Nelson 1993b, 1994). With respect to the significance of upper level winds on fire behaviour, Luke and McArthur (1978) had this to say:

> *Workers in North America have given considerable importance to upper wind profiles as determinants of convection column formation and, to some extent, fire behaviour...*
>
> *In Australia there appears to be no strong evidence to suggest that the upper wind profile plays an important role in determining fire behaviour in forest or grassland situations. Towering convection columns to 7500 m or more have been observed in both grasslands and forest situations associated with very fast-spreading fires yet these have been burning under wind profiles which theoretically should not allow this type of convection column development.*

Furthermore, Rothermel (1991a 1991b) claims that both the 1980 Mack Lake Fire which occurred in the jack pine forests in northern Michigan, U.S.A. (Simard et al. 1983) and the 1985 Butte Fire which occurred in lodgepole pine forests in central Idaho, U.S.A. (Rothermel and Mutch 1986) were both blowup or plume-dominated crown fires. Yet, their average spread rates are in general agreement with Canadian observations and models in similar fuel complexes for the comparable burning conditions (Stocks 1987b, 1989; Alexander 1991a).

As alluded to earlier on, the attention given to extreme fire behaviour and the possible role(s) of atmospheric conditions aloft has in the past and continues to be driven to a very large extent by wildland firefighter fatalities, especially in the U.S.A. This makes it difficult to separate human factors from technical issues. In discussing the prediction of blowup fires or "... unexpectedly severe fire behaviour ..." in the jarrah (*Eucalyptus marginata*) forest of Western Australia, Burrows (1984b) makes some excellent points germane to the present discussion:

> *... any fire burning in dry conditions has the potential for rapid and violent build-up in intensity, or rate of spread, threatening the lives of unwary fire fighters.*

> *Forest fires behave according to reasonably well understood physical laws. If fire fighters understand these interactions they will be better able to anticipate lethal situations...*
>
> *Experienced fire fighters expect fires burning under heavy fuel and severe weather conditions to display violent behavior. The dangers of such fires are obvious, and precautions and suppression strategies are implemented accordingly. However, it has often been small fires burning under seemingly mild conditions which have, for no apparent reason, escalated in behaviour, and endangered the lives of fire fighters...*
>
> *Expectations of how a fire should behave are based largely on experience, and to a lesser extent, on fire behaviour guides.*

Burrows (1984b) felt that certain wildfires were considered unusual only because the changes in the conditions influencing the fire's behaviour were either not anticipated or were severely underestimated. In commenting on the value of experienced judgement in predicting fire behaviour Gisboune (1948) expressed the view that unless one has had experience with "... all sizes of fires in all kinds of fuel types under all kinds of weather, then your experience does not include knowledge of all the conditions". The guidelines for estimating the probability of extreme fire behaviour, including crown fire potential, have steadily involved over the years (*see* Sections 1.3 and 2.5) largely from a qualitative basis to a far more quantitative nature, yet they have presumably been adequate as general indicators for their time. For example, Byram (1954) noted that the fire danger rating systems in use in the southeastern U.S.A. in the early 50s were capable of giving "... advance warning when fuels are approaching the point where they will support conflagration-type fires". However, the predictive capability of such guides are dependent to a large extent on various fire weather inputs, either observed or forecasted. Assuming that surface burning conditions (e.g., fuel type, fuel moisture, slope) have been properly evaluated and fire weather forecasts are reasonably valid and applied (Cuoco and Barnett 1996), some of the unexpectedness associated with extreme fire behaviour should to a large extent be eliminated. In this reagard though, it's worth noting that Chandler (1976) found that more than half the weather-related incidents causing loss of life or property during large wildfires in the U.S.A. that the examined were the result of mesoscale phenomena (i.e., those weather changes which result from causes too localized to be identifiable from the basic network observations, yet too widely separated to be reasonably deduced from observations at a single local station) and therefore if any significant improvement in fire danger rating performance or fire behaviour prediction reliability was going to be achieved, accurate timely mesoscale forecasts would be needed. Even then the onus is on the individual to properly consider how all the forces influencing fire behaviour will align themselves (Campbell 1995).

At the USDA Forest Services's 1980 National Fire Behavior Research Conference, it was acknowledged that the connections between certain wind profile types and atmospheric stability to severe fire behaviour had been postulated in the past, but such relationships had never been definitely refuted nor substantiated (Anon. 1980). At the USDA Forest Service's Atmospheric Sciences Research and Application Workshop two years later the following statements were made concerning fire/atmospheric interactions and extreme fire behaviour (from Anon. 1982):

> *Erratic or unanticipated fire behaviour has been cited as the most significant cause of casualties in fire suppression. Although no causal connection has been demonstrated between such behavior and interactions between fire and atmosphere, such a connection has been suspected many cases. The phrases "fire blowup" and "erratic fire behavior" have been used to describe unexpected severe fire behavior. Research investigation of such phenomena has been suggested several times; but, to date, little in the way of guidance of a practical nature has been produced. The reason for this is that the mechanisms of fire/atmospheric interaction on the mesoscale are complex, so models of the processes have not been developed.*

Computer simulations like those recently undertaken by Clark et al (1996a, 1996b) and others working in this area using coupled fire-atmosphere models perhaps in conjunction with a geographic information system (GIS)-based fire growth model (e.g., Finney 1996), may finally help to answer some of the questions that have plagued wildland fire behaviour research scientists and specialists alike for over 50 years. Outdoor experimental fires will no doubt be required as well. It's also equally apparent that these efforts must also be combined with a more concerted, systematic approach to monitoring and documentation of going wildfires such as was undertaken by the USDA Forest Service's Southern Forest Fire Laboratory between the late 50s and early 70s (e.g., Wendell et al. 1959; DeCoste and Sackett 1966; DeCoste et al. 1968; Wade and Ward 1973) but using the latest technology for monitoring fire behaviour and atmospheric conditions aloft (e.g., Ogilvie et al. 1995).

2.5 Operationally Appraising Crown Fire Potential

Some 45 years ago Barrows (1951) outlined a basic 5-step process to the "art and science" of predicting wildland fire behaviour that is still valid today. The most significant "change" has been in the gradual sophistication of the "aids and guides" to evaluating the fire environment (Countryman 1972). Rothermel (1987) has articulated the perpetual challenge faced by wildland fire behaviour model developers in meeting the present and future needs of fire practioners:

> *... experience shows that predicting fire behavior is not easy and that the fire prediction systems and their models are not perfect. Users who want more accuracy urge us to include additional features such as methods for accounting for nonuniform fuels, or description of nonsteady state fire behavior. In contrast, those who believe the system is too complicated would like a bare-bones product that anyone can pick up and learn to use quickly. Viewing this situation and attempting to serve these needs leads to the paradox:*
>
> - *The models and systems aren't accurate enough*
> - *The models and systems are too complicated*
>
> *The resolution of either one of these problems worsens the other.*
>
> *The best example of increased complexity can be found in the fine dead fuel moisture model several of us produced recently (Rothermel et al. 1986). The primary aim was to increase the accuracy of fine fuel moisture predictions. We tried*

> *to account for a large number of factors ... The result was a better model. But more dramatically, we identified 52 variables that might be required ...*

Persumably what is required at the field level are crude but reliable models or decision aids for predicting fire behaviour (Lawson 1989), including crown fire-related phenomena, which wildland fire behaviour research should be able to provide (Alexander 1991e). If they are "... complicated, then the complexity should be buried out of sight, as in prepared tables or computer programs" (Van Wagner 1971).

In general terms, the requirements for extreme fire behaviour in a forest environment, such as the occurrence of a high-intensity crown fire, are fairly well known given an ignition source during or before the following predisposing conditions (Barrows 1951; Byram 1954, 1955, 1959b; Beale and Dieterich 1963; Cheney 1976, 1985a, 1985d, 1989; Burrows 1984b; Beighley and Bishop 1990; Rothermel 1995):

- continuous fine fuels in sufficient quantity, both vertically and horizontally;
- a dry spell of sufficient length to reduce the moisture content of dead fuels to a uniformly low level coupled with high air temperatures and/or low relative humidities;
- strong winds and/or steep slopes; and
- an unstable atmosphere.

One very common misconception concerning the development of crown fires is that a prolonged or severe drought is a necessary prerequisite. This perception has probably been perpetuated in part by the conditions associated with major disastrous wildfires (Haines and Sando 1969; Noble 1977; Cohen and Miller 1978). Crown fires are more likely to occur under a prolonged drought simply because more fuel is generally available for combustion which in turn increases the potential surface fire intensity. This is not to suggest that extreme fire intensities are not possible in certain hardwood or deciduous forest fuel types which are normally considered to exhibit relatively mild fire behaviour (Quintilio et al. 1991).

Determining the specific environmental conditions conducive of a crown fire, and then making a prognosis of the probable rate of spread and intensity for a particular site is nothing less than a complete system for the prediction of wildfire behaviour. Furthermore, as Van Wagner (1979b) points out, "The prediction of surface fire behavior is, in fact, probably more difficult than the prediction of crowning potential, because of the multiplicity of possible forest floor and understory fuel complexes". Thus, the degree of sophistication in estimating crown fire potential simply reflects our current state of knowledge gained through field experience and advances in the science of fire behaviour at any given moment in time. The earliest methods relied solely on current weather elements such as relative humidity and/or wind speed as a means of judging fire potential, including the likelihood of crowning fire development (Show and Kotok 1925; Gisborne 1929), and gradually evolved into rudimentary indexes for rating fire danger that considered several weather elements and other factors (Brown and Davis 1973; Chandler et al. 1983; Luke and McArthur 1978; Van Wagner 1987).

2.5.1 Fuel Type and Fire Hazard Classification Schemes

Beginning in the early 1930s, the methodology was established for classifying fuel types on the basis of obvious properties, taking into account topography, and then applying objective rankings to each type in terms of "rate of spread-resistance to control" such as "Medium-Medium (M-M)" (*see*, for example, Barrows 1951). This concept of fuel appraisal lasted for nearly 40 years (Muraro 1965, Brown and Davis 1973). Since then a great many other schemes have appeared (e.g., Wendel et al. 1962, Fahnestock 1970; Walker 1971; Coulter 1980; Fischer 1981; Chrosciewicz 1983) as a guide specifically designed for appraising crowning potential, Fahnestock's (1970) his dichotomous keys for rate of spread and crowning potential are certainly the most well known. Various semi-quantitative guidelines exist. For example, Dr. J.K. Brown (*in* Aldrich and Mutch 1973) of the USDA Forest Service's Northern Forest Fire Laboratory in Missoula, Montana, suggested that the potential for crown fire development in a conifer forest stand should be considered "high" when z is 3.0-6.1 m (10-20 ft) or less and one of the following conditions exist:

- The surface fuel load of material less than 7.6 cm in diameter is reated "medium" (4.5-11.2 t/ha [2-5 T/Ac]) or "heavy" (> 11.2 t/ha [> 5 T/Ac]) and there are ≈ 500-750 trees per hectare (200-300 trees per acre) in the 0-2.5 cm diameter-at-breast height outside bark (**DBHOB**) size class.

- The surface fuel load of material 7.6 cm in diameter is rated "heavy" (Fig. 2.15) and trees < 2.5 cm **DBHOB** are present.

No doubt other fire hazard classifications will appear, especially in light of the increasing fire problems at the wildland-urban interface (Davis 1986). None of these approaches predict when (only perhaps whether) to expect the onset of crowning, let alone the ensuing fire behaviour characteristics. Their technical bases vary from the intuitive judgement of experienced fire researchers and/or manager to preconceived criteria, sometimes based on theoretical considerations. The style of presentation varies from qualitative ratings (e.g., nil to extreme) to relative numerical values (e.g., 1 to 10 or 1 to 100). The result is a comparative ranking of fuel types in terms of their general flammability. Certain types are considered as being prone to crown fire development because of their fuel characteristics. A major limitation with any of these classification schemes is the fact that the fire weather and/or fuel moisture conditions are either not considered or are limited to a fixed level. Very often they imply far more real knowledge than available information and data warrant. This should not be construed as a criticism, but simply as a fact worth bearing in mind, especially in light of the euphoria associated with their periodic popularity among ill-informed users. It is worth repeating that fire behaviour is a very complex phenomenon which is governed by a large number of interacting variables that are not yet completely understood.

2.5.2 Fire Danger Rating Systems

Wildland fire managers have generally come to depend upon forest fire danger rating systems as a means of evaluating the potential for crown fires on a routine daily basis. Crowning is most commonly expected at the *Extreme* level of fire danger (Nelson 1961;

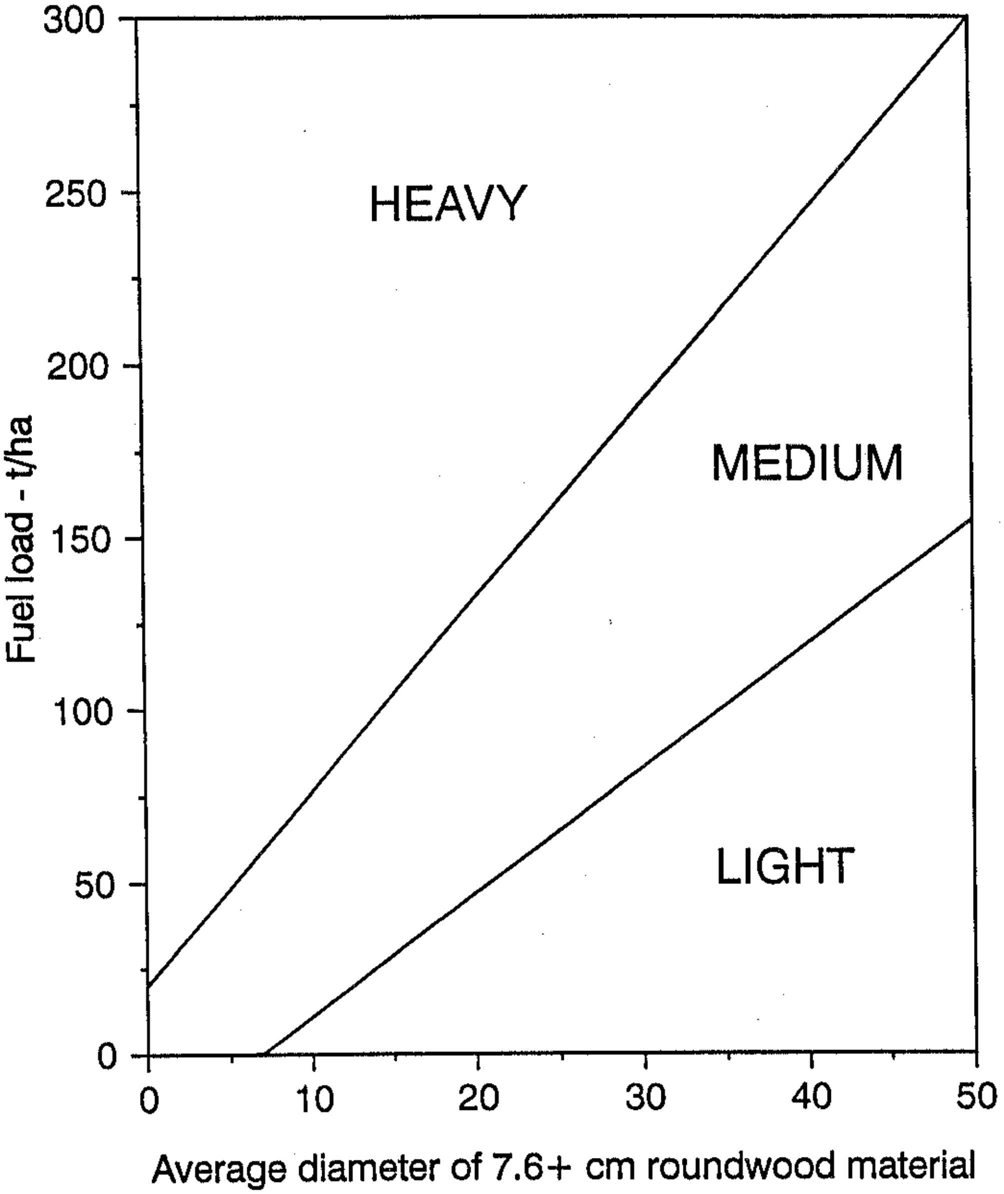


Figure 2.15: Criteria for suggested adjective descriptions of dead and downed roundwood fuels greater than 7.6 cm in diameter based on weight per unit area and average piece diameter according to Dr. J.K. Brown (*in* [adapted from] Aldrich and Mutch 1973).

Canadian Forestry Service 1970). All fire danger rating systems depend on simple weather elements as inputs such as dry-bulb temperature, relative humidity, wind speed, and precipitation amount (Reifsnyder 1978). These systems are subject to periodic revisions but, provided the weather records are retained, it is still possible to reconstruct past burning conditions that contributed to incidence of crown fires (e.g., Fryer and Johnson 1988) or analyze their frequency of occurrence (e.g., Kiil et al. 1977). When relying on a fire danger rating classification that is based on the variation in weather elements affecting potential fire behaviour for a single representative fuel complex, what must be kept in mind is that crowning can occur at much less severe burning conditions in other fuel types. The Canadian Forest Fire Weather Index (FWI) System is a good example of this since it is solely a simple weather-based fire danger rating system for which a mature jack or lodgepole pine stand is considered the standard or reference fuel type. In Alberta, Canada, for instance, an FWI value greater than 30 is considered the lower limit for an *Extreme* fire danger class (Kiil et al. 1977) as there are certainly ample observations and empirical evidence that jack pine forests are susceptible to crowning at or near this level (Simard 1973; Quintilio et al.1977; Alexander and De Groot 1988, 1989). However, in black spruce stands the threshold for crowning can certainly occur at FWI values of 16 (Newstead and Alexander 1983) and lower (personal observations of author), in other words a *High* fire danger class. For this reason, fuel type-sensitive guidelines have been conceived as a basis for rating fire potential in relation to forest cover type and fire danger index values (e.g., Grigel et al. 1971; Kiil et al. 1973; British Columbia Ministry of Forests 1983).

Other developments in fire danger measurement include the special index developed by Van Wagner (1974) for rating the relative rate of spread of crown fires during spring and early summer where conifer crowns tend to be more flammable than at mid summer, at least in Canadian forests, because of their reduced foliar moisture content (Van Wagner 1967c; Chrosciewicz 1986a). Fuglem and Murphy (1980) constructed a graph indicating the minimum FWI required for crowning in relation to foliar moisture content and height to live crown base utilizing Van Wagner's (1977a, 1987) theoretical and empirical work.

2.5.3 Aids and Guides to Quantitative Prediction of Fire Behaviour

U.S.A. Rothermel's (1972) fire spread and intensity model is the principal basis for nearly all the various methods and systems of rating fire danger and predicting fire behaviour in the United States (Albini 1976a, 1976b; Deeming et al. 1977; Rothermel 1980, 1983; Andrews 1986a, 1986b; Rothermel and Andrews 1987); *see* overview by Pyne et al. (1996). Stylized and customized fuel models are available but only surface fuel components are considered (Anderson 1982; Burgan 1987). Rothermel (1972) clearly enunciates the limitations of his research effort in the following passage taken from the preface of his publication:

> *This mathematical model has been developed for predicting rate of spread and intensity in a continuous stratum of fuel that is contiguous to the ground. The initial growth of a forest fire occurs in the surface fuels (fuels that are supported within 6 feet* [≈ 1.8 m] *or less of the ground). Under favorable burning conditions, if sufficient heat is generated, the fire can grow vertically into the tree tops causing a crown fire to develop. The nature and mechanisms of heat transfer in a crown fire are considerably*

> *different than those for a ground* [surface] *fire. Therefore, the model developed in this paper is not applicable to crown fires.*

The 1972 U.S. National Fire Danger Rating System (NFDRS) constituted one of the first applications of Rothermel's (1972) fire prediction model. Deeming et al. (1972) reiterated Rothermel's (1972) sentiments concerning his model in their philosophy of the NFDRS:

> *The system would consider only the "initiating fire". This is defined as a fire which is not behaving erratically; it is spreading without spotting through fuels which are continuous with the ground (no crowning). The "state of the art" cannot yet consider fires which exhibit erratic behavior other than to show that extreme behavior is correlated with increasing fire danger.*

In this regard, McArthur (1977) considered that "After forty years of research into fire weather and fire behaviour, it is a shocking admission of the inadequacy of the research program if we must eliminate that segment of the fire danger/fire behaviour spectrum which includes all major fires which probably account for around 90-95 percent of the fire damage in a severe fire season".

As noted above, Rothermel's (1972) semi-physical model is not considered to be directly applicable to the prediction of crown fire rate of spread and intensity, especially in conifer forests, although chaparral or other types of shrublands are deemed to be the exception (Rothermel and Philpot 1973; Albini and Anderson 1982; van Wilgen et al. 1985; Cohen 1986; van Wilgen et al 1990) because such fuel complexes are "... characterized by many stems and foliage that are reasonably contiguous to the ground, making it suitable for modeling as a ground [surface] fire" (Rothermel 1972). However, the predicted surface fire intensity or flame length inferred from Byram's (1959a) relation is considered useful in identifying the onset of crowning which is assumed to occur at frontal fire intensities of about 1730 to 3460 kW/m (Andrews and Rothermel 1982), regardless of the stand structure. One exception is for the slash/longleaf pine-palmetto-gallberry fuel complexes in the southeastern United States (Hough and Albini 1978).

Roussopoulos (1978a, 1978b) used Rothermel's (1972) surface fire model and Van Wagner's (1977a) crown fire theory for determining crowning thresholds in a specific forest region in northeastern Minnesota where an extensive forest-fire fuel inventory had been completed. Keyes (1996) has undertaken simulations of crown fire potential in the northern Rocky Mountains using BEHAVE (Burgan and Rothermel 1984; Andrews 1986a; Rothermel et al. 1986; Andrews and Chase 1989) and Van Wagner's (1977a) models. The tables produced by Alexander (1988) based on Equation 2.6 have been included in the field behaviour field reference published by the U.S. National Wildfire Coordinating Group (Anonymous 1992b) which has in turn led to applications other than wildfire management (e.g., Custer and Thorsen 1996). Furthermore, Rinehart (1994), a very experienced fire behaviour analyst in the U.S.A., has utilized the graphs, tables and concepts presented in Alexander (1988) in developing a "Wildfire Blowup Checklist" (unpubl.).

Norum (1982) claims to have successfully predicted forward rate of spread in Alaskan black spruce stands for 6.1-m (20 ft) open winds of up to 40 km/h using the nomograph version

(Albini 1976a) version of Rothermel's (1972) model. Fires in such fuel types, both in Alaska and parts of western and northern Canada, tend to typically propagate by intermittent crowning, sometimes at very slow spread rates (Kiil 1975; Dyrness and Norum 1983) although continuous crowning is certainly possible, especially in densely stocked stands (Juday 1985, Alexander and Lanoville 1987). Recently, comparisons between the surface fire spread rates predicted by Rothermel's (1972) model and documented high-intensity wildfires has indicated that observed crown fire rates of spread are generally two to four times faster and some times higher (Rothermel 1983; Rothermel and Mutch 1986). This concept has been expanded into a method for predicting the rate of spread of wind-driven crown fires in the Northern Rocky Mountains by Rothermel, (1991a, 1991b, 1995). From an analysis of eight wind-driven crown fire observations involving seven documented wildfires (with decidingly different stand and crown fuel characteristics), Rothermel (1991a) found that their average spread rate was 3.34 ± 0.59 times greater than the spread rate predicted by the standard Fuel Model 10 (Timber-Litter and Understory) described by Anderson (1982) for the same set of environmental conditions (i.e., fuel moisture, wind and slope inputs). Thus, to predict crown fire spread rates, one would simply multiply the Fuel Model 10 spread rate by 3.34. The nomograms developed for this application also include methods of predicting the intensity and flame length of a crown fire that includes the heat generated by both surface and crown fuels. As mentioned in Section 2.4.6, to help identify the possibility of a blow-up or plume-dominated crown fire, a simple means of comparing $\boldsymbol{P_f}$ with $\boldsymbol{P_w}$ was included on the nomograms..

Bessie and Johnson (1995) used Rothermel's (1991a) simple statistical crown fire rate of spread model in their fire behaviour simulations but used measured surface fuel characteristics rather than the standard values as embedded in Anderson's (1982) Fuel Model 10. Because of the empirical nature of the correlation derived by Rothermel (1991a), the validity of doing this seems open to question. Furthermore, recent analyses undertaken Mr. S.J. Munson, a graduate student at the University of Montana, indicates that Rothermel's (1991a) 3.34 multiplier generally results in overpredictions of crown fire rate of spread and suggested that simply multiplying the predicted surface fire spread rate by a factor two was sufficiently adequate.

Aronovitch (1989) has recommended that the U.S. NFDRS and/or the BEHAVE system be used in conjunction with observed winds aloft to produce forecasted N_c values. However, neither the NFDRS nor BEHAVE can predict fire spread rates and intensities for conifer forest fuel types that are susceptible to crowning as mentioned earlier on (Rothermel 1972, 1983). Rothermel's (1991a, 1991b, 1995) predictive guidelines for crown fire behavior could possibly be coupled with either system. However, Rothermel (1991a) explicitly noted that his methods for predicting crown fire behaviour were only "Applicable to the Northern Rocky Mountains or mountainous areas with similar fuels and climate". Furthermore, his criteria for the surface-crown fire transition remains exceedingly vague, although he has suggested that when $\boldsymbol{I_B}$ exceeds 3500 kW/m, fires "... have been found to be uncontrollable" and uses this level to separate the use of Byram's (1959a) $\boldsymbol{L\text{-}I_B}$ relation (Equation 2.2 here) for surface fires and Thomas' (1963) $\boldsymbol{L\text{-}I_B}$ relation (Equation 2.13 here) for crown fires (Rothermel 1991b).

Russia. Several forest fire danger rating systems have been developed in Russia, but the one originally devised in 1930 by Nesterov (1962) is the most widely used (Reifsnyder 1978; Chandler et al. 1983). The system consists of a single index based solely on air temperature, dew-point temperature, and the number of days since more than 3.0 mm of rain. Soviet fire behavior researchers have undertaken a considerable amount of research concerning the relationships between forest fire spread and weather conditions, although mainly for surface fires (*see* Vakurov 1975; Konev 1977; Artsybashev 1984). However, Sheshukov (1983) has prepared a table indicating the rate of spread of both surface and crown fires in relation to the fire danger class associated with Nesterov's index, wind speed, season, slope, and fuel type based on some of these earlier studies. Konev (1986) recently constructed a circular slide-rule for calculating surface and crown fire spread rates based on a semi-empirical model which he had earlier formulated (Konev 1984).

Canada. The value of the Canadian FWI System, one of the two major sub-systems in the Canadian Forest Fire Danger Rating System (CFFDRS) (Stocks et al. 1989, 1991; Alexander et al. 1996), as a guide to estimating crown fire potential has already been mentioned (Van Wagner 1986; Alexander and De Groot 1988; Stocks and Hartley 1995). The Canadian Forest Fire Behavior Prediction (FBP) System is the second major subsystem of the CFFDRS. The FBP System is unique in that it is based on the most extensive experimental crown fire data set in existence (Van Wagner 1964, 1965b, 1968; Stocks 1975; 1987a, 1987b, 1989; Weber et al. 1987; Alexander and Quintilio 1990; Alexander, Stocks and Lawson 1991; Van Wagner 1993). Supplementing this data base with information obtained from well documented wildfires (e.g., Van Wagner 1965a; Stocks and Walker 1973; Stocks 1975; Alexander 1983; Alexander et al. 1983; Alexander and Lanoville 1987) has been particularly useful at the extreme end of the fire behaviour scale where experimental fires are difficult to arrange and manage. In 1984, an interim user guide (Alexander et al. 1984) for a portion of the FBP System was released for field testing by fire management agencies in Canada (Lawson et al. 1985). Some of the material was later published in various forms to further the technology transfer of the system (Lawson et al. 1985; Stocks 1986; McAlpine 1986, 1987; Van Wagner 1986; Alexander and Lanoville 1989). Surface-crown fire thresholds were delineated on the basis of the Initial Spread Index (ISI) component of the FWI System for fires burning on level ground, or in terms of head fire rate of spread for fires burning up a slope. Eight of the fourteen fuel types were considered to be susceptible to crowning. Two additional types have since been added (De Groot 1993).

The Canadian approach to the prediction of crown fire spread rates is reflected in the manner in which the FBP System has been developed. The large database used in the FBP System was compiled through the monitoring of numerous wildfires and an extensive experimental burning program, and includes a large number of crown fires which exhibited a wide range of fire behaviour (McAlpine et al. 1990). The FBP System largely constitutes a series of empirical predictive equations in which observed fire behaviour characteristics in different fuel types have been related to the system of indices used to quantify forest fire danger in Canada (i.e., the FWI System). The FBP System is in use throughout the country (Stocks et al. 1989, 1991; Van Wagner 1990; Alexander et al. 1996). The forward rate of fire spread is predicted, for example, in terms of the Initial Spread Index (ISI) component of the FWI System and, as spread rate increases with increasing ISI levels, the transition from surface to crown fire is automatically taken into account (Fig. 2.16). This empirical approach yields very good relationships which have proven very useful to fire managers grappling with the problem of predicting crown fire spread rates. Verified after-the-fact predictions of crown fire rate of spread have shown quite good agreement between observed versus predicted values (e.g., Lawson et al. 1985; De Groot and Alexander, 1986; Stocks and Flannigan 1987; De Groot and

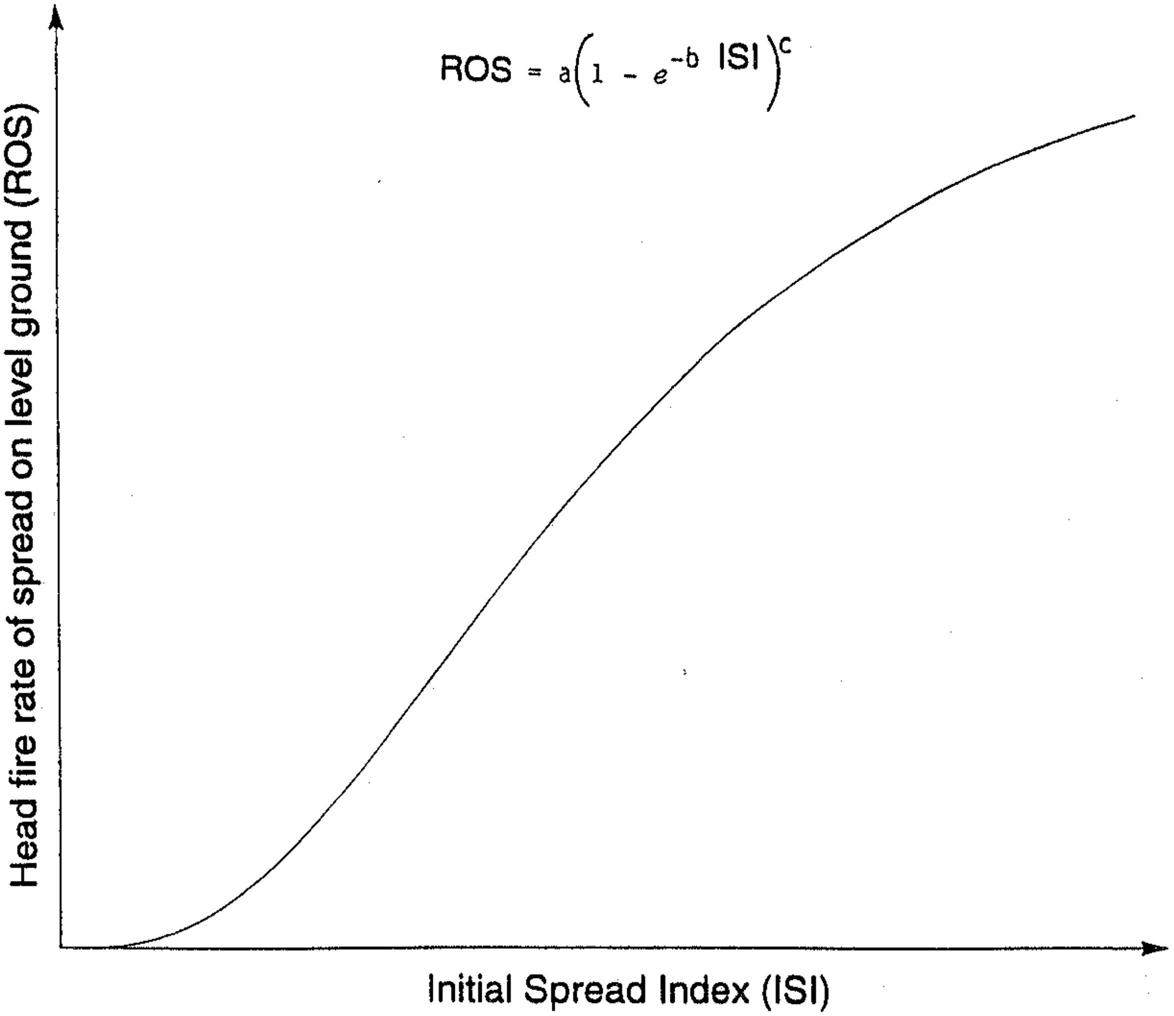


Figure 2.16: Generalized relationship between the initial Spread Index (ISI) component of the Canadian Forest Fire Weather Index System and head fire rate of spread (ROS) on level ground to gently undulating terrain for surface and crown fires in conifer forest stands as embodied in the Canadian Forest Fire Behavior Prediction System. Typically, the lower section of the S-shaped curve represents surface fires, the upper flattening section represents continuous crowning situations and the relatively steep intermediate section a transition zone characterized by very high-intensity surface fires with significant torching and intermittent crowning activity. The fuel type specific regression coefficients (*a, b, c*) in the ISI-ROS equation are derived largely from an analysis of experimental fires conducted at low to moderate ISI levels and from well-documented wildfires at very high to extreme ISI values.

Schisler, 1989; Hirsch 1988, 1989a, 1989b; Stocks 1988; McAlpine et al. 1990, 1991; Alexander 1991, 1992c, 1995).

The first complete edition of the FBP System, was formally published in 1992 (Forestry Canada Fire Danger Group 1992), provides for the prediction of surface and crown fire behaviour (Fig. 2.17) of both point-source ignitions, using a simple elliptical fire growth model (Van Wagner 1969; Alexander 1985a; Alexander et al. 1988) with consideration for acceleration to a steady-state condition, and line-source ignitions (Alexander and Maffey 1992-93; Hirsch 1993). In addition to the effects of slope (Van Wagner 1977b), fine fuel moisture content, and wind (represented by the ISI) on rate of spread, the effect of variable fuel consumption on spread rate (Van Wagner 1973a) has also been taken into account (Van Wagner 1989). Furthermore, a computational scheme for estimating foliar moisture content (FMC) based on calendar date, geographical location (i.e., latitude and longitude), and topography (i.e., elevation, slope, and aspect) has been developed in order to take the FMC into account when predicting crowning tendency and crown fire spread rates. A field-oriented guide to the FBP System has recently been published (Taylor et al. 1996) as well as a self-guided interpretive manual (Hirsch 1996a) and several decision aids related to the system's application (e.g., Alexander and De Groot 1988, 1989; Alexander and Cole 1995; Cole and Alexander 1995).

With the aid of the Canadian FBP System it would be possible to implement Byram's (1959a) P_f/P_w or N_c concept across Canada. The inputs for I_B and R in Equation 2.18 could be based on observed or forecasted weather conditions as the System is capable of predicting fire spread rates and intensities over the complete range of possible fire behaviour (i.e., both surface and crown fire, including explicit criteria for the transition to or onset of crowning).

2.6 Conclusions

The ultimate goal of wildland fire behaviour research is to provide fire managers with simple, timely answers to the following types of questions (given an actual ignition or a simulated fire occurrence) for any specified fuel, weather, and topographic situation (after McArthur 1958; Luke and McArthur 1978; Alexander 1991e):

> *What will be the head fire rate of spread? What will be the area, perimeter length, and forward spread distance after 1 hour, 2 hours, 3 hours, and so on?*
>
> *Will it be a high-intensity or low-intensity fire? Will it be a crown fire or a surface fire? How difficult will it be to control and extinguish? Will mechanical equipment and/or airtankers be required, or can it be handled safely by a suppression crew? Will the mop-up efforts require more time than normal?*
>
> *If there a possibility of it "blowing up"? If so, will it produce a towering convection column or have a wind-driven smoke plume? What will be the spotting potential -- short or long range? Are fire whirls and/or other types of wildland fire vortexes likely to develop? If so, when and where?*

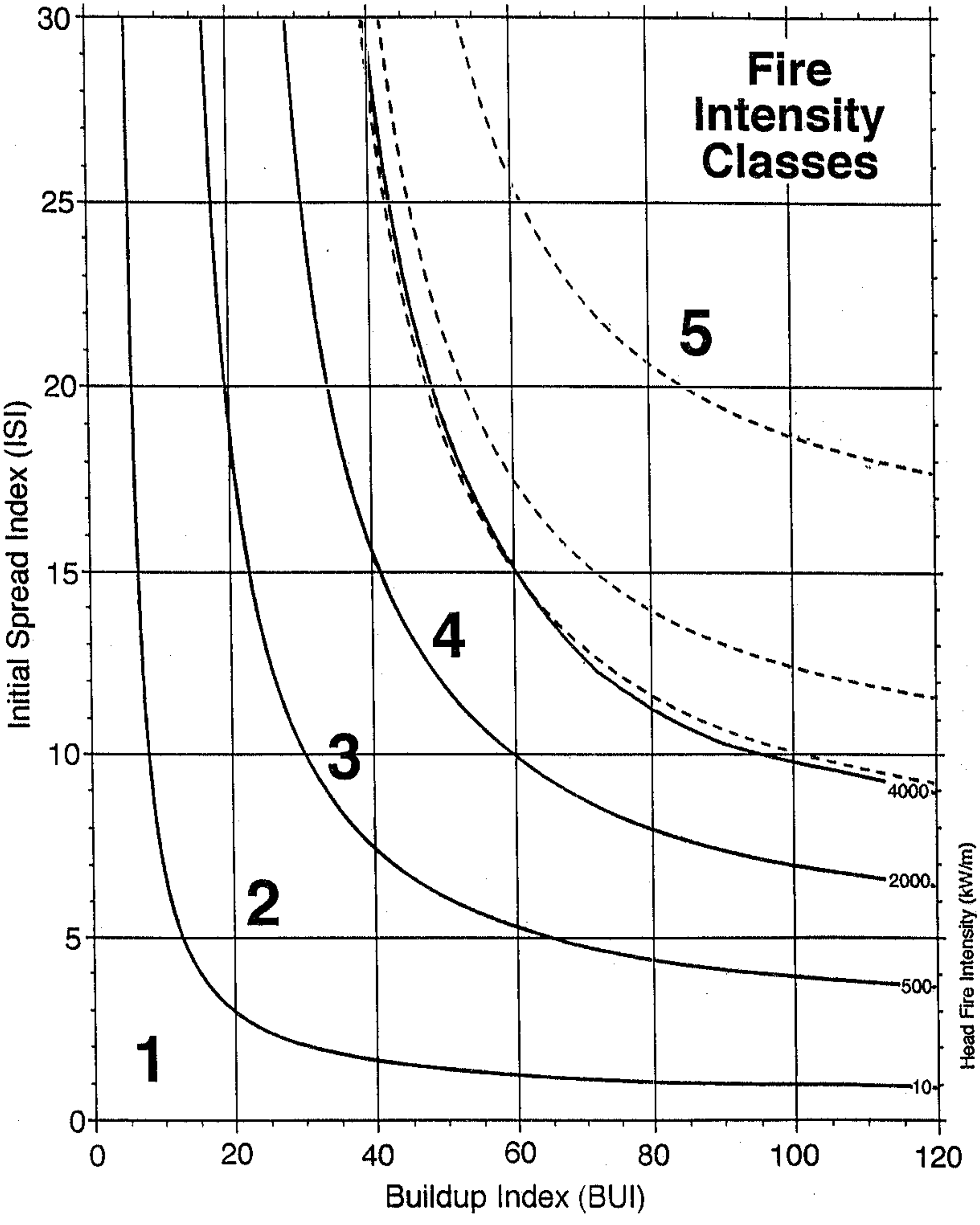


Figure 2.17: Head fire intensity class/type of fire graph for Canadian Forest Fire Behavior Prediction System Fuel Type C-6 (Conifer Plantation) on level to gently undulating terrain (i.e., 0° slope) and at 145% foliar moisture content.

In regards to the first question, Jemison (1939) made the following remarks some 60 years ago:

> *Rates of spread vary in a bewildering way. It would be easy to yield to the temptation to throw up our hands and say that it is useless to try for anything but good guesses at the rate a given fire will spread under given conditions of fuel, weather, and topography. The saner attitude is to keep digging away at the effect of this or that factor on rate of spread in the belief that in time the intricate puzzle will be solved by the creation of something that can rightfully be called the science of rate of spread.*

Significant progress has been made globally during the past 70 years in the description, measurement and understanding the behaviour of free-burning wildland fires in providing complete, partial or temporary answers to all of the questions raised above, yet much remains to be accomplished as evident for example by the 1988 fires in the Greater Yellowstone Area, U.S.A. (Rothermel 1991c; Thomas 1991).

There has been very little theoretical work on the subject of surface-crown fire initiation although both Van Wagner (1977a, 1993) and Xanthopoulos (1990) have developed and tested semi-empirical relationships. In contrast, the theoretical efforts of Grishin (1992, 1996) remain essentially untested for a variety of reasons; the translation of Grishin's (1992) book currently being undertaken with the assistance of the Canadian Forest Service amongst others, from Russian to English should facilitate this process to some degree. Predictions of crown fire rate of spread have been tackled both empirically (e.g., Rothermel 1991a; Forestry Canada Fire Danger Group 1992; Bilgili 1995) and theoretically (Albini and Stocks 1986; Grishin 1992, 1996). However, there still remains the very basic question: when does a surface fire become a crown fire? Few models actually attempt to distinguish the point at which surface fire behaviour has reached a stage, relative to fuel complex characteristics, that crowning is possible. Several generalized rules of thumb exist (e.g., Sibley 1971; Hough and Albini 1978; Rothermel 1983). However, Van Wagner (1985) as notes:

> *The fire world would beat a path to the door of the modeller who could account for vertical gradients and interruptions in moisture content and fuel density as well. Crowning fire is the most obvious application for such a comprehensive model.*

Bevins (1979) has offered some possible ways of dealing with the interaction of separate surface fuel layers, but hasn't examined the complex issue of surface-to-crown fire transition. As Rothermel (1991a) points out, "The onset of crowning is exceedingly complex; wind, slope, humidity, fuel moisture, atmospheric stability, inversions, surface fire intensity, ladder fuels, time of year, amount of exposed fireline, and frontal passage can all play a role". Both Van Wagner (1977a) and Xanthopoulos (1990) have attempted to address this problem, although there are a number of limitations with their models as discussed in this chapter such as the lack of fuel type distinction and accounting for the effect of wind as well as scale effects in the latter case; Van Wagner (1977a) did acknowledge that his approach was elementary and that the aim was to deduce simple functions that could be calibrated by field observation although he offered no specific guidelines or techniques of how to do so. In spite of any possible limitations, elements of their work certainly constitute the starting point for any new model development.

CHAPTER 3:

DEVELOPMENT AND TESTING OF A MODEL TO PREDICT THE ONSET OF CROWNING

3.1 Model Idealization, Simplifying Assumptions and Possible Limitations

In order for a crown fire to occur, it must first be initiated by a surface fire. As Byram (1957, 1959a) and others (e.g., Barrows 1951; Brown and Davis 1973; Luke and McArthur 1978) have pointed out many times in the past, convection, with some assistance from radiation is the principle means of vertical heat transfer from a surface fire to the crowns of an overstory stand (Fig. 3.1). Convection is "The transfer of heat by the movement of masses of hot air; the natural direction is upwards in the absence of any appreciable wind speed and/or slope" (Merrill and Alexander 1987). The heat energy held by the hot gaseous products of combustion, being lighter than the surrounding ambient air, experience an upward buoyant force or momentum (Murgai 1976) -- thus, a rising fire-induced convection column or "fire plume" is formed (Heskestad 1984; Drysdale 1985). Provided the surface fire is sufficiently intense enough, relative to the height of the canopy base above the ground surface, the hot buoyant gases rising upwards will rapidly drive off the moisture contained in the live foliage. Sufficient heat must be transferred to the lower crown base not only to dry out the foliage, but to raise its temperature to the point where flammable gases are evolved. Ignition or kindling temperature for fine forest fuels has generally been assumed to be around 320-350°C (e.g., Van Wagner 1967a; Rothermel 1972); in other words, ambient air temperatures must attain or exceed this critical level for some specified period of time as determined by the moisture content of the needle foliage. Before ignition can possible occur, the internal temperature of the fuel must first exceed 100°C in order for evaporation of the water or moisture held in the fuel to begin (Hawley 1926). Several authors (e.g., Wade and Johansen 1986; de Ronde et al. 1990; Robbins and Myers 1992) have stated that temperatures of over 200°C are required to ignite pine foliage. This in fact constitutes the approximate level where liberation of combustible gases begins (Albini 1980) and is very near complete at around 400°C (Susott 1982a, 1982b, 1984). It logically follows that, for a given ambient air or external temperature, the higher the moisture content the longer the delay in time for ignition to occur. Conversely, for a given moisture content, the higher the temperature the shorter the time to ignition. Once the foliage at the crown base has been heated sufficiently to where flammable gases are given off, then the catalyst for crown fire initiation is by pilot ignition as advocated by King (1961) as opposed to spontaneous ignition. In this regard, King (1961) made the following statement:

> *Limited field experiments on major fires seem to indicate that usually ignition is by the pilot ignition process. Spontaneous ignition may occur in the worst conflagrations ... Tree crowns that have appeared to "explode into flames" when well above the ground* [surface] *fire have been shown cinematographically to have been lit by pilot ignition sources; the "explosive" effect actually was a very rapid propagation of flame through the crown taking less than one second (during fires, it is very difficult to observe and follow flame phenomena taking less than one second to complete).*

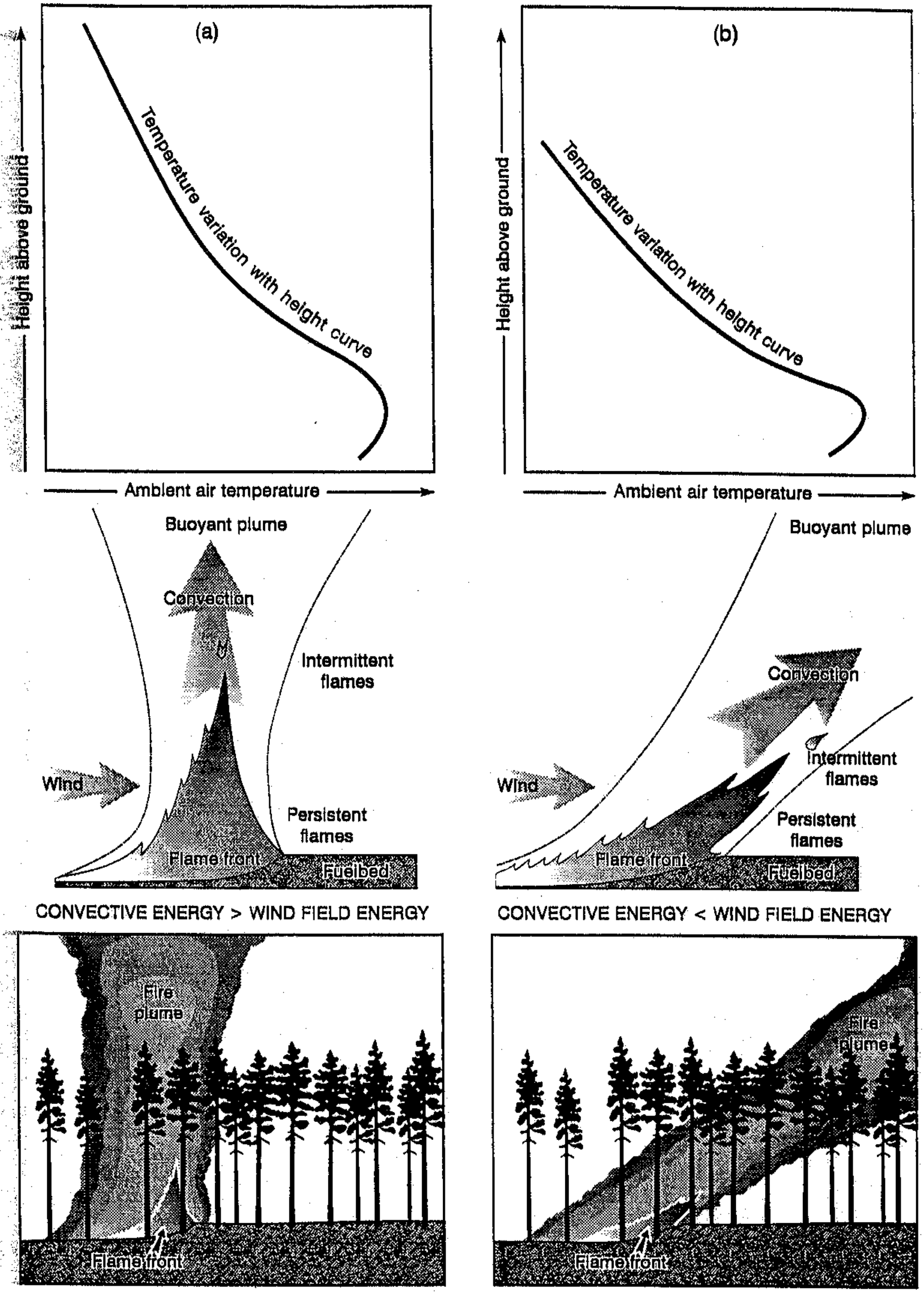


Figure 3.1: Schematic illustration of the plume or convection column angle characteristics associated with surface fires in (a) calm or light winds versus (b) moderate to strong winds (adapted from: Byram 1966; Rothermel 1972; Brown and Davis 1973; Moberly et al. 1978; and Burrows 1984a).

At the USDA Forest Service's Southern Forest Fire Laboratory in Macon, Georgia, U.S.A., Dr. W.A. Hough has demonstrated that recently cut palmetto (*Serenoa repens*) fronds that have been preheated with an infrared heater for as long as 10 minutes would not ignite without a pilot flame, yet after just two minutes preheating a small pilot flame would "... set the plant material into an almost explosive blaze" (Sackett 1972).

The pilot ignition source is not necessarily stationary, but some form of a pilot flame of some sort is presumed to exist in the immediate vicinity of the lower crown base at the time the surface fire is passing or beginning to pass beneath the crowns provided the foliage has been preheated sufficiently to its ignition point. Van Wagner (1961, 1967b) has demonstrated in the laboratory that conifer trees can be ignited with matches when the moisture content of the needles drops to about 50% and "... will burn with great violence..." when the moisture content falls below 20%. The source of the pilot ignition may be either from: (*i*) the embers and flaming firebrands that are carried aloft in the updrafts of the surface fire's convection column (Albini 1983a, 1983b; Chase 1984; Morris 1987); (*ii*) from the scattered bits of flame that can become established on the loose bark of the tree boles or in the concentration of suspended needles if dead branches are present (McArthur 1971; Just 1974; Sackett 1975; de Ronde 1980; Burrows, Smith and Robinson 1988; Burrows, Ward and Robinson 1988); (*iii*) from the occasional flashes of flame which rise above the general level of the surface fire flame front due to a surface fuel concentration such as a pile of thinning and/or pruning slash (Gilmour and Cheney 1968); (*iv*) as a result of the low pressure area that builds up on the lee side of tree stems creating more intense and persistent flames (Subramanyam et al. 1971); and (*v*) from the torching of wilding or volunteer pines (i.e., advanced regeneration) in the understory of mature pine plantations (Methven and Murray 1974; Underwood et al. 1985; Burrows et al. 1989; Weise 1989). With respect to the last case, the late Alan G. McArthur, reknown pioneer fire behavior researcher in Australasia (Pyne 1991), has observed surface fires "... crown via isolated unpruned trees." in plantations that had been selectively pruned (Tustin and Bunn 1970, p. 56).

Young unpruned and unthinned exotic pine plantations are especially prone to crowning at virtually any level of fire danger, even "mild" burning conditions, because of the vertical fuel continuity afforded by the high stem density and the large mass of suspended needles that extend from the ground surface up to and through the green crown layer (McArthur 1965; Cheney 1975). Relatively low-intensity surface fires can easily induce torching in such situations and depending on the winds, lead to the development of a crown fire; Pyne (1995) notes that "... the threat of crown fire ... plagues closely packed pines". Thus, predicting the onset of crowning in these kind of fuel complexes is largely a question of defining the limiting conditions for surface fire spread in terms of litter moisture content and wind speed. The primary emphasis here is predicting the onset of crowning where a relatively substantial "vertical fuelbreak" (Countryman 1969a) exists between the surface fuels and the line crown base. Model applicability is, therefore, extended to juvenile or older plantations that have undergone low pruning to ≈ 2-2.5 m perhaps in conjunction with a precommercial thinning or if left unpruned, then the stand is middle aged and has received one or more thinnings. Thus, an idealized exotic pine plantation fuel complex is envisioned here consisting of two distinct fuel layers (i.e., surface fuels and the live or green foliage in the tree crowns) separated by a variable gap, constituting the trunk space of the stand (Fig. 2.2). Ladder or bridge fuels may or may not be present.

As is true with most mathematical models developed for predicting various wildland fire behaviour phenomena (*cf.* Albini 1979, p. 21), this particular effort involves many simplifying assumptions. In order that the reader can more effectively judge the relevancy of the idealized model against the real world, the assumptions used in the development of present model are set out below in considerable detail.

Assumption No. 1. In applying or implementing the model, homogenous conditions are assumed to prevail (i.e., constant wind velocity, uniform fuel moisture contents and terrain slope, and continuous forest cover) even though in reality such an idealization is only relative. For example, variations in the moisture content of the surface little layer exists, even after a significant dry spell, due to differences in solar heating at the ground level (Countryman 1977). Although momentary gusts of wind may have little effect on a surface fire's overall rate of spread and intensity, they can produce large fluctuations in flame size which can easily trigger crowning (Crosby and Chandler 1966). In natural conifer forests, it's readily acknowledged, for example, that fuel concentrations such as dense clumps of saplings in an otherwise moderately stocked stand of mature trees can initiate crowning (Hirsch et al. 1979). In contrast, the vertical and horizontal fuel structure in conifer plantation forests generally exhibits a great deal of uniformity. However, discontinuities in the overstory canopy can contribute to the crown fire initiation process (McArthur et al. 1966; Roberts 1969). Finally, the fire is considered to be at or have reached an equilibrium or pseudo, quasi-steady state rate of spread and intensity for a given set of burning conditions (i.e., a stabilized "line of fire" as opposed to a point source fire that is continuing to accelerate). This is in fact an assumption common to many mathematical models of wildland fire behaviour phenomena (e.g., Rothermel 1972; Albini et al. 1978).

Assumption No. 2. The flames of a surface fire do not necessarily have to reach into the bottom of crown fuel layer along a broad front (e.g., the entire head fire portion of the fire perimeter) in order to initiate crowning. This is contrary to Anderson (1974) who considered that the potential for crowning existed when the simple ratio of flame height to crown base height exceeded a value of 1.0 (i.e., direct flame contact was necessary to initiate crowning) and Keane et al. (1996) who assumed that crowning or torching would occur when the flame length exceeded the live crown base height. Both theoretical (Fig. 2.6) and empirical evidence (e.g., FIRESCAN Science Team 1994, 1996) exists to support the claim or assumption made above. For example, as discussed in Section 2.4.1, Van Wagner (1977a) pointed out that the onset of crowning in a red pine (*Pinus resinosa*) plantation where the crown base height was approximately 7 m occurred when a surface fire intensity of 2500 kW/m (Byram 1959a) was attained; the head fire rate of spread $\boldsymbol{r}$ was ≈ 0.09 m/sec (Van Wagner 1964, 1968). According to the flame length-fire intensity relationships of Byram (1959a), and Nelson and Adkins (1986), and Thomas (1963) represented by Equations 2.2, 2.3 and 2.13, this is equivalent to flame lengths of 2.8 m, 2.3 m, and 4.9 m, respectively; the observed flame lengths were certainly less than 3 m (*see* Macleod 1969, p. 1862). Van Wagner (1977a) indicated that the relation of Thomas (1963) would yield a $\boldsymbol{L}$ of "... just about 6 m ..." for an I_B of 2500 kW/m. Taking into account Putnam's (1965) relationship (*see* Equation 3.33) between flame angle versus flame length and wind speed (in this case, ≈ 5.5 km/h), the corresponding flame heights by simple trigonometry (*cf.* Alexander 1982, Equation 7) would in turn be 2.6 m, 2.1 m, and 4.7 m, respectively. Similarly, a flame height of 4.2 m was calculated by Equation 2.4 of Nelson and Adkins (1986, Equation 6) relating fire intensity to wind speed and flame height. A flame height of 1.8 m was calculated by Equation 2.5 (Simard et al. 1989, Equation 6, as derived by Dr. R.M. Nelson, Jr.) relating fire intensity to rate of fire spread and flame height.

Assumption No. 3. The isothermal structure of the convection column above the surface fire is judged, at least for modelling purposes, to be "well behaved" (Fig. 3.2) as envisaged by Martin et al. (1969) and Cesti (1990) regardless of the slope and wind conditions although at any instant in tine, the isotherms would be quite irregular due to the turbulence within the column. In turn, the temperature within the "core" of the convection column decreases with height above the flame zone as depicted in Figure 3.1. Very high temperatures are produced in the flames of burning forest fuels and the hot buoyant gases that are in turn evolved cool rapidly as they rise above the flame zone and are back to a few degrees above the prevailing ambient temperatures within a short distance from the source as cooler surrounding air is entrained or flows into the convection column (Countryman 1964). The buoyancy in the convection column changes with the temperature of the ambient air through which it ascends; when the convection column and ambient air temperatures become equal (i.e., no temperature rise), then buoyancy is lost. In head fires, the maximum temperature occurs near the ground level above the upper surface of the driest fuel (Davis and Martin 1960). Temperatures are lower in the upper reaches of the flame zone due to entrained air as the flame gas rises (Rothermel and Anderson 1966). Weber, Gill, Lyons, Moore, Bradstock and Mercer (1995) have developed a mathematical model which incorporates the variation in temperature in the flaming combustion region immediately above and within the fuelbed as well as above a spreading fire. However, the sole interest here is in the temperature variation with height attained above the active flame front of a surface fire.

Assumption No. 4. The "thermal pulse" (Countryman 1969a) or "convective pulse" (Rothermel 1994) at a fixed point above a surface fire as envisioned here is schematically presented in Figure 3.3. It's readily acknowledged that other interpretations exist (e.g., Gill 1995; Moore et al. 1995). Initially there is a rapid rise in temperature as the flame front approaches (Rothermel and Anderson 1966; Rothermel 1972, 1990; Konev and Sukhinin 1977; de Mestre et al. 1989) followed by a slower exponential decay, the slope of which will be determined by the composition of the surface fuelbed (Martin and Davis 1961; Vasander and Lindholm 1985; Cheney 1990a). As Van Wagner (1973b) notes, "The main convective heat pulse from a forest fire lasts only a few minutes" in total. In actual fact there are two separate heat pulses as Byram (1948) points out:

> *... recent thermocouple measurements indicate that... When a line of fire passes under a tree, the foliage is subjected to two peaks of intensity. One peak is the result of radiant energy from the approaching fire line; the other is caused by convective heat from in the burning gases. For a backfire the peak for radiant heat comes first, and for a head fire the peaks occur in reverse order. In calm air they occur simultaneously.*

Our main interest here is of course is the surface head fire in relation to the onset of crowning. It's already been stated earlier on that convection resulting from surface burning is presumed to be the main heat transfer mechanism responsible for the crown fire initiation process. Upward radiation from the surface fire would only tend to reinforce or enhance the actual ignition phase. Thus, in terms of the present model development the convective and radiant heating components of an advancing surface are considered as one and no claim is made here to being

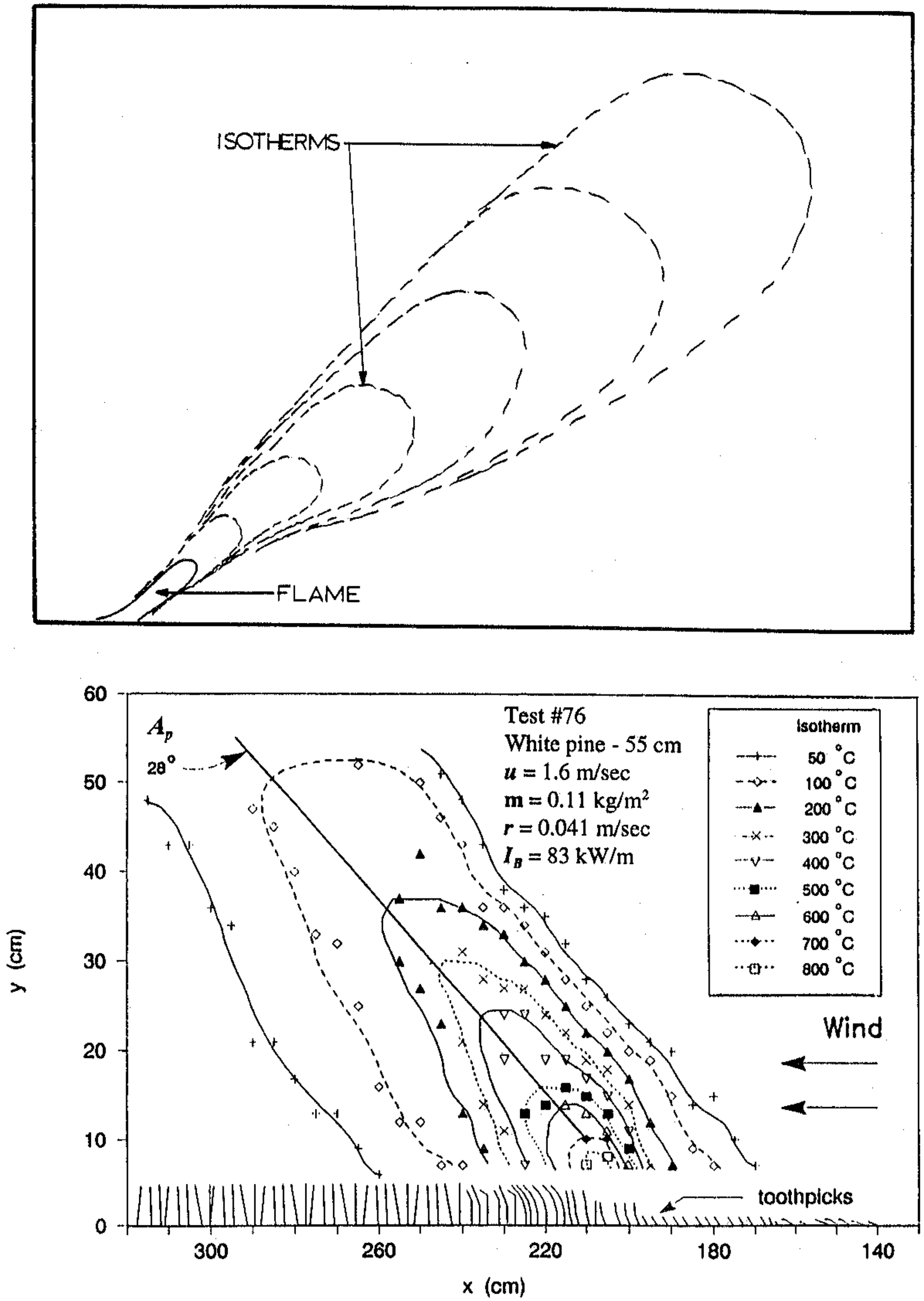


Figure 3.2: Idealized isotherms (a) in the plume above a surface fire (from Martin et al. 1969) and (b) an actual plot from an experimental fire conducted in a wind tunnel (after Carrier et al. 1991); test #76 according to Wolff (1995). Note that the x and y axes of the latter diagram do not have a 1:1 relationship.

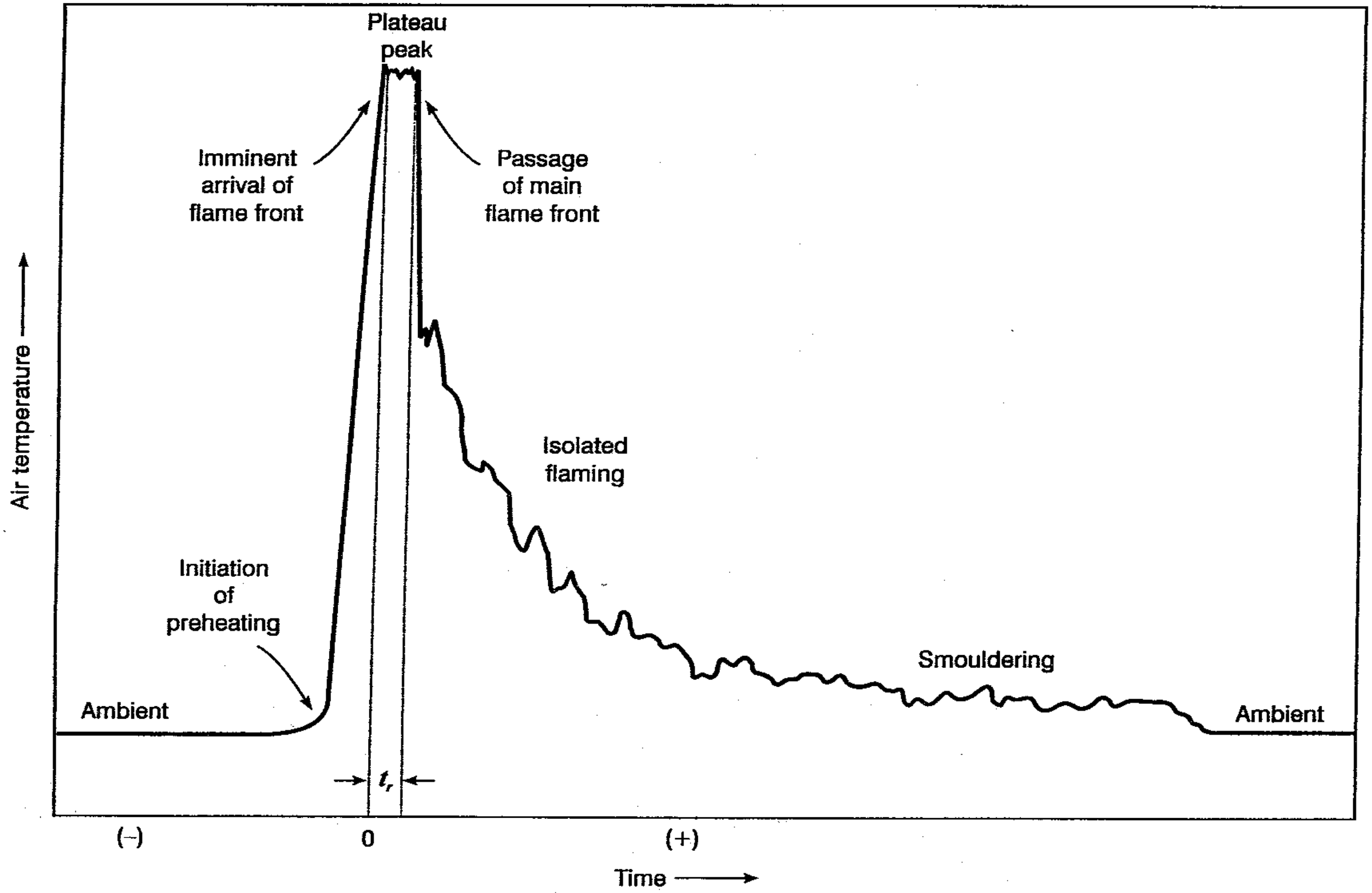


Figure 3.3: Conceptual time-temperature history at a fixed point above a surface fire in relation to the passage of the flaming front and the flame front residence time (t_r).

able to distinguish between their separate effects. The peak in the thermal pulse is presumably maintained as roughly a plateau rather than a distinct apex for a duration related to the fire's rate of advance and the depth of the flame front. This is intuitively what one would logically expect in an idyllic sense -- i.e., as a fire passes underneath a point above the ground, the temperature rises immediately to a certain level as the leading edge reaches this position and is maintained at this level until the trailing or upwind edge progresses pass the point; put another way, the duration of heating received at a vertical distance above a stationary but constant heat source would be largely a function of the depth or area of the heat source and the velocity of horizontal movement.

Anderson and Rothermel (1965) have in fact defined residence time "... as the time from the temperature rise to the temperature drop from the plateau temperature, as measured from the temperature profile provided by ..." a thermocouple. Actual representative time-temperature profiles similar to Figure 3.3 include, for example, those by Pagni (1972), Trabaud (1979), Vasander and Lindholm (1985), Bond and Cheney (1986), Knight (1988), Stronach and McNaughton (1989), Cheney (1990a), Burrows (1995b), Weber, Gill, Lyons and Mercer (1995), and the FIRESCAN Science Team (1996). It's readily acknowledged that other time-temperature profile shapes have been reported in the literature (e.g., Davis and Martin 1960; Beaufait 1961; Martin and Davis 1961; Martin 1963a, 1963b; Martin et al. 1969; Engle et al. 1989). However, it's felt that the wide variety in the quality and type of thermocouple instrumentation, differences in surface wind velocity and exposure to the wind field (Martin and Davis 1961), nature of the advancing flame front (i.e., uniformity), and the height of measurement relative to the height of the flames probably renders comparisons to the present model profile as completely inappropriate. From the standpoint of the potential for crown fire initiation, the duration or length of time for the most significant phase of convective preheating that occurs at the level of the crown bases during the active flaming stage of combustion at the ground surface can at least as a first approximation be inferred from the fire's residence time as first defined by Fons et al. (1962):

$$t_r = \frac{D}{r} \tag{3.1}$$

where t_r is the residence time (sec), D is the flame depth (m) as illustrated earlier on in Figure 2.3, and r is the rate of fire spread (m/sec). This definition differs from Cheney (1990a) who includes the time for all fractions of the fuelbed to cease flaming, not just the fine particles or just individual elements. The flaming time of individual fuel particles burning in a uniform fuelbed can be approximated from the particle size (after Anderson 1969):

$$t_R = 189\ \mathbf{d} \tag{3.2}$$

where t_R is used to distinguish the fuel particle residence time (sec) from the flame front residence time t_r and $\mathbf{d}$ is the fuel particle diameter (cm).

Admittedly the above assumption "... is not a true representation of the temperature exposure in a fire, due to many factors including the variability in the thermal environment associated with wildland fires ..." (Weber, Gill, Lyons and Mercer 1995). Others have made a somewhat similar assumption in their fire modelling scenarios involving convective heating above surface fires (e.g., Byram and Nelson 1952; Byram 1958; Van Wagner 1973b; Johnson and Gutsell 1993); however, in the latter study, the authors assumed a constant ***D*** (2.0 m) and then varied ***r*** which has, in this author's opinion, resulted in both erroneous outputs and conclusions (Alexander 1996). It's readily acknowledged that this may possibly be the weakest assumption made in the course of developing the present model. However, this is considered a reasonable assumption given that the distance above ground of interest here is typically less than 5-10 m and is certainly no greater than about 20 m as opposed several hundred metres above the surface. Furthermore, by considering t_r to constitute the duration of effective heating at any point above the surface fire, one is erring on the conservative side. To reduce the value of t_r would only result in the possibility of underestimating the potential for crown fire initiation. It's felt that neither a "degree-seconds" (°C-sec) or "degree-minutes" (°C-min) concept (Potter et al. 1983; Engle et al. 1989; Bidwell and Engle 1991, 1992) has no relevancy nor any real physical meaning for that matter.

During the course of the present investigation, its become painfully obvious that no standard exists within the international wildland fire research community that sets out the procedures to be followed for the proper interpretation of a time-temperature profile trace obtained in the field or laboratory for deducing t_r, ***D*** and ***r*** or one of the unknown variables using the interrelationships embraced by Equation 3.1. This has led to erroneous results such as those reported on by Engle et al. (1989) who indicate t_r values of 63 and 166 sec, respectively, for two experimental fires in grass fuels (*see* also Bidwell and Engle 1991) which when coupled with ocularly derived values for ***r*** (0.32 and 0.25 m/sec, respectively) give, by a rearrangement of Equation 3.1 (i.e., $D = t_r\, r$), flame depths of 20 and 42 m which are equal to or greater than twice the plot size of 10 x 20 m! Admittedly, part of this apparent problem has come about as a result of confusion in terminology (McArthur and Cheney 1966; McArthur 1976b; Cheney 1981) as a result of some authors such as Engle et al. (1989) and others (e.g., Stocks et al. 1996) using the term "residence time" when they are actually referring to total "burn-out time" (Alexander 1982). Thermocouples have been used on laboratory fires for many years now to determine ***r***, ***D*** and t_r (e.g., Fons et al. 1963; Anderson 1964; Breuer 1965) and yet the manner in which the data should be manipulated to derive these variables remains largely unresolved (Wilson 1982) even when problems in their use became apparent earlier on (Anderson et al. 1966).

Assumption No. 5. Byram's (1959a) fire intensity is used inspite of some limitations in the present work because of its nearly universal acceptance amongst operational fire management agencies as a basic measure of fire behaviour. There are many more guidelines available for predicting rate of fire spread than there are for flame dimensions and thus given an estimate of available fuel, the intensity of a surface fire can be readily made (Albini 1984). In fact, most so-called physical models for predicting fire behaviour assumed that the flame characteristics (e.g., height) are inputs (Catchpole and de Mestre 1986). It could be argued that, only convectional heat should be considered for present purposes and a deduction made for radiant heat in the calculation of fire intensity. Although several laboratory and field studies have been made of the relative contribution of convection versus radiation (Fons et al. 1962; McCarter and Broido 1965; Fang 1969; Packham 1970; Konev and Sukhinin 1977; Knight and Dando 1989), there is as yet "... no sound available basis for estimating radiant heat as a proportion of the total energy output of individual fires of different intensities ..." (Van Wagner 1973b).

Assumption No. 6. The ignitability of green or live pine needle foliage was judged to be solely a function of one physical fuel property, namely moisture content (Countryman 1974). Differences in particle size or surface area-to-volume ratio amongst the pine species under study were felt to be inconsequential for practical purposes. Nor has any allowance been made for any aspect of fuel chemistry, such as solvent extractives (e.g., fats, resins, waxes, oils, terpenes) (Susott 1980; Rogers et al. 1986) which might possibly play a role in effectively lowering the temperature requirement (*cf.* Mutch 1964) for crown fire ignition (Philpot and Mutch 1971; Hough 1973). This conclusion is reached on the basis that at the present time there is simply insufficient knowledge upon which to base a quantitative effect. Nevertheless, it's difficult to avoid the feeling, for example, that terpenes (with their low boiling points), which are responsible for giving pine forests their characteristic aromatic smell on warm sunny days (Chandler et al. 1983), don't somehow have a role to play in the crowning process.

Assumption No. 7. The initial temperature of the foliage is equivalent to the ambient air temperature. Admittedly, crown temperatures can in the absence of wind under clear sky conditions exceed the ambient temperature by more than 13 °C (Reifsnyder and Lull 1965) to 22 °C (Ansari and Loomis 1959; Wade and Johansen 1986) because of solar radiation (Knoerr 1967), but small amounts of wind (say just 5 km/h) can easily reduce leaf temperatures nearly to the prevailing air temperature (Tibbals et al. 1964; Gates et al. 1965).

Assumption No. 8. The dry-bulb temperature as measured in a Stevenson screen or radiation shield (Finklin and Fischer 1990) at a height of ≃ 1.2 m above ground shall be considered the ambient air temperature at the crown base regardless of the distance above ground. Admittedly, temperatures at and near the ground surface can be considerably higher depending on the crown density and cloud cover (Roberts 1969).

Assumption No. 9. The wind speed in the lower trunk space of the plantation forest is constant with height above the ground, or nearly so for practical purposes (Curry and Fons 1940; Fons 1940b; Countryman 1956; Buck 1964; Schroeder and Buck 1970). In Australasian forest fire research, in-stand wind speeds have been measured at anywhere from 1.0 to 2.0 m above ground (Cheney 1981; Beck 1995a). From the standpoint of the present work, the significance of this difference is considered to be inconsequential.

Assumption No. 10. That the user can readily estimate and/or measure the six or seven primary variables required to determine whether the onset of crowning is possible or not, namely ambient air temperature, in-stand wind speed, foliar moisture content, crown base height, surface fire intensity (Byram 1959a), and flame front residence time (Fons et al. 1962) as well slope steepness, if necessary. Heuristically, it's believed that these are the most important factors affecting the onset of crowning in conifer plantation forests.

Assumption No. 11. The model for predicting the onset or initiation of crowning as outlined here is deemed to be most applicable to situations were level or gently undulating terrain is involved. Even in the absence of wind, flames will lean toward the slope. Although it is possible to include the mechanical effects of slope steepness on the fire spread rate (Fig. 2.11) and in turn surface fire intensity, there is at present no reliable way to account for the decrease in the angle of the convection column due to the fact that the flames from a surface fire tend to attach themselves to the slope (Albini 1976c; Rothermel 1985). When this happens, the hot convective gases flow up the slope closer to the ground surface rather than rising near vertically, as they would on flat terrain or on a shallow slope in light winds, unless a bench or the ridgetop is encountered (Fig. 3.4). Laboratory studies have shown that as slope steepness gradually increases, the flames lean more and more toward the slope surface (Van Wagner 1977b), even in still air conditions. Rothermel (1985) points out that "... there is no definitive research on the problem of flame attachment ..." and goes on to point out that "It appears that both lab work and discussions with users that the flame becomes attached near 50 percent [≈ 27°] slope with no prevailing wind". Van Wagner (1977b) in turn has indicated on slopes greater than 31-35° that the "... flames would tend to bathe the slope directly and fire behaviour would become very intense and unstable." Although it might be possible to artificially reduce the angle of the convection column based on a wind speed-slope equivalency concept (e.g., McAlpine et al. 1991), there appears to be no reason for doing this since by ignoring the effect, one is simply overestimating the potential for crown fire initiation in such cases because the convection column would simply be judged to be tilted as a result of the wind (this is discussed more fully in Section 3.2.3) and not due to the combined effects of wind speed and slope steepness[1]. However, the validity of assuming that t_r adequately reflects the duration of the most significant preheating in the lower crown space remains unknown.

Assumption No. 12. Because trees grow vertically and not perpendicular to the terrain slope, the uphill sides of their crowns will in turn be much closer to the ground (de Ronde et al. 1990) and, therefore, subject to an increased probability of crown fire initiation. Xanthopoulos (1990) has suggested that the distance to the crown base on the upslope side of trees "... should be measured perpendicular to the horizontal plane rather than perpendicular to the slope surface. The rationale behind this suggestion is that hot gases convect upwards, unaffected up slope, when wind is not present". For the reasons already discussed under the previous assumption, it's felt that the distance from the ground to the upslope side of the tree crowns should in fact be measured perpendicular to the terrain slope, contrary to Xanthopoulos' (1990) suggestion. In instances where plantations growing on a slope are pruned to a specified height (Maclaren 1993), it's assumed that the crown base has not been pruned parallel to the terrain slope based on current practices (Fogarty 1995).

Assumption No. 13. Once ignition of the lower crown base has been achieved and active flaming combustion has been initiated, vertical fire spread throughout the entire length of the crowns is assumed to take place, probably as a result of a combination of heat transfer mechanisms (i.e., radiation, convection and direct flame contact) although a precise interpretation of the physical processes involved is not professed. This supposition is easily substantiated on the basis of both laboratory (Van Wagner 1961, 1967b; Quintilio 1977; Fuglem and Murphy 1979) and field (Billing and Bywater 1982) studies involving pilot ignition at the crown base of individual conifer trees. For present purposes, crown fire initiation is judged to be independent of stand structure or crown characteristics (i.e., presumably the minimum crown bulk density necessary to support initial crown combustion exists).

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[1] Please note that this rationalization would **NOT** be appropriate when considering firefighter safety. Convective heat transfer does not normally affect firefighters directly. However, on steep slopes with moderate to strong winds, the hot convection gases, although rising will remain relatively close to the ground and for this reason is an important aspect of human survival in wildland fires (McArthur and Cheney 1972) in addition to fire suppression strategies and tactics by ground forces.

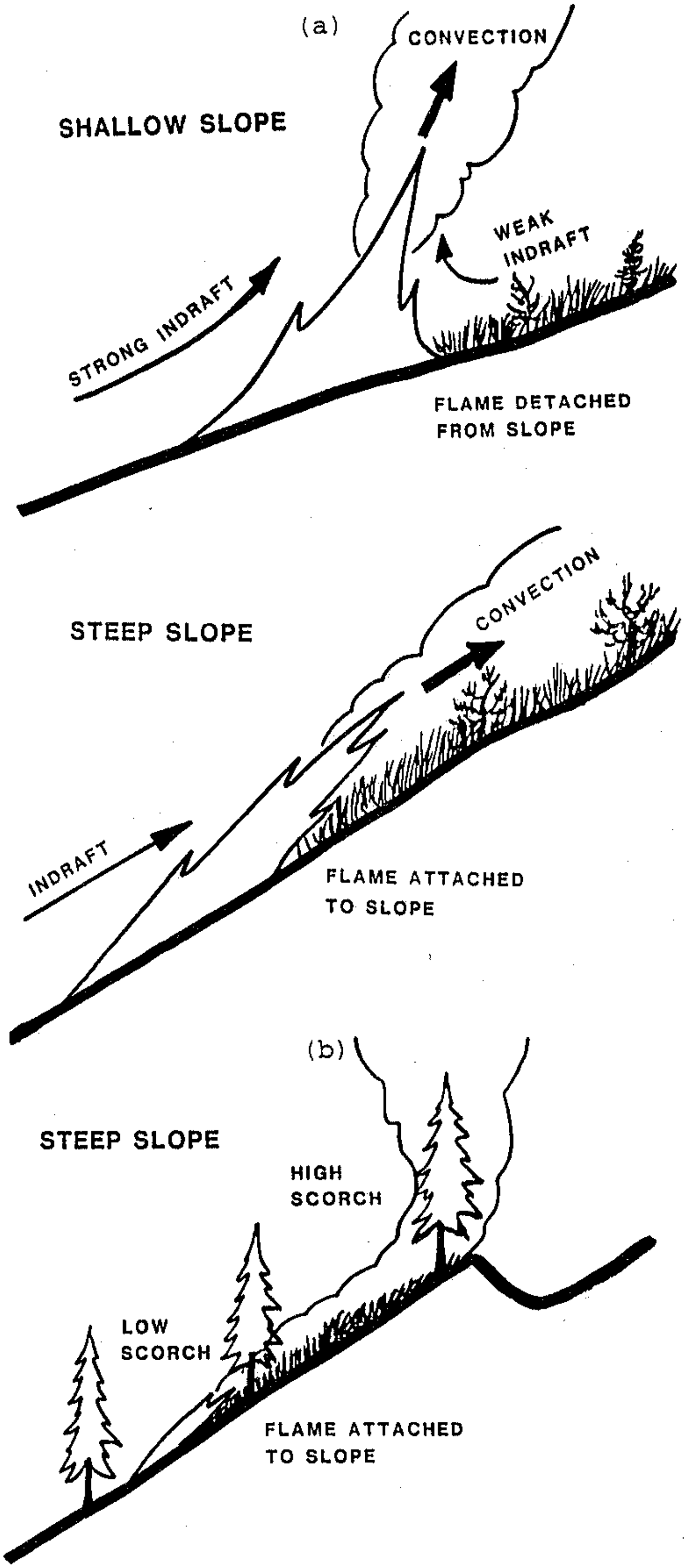


Figure 3.4: Schematic illustrations of (a) the effects of fire-induced indrafts on the plume trajectory for two contrasting slope situations and (b) the increased crown scorch heights associated with discontinuities in sloping terrain (from Rothermel 1985).

3.2 Model Formulation and Equations

Van Wagner (1977a) made the following statements with respect to his theory on the conditions necessary for the initiation of crowning in conifer forests:

> *Consider first the ignition of the tree crowns and suppose that it depends merely on the attainment of a certain minimum temperature at the base of the crown layer .... The actual temperature needed at the crown base is not important here since the main goal is to deduce a valid criterion that can be calibrated by field observations.*

The inherent weaknesses or limitations with Van Wagner's (1977a) crown fire initiation model have been enunciated in Chapter 2. It's readily acknowledged that any consideration of temperatures associated with forest or wildland fires and their measurement is indeed froth with problems (Van Wagner 1970; Alexander 1982). Nevertheless, any further major advances in the understanding or modelling of the crown fire initiation process are unlikely to be realized simply by continued application of traditional methods. What is required is a more fundamental approach involving a detailed understanding of fire behaviour than can be applied at the design stage (Drysdale 1985).

3.2.1 Foliar Ignition Criteria

The first component of the model is based on the results of the time to ignition study of Xanthopoulos (1990) as mention earlier in Section 2.4.1; the results have also been published in Xanthopoulos and Wakimoto (1993). His results were favoured over that of other investigations involving live foliage material because of: (1) the variation in simulated plume or convection temperatures and foliar moisture contents over which he sampled and, (2) his instrumentation appeared to more realistically simulate the convective thermal currents in the environment or "thermoclimate" (Methven 1971) above a surface fire than would be the case with a muffle furnace (e.g., Montgomery and Cheo 1969, 1971; Gill and Pook 1991), propane torch (Bunting et al. 1983), bunsen burner or other similar device (Mutch 1964; Burgan 1966; Stockstad and Lory 1970; Stockstad 1972, 1975; Valette 1990; Dimitrakopoulos 1994), even though they all demonstrate a decrease in time to ignition with decreasing foliar moisture content or fine dead fuel moisture content. Van Wagner's (1961, 1967b) laboratory findings of simulated crown fire activity versus foliar moisture content mentioned earlier on in Section 3.1 would certainly support the use of Xanthopoulos' (1990) empirical relation as opposed to assuming that all of the moisture must be driven off for ignition and combustion to occur as implied by Equation 2.7 and similar ones (Fig. 2.4).

The empirical equation derived by Xanthopoulos (1990) for ponderosa pine (*Pinus ponderosa*) needle foliage was adopted for present purposes (Fig. 3.5):

$$\boldsymbol{t_l} = 291.917e^{(-0.00664\boldsymbol{T_c} + 0.00729\boldsymbol{m})} \qquad \boldsymbol{T_c} \geq 400 \qquad (3.3)$$

where $\boldsymbol{t_l}$ is the ignition delay time (sec), $\boldsymbol{m}$ is the foliar moisture content (% oven dry weight basis), and $\boldsymbol{T_c}$ is the thermal fire plume or convection column temperature (°C). The interpretation is straightforward. For example, ponderosa pine foliage at 140% moisture content

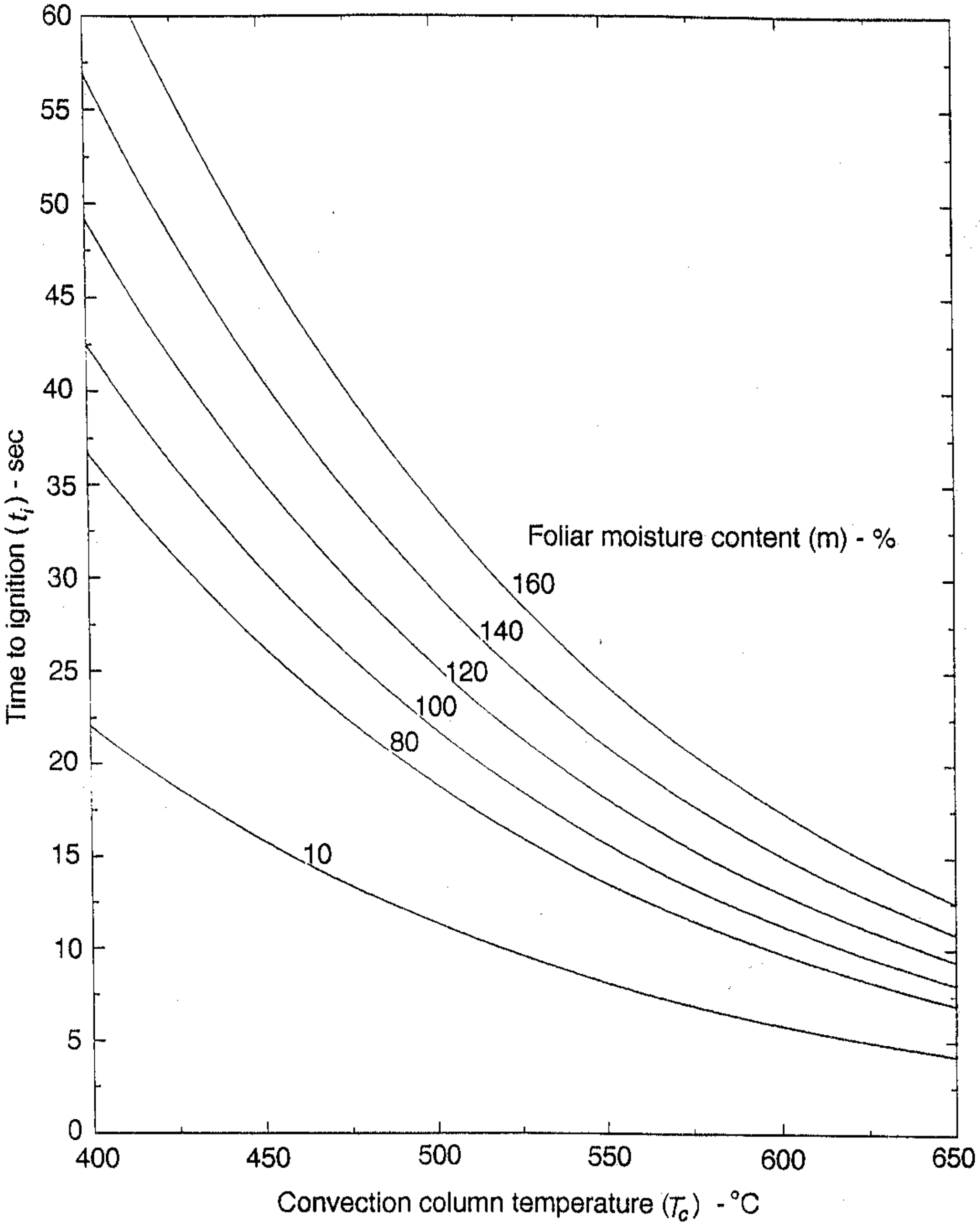


Figure 3.5: Time to ignition as a function of convection column temperature and moisture content of ponderosa pine needle foliage according to Xanthopoulos (1990).

is presumed to ignite when exposed to a convection column temperature of 500°C for 30 sec when a pilot flame is present.

Xanthopoulos (1990) did in fact also develop relationships similar to Equation 3.3 for Douglas-fir (*Pseudotsuga menziesii* var. *glauca*) and lodgepole pine (*Pinus contorta* var. *latifolia*). At a nominal m of 120%, the calculated t_i values for the three species when T_c = 550°C would be as follows:

Species	t_i
Lodgepole pine	14
Douglas-fir	16
Ponderosa pine	18

The t_i values for lodgepole pine and ponderosa pine appear logical relative to each other given the characteristic surface-area-to-volume ratios (σ) and particle diameter (**d**) for individual needles (Table 3.1). However, one would expect Douglas-fir to have a t_i less than lodgepole pine given the higher σ and smaller **d**. This may be due "... to the fact that many branch samples had to include more than one needle age, which resulted in higher moisture content variation" and "... the higher variability in bulk density of Douglas-fir branches" (Xanthopoulos and Wakimoto 1993).

Although Equation 3.3 was derived specifically for ponderosa pine needle foliage, it is felt to be sufficiently valid for the *Pinus* spp. of interest in this thesis because of the general anatomical similarity in individual needle and foliar characteristics (e.g., relative needle length, thickness and shape as well as foliage structure) even though their surface area-to-volume ratios may vary slightly (Table 3.1). By exposing various fresh hardwood leaf and conifer needle samples in a muffle furnace set at 600°C, Gill and Pook (1991) found that the delay in ignition was related to the fuel particle's surface area-to-volume ratio. However, the difference in ignition delay was just 2.3 sec (i.e., 9.0 versus 6.7 sec) for maritime pine and radiata pine at nearly the same moisture content (142 vs. 143%); note that according to Equation 3.3, for m = 142-143% at a presumed T_c = 600°C, that $t_i \approx 16$ sec. Therefore, while acknowledging this potential source of variation in the model with respect to species differences, it's believed that the effect is minor based on this relative comparison afforded by the work of Gill and Pook (1991).

The general form of Xanthopoulos' (1990) relationship, as graphically illustrated in Figure 3.5 is in agreement with similar studies for dead woody fuel particles at relatively low moisture contents (e.g., Prince 1915; Fons 1950; Beaufait 1959, 1960). If his equation is extrapolated beyond its observational base to 800-1000°C, a commonly accepted range for flame temperatures in forest fires (Van Wagner 1963a; Van Wagner and Methven 1978), then t_i at a nominal m of 120% would vary from ≈ 1-3 sec which is judged to be quite reasonable for direct flame contact based on informal "campfire experiences" and formal laboratory experiments (Van Wagner 1961, 1967a; Quintilio 1977; Fuglem and Murphy 1979). These computations also roughly match Anderson's (1970) theoretical computations.

The relevancy of Xanthopoulos' (1990) relationship to dead pine needles that are typically suspended on the dead branches in the lower portion of the bole of unpruned exotic pine trees is worth bringing up at this stage. Unfortunately, he did not measure t_i for dead ponderosa pine

Table 3.1: Comparison of representative surface area-to-volume ratios (σ) and particle diameters (*d*) for the individual needles of the main exotic pine species planted in Australasia and several of the North American conifer tree species referred to in the text.

Species	Nominal σ (cm^2/cm^3)	Reference	Nominal $\mathbf{d}$[a] (cm)	t_R[b] (sec)
Radiate pine[c]	51	Luke and McArthur (1978)[d]	0.078	15
Maritime pine[e]	45	Valette et al. (1994)[f]	0.089	17
Slash pine[g]	62	Hough and Albini (1978)[h]	0.065	12
Ponderosa pine	58	Brown (1970)[i]	0.069	13
Lodgepole pine	65	Brown (1970)[i]	0.062	12
Douglas-fir	69	Brown (1970)[i]	0.058	11
Red pine	49	Roussopoulos (1978b)[j]	0.082	15

[a] Assumed that $\mathbf{d} = 4/\sigma$ (*cf.* Luke and McArthur 1978).

[b] Computed from Equation 3.2.

[c] Gill and Pook (1991) have reported $\sigma = 49\ cm^2/cm^3$ for live or green needles and $59\ cm^2/cm^3$ for brown or air-dried needles whereas Williams (1977a) determined for live or green needles that $\mathbf{d} = 0.065$ and σ in turn was $\approx 62\ cm^2/cm^3$.

[d] Value for σ presumably represents "cured" needles (i.e., freshly fallen needle litter).

[e] Viegas and Neto (1990) have reported $\sigma = 24\ cm^2/cm^3$ for brown or air-dried needles but this is definitely incorrect (Viegas 1995). Gill and Pook (1991) indicate that $\sigma \approx 32\ cm^2/cm^3$ regardless of the condition (i.e., live or green versus brown or air dried ones).

[f] Value for σ presumably represents "cured" needles (i.e., freshly fallen needle litter). Alexandrian and Rigolot (1992) report the same σ value. Daligault (1991) has found that σ varied from 41-50 cm^2/cm^3 based on sampling at four sites.

[g] For practical purposes, Honduras Caribbean pine should be nearly identical given the close similarity between these two species (Little and Dorman 1952).

[h] Value for σ presumably represents "cured" needles (i.e., freshly fallen needle litter).

[i] Value for σ is for live or green needles.

[j] Value for σ presumably represents live or green needles.

needles which would have made a valuable comparison with his live foliage samples. However, at a nominal dead fine fuel moisture content of 10% for suspended needles in the lower tree bole (*cf.* Pook 1993), t_i from Equation 3.3 is predicted to range from 4-22 sec as T_c is varied from 650°C to 400°C.

3.2.2 Convective Temperatures Above Fires in Calm Air

Over 45 years ago, Yih (1951) determined the following relation for the air temperatures reached in the plume above a line heat source:

$$\Delta T \propto \frac{I^{2/3}}{Z} \tag{3.4}$$

where ΔT is the temperature increase above ambient conditions at height Z, I is the intensity of the line heat source and Z is the height above the line heat source; in his own work, Thomas (1963) envisioned Z to be the height above ground as opposed to the height above the flame zone (Thomas 1991).

Interestingly enough, the basic relationship represented by Equation 3.4 is used in many applications such as the placement of ceiling-mounted fire detectors in buildings (Alpert 1972; Drysdale 1985). Thus, as Weber, Gill, Lyons, Moore, Bradstock and Mercer (1995) quite rightly points out, Equation 3.4 is, strictly speaking, applicable to a stationary heat source such as presented by Rankine (1950) or Taylor (1961, p. 19, Fig. 4) but is deemed to be a reasonable approximation for wildland fires because when viewed from distance above the ground, the flame front advances relatively slowly as would be the case for a surface fire in a pine plantation. Equation 3.4 depicts temperature falling off with height above the flame front in a sloping curve as illustrated in Figure 3.1. The general form of the relationship described by Equation 3.4 has been directly confirmed by temperature measurements made over a considerable height above the flames of spreading fires, as opposed to stationary ones or area fires, in the laboratory (Fons et al. 1961, 1963; Anderson 1964; Byram et al. 1966) under still air and wind-driven conditions (Carrier et al. 1991) as well as in the field with assembled slash fuelbeds (Anderson et al. 1966; Countryman 1969b) and naturally occurring fuel complexes (Lindennuth and Byram 1948; Van Wagner 1975; Tunstall et al. 1976; Trabaud 1979; Williamson and Black 1981; Moore et al. 1995; Weber, Gill, Lyons, Moore, Bradstock and Mercer 1995). It's worth noting that Equation 3.4 constituted the fundamental basis for Van Wagner's (1977a) theory of crown fire initiation as well as his analysis of the height of lethal crown scorching (Van Wagner 1973b).

3.2.3 Inclination of the Surface Head Fire Plume in Relation to Wind Speed and Fire Intensity

Equation 3.4 is valid for perfectly calm conditions only. In such instances, the hot plume above the fire's flame zone forms a wedge whose thickness increases with height as air is entrained from the sides as illustrated, for example, schematically by Byram (1966) and photographically by Yih (1969). The addition of wind presumably causes the plume or convection column to be simply tilted for light winds without being greatly distorted (Byram et al. 1964; Carrier et al. 1991) or for the rising gases to become quickly mixed with the horizontal airstream under very strong winds (Mercer and Weber 1994). Hanna et al. (1982) have, in fact, stated that "A plume is usually more or less 'vertical' if wind speed is less than about 1 m/sec" or 3.6 km/h. In the following formulation, presumably the thermal plume stays intact and tilts at an angle as long as the horizontal wind does not exceed the vertical wind speed (Cramer 1974). Updraft velocities measured experimentally in the field within 10 m or less of the ground surface above low to moderate-intensity experimental fires have seldom exceeded more than 6 m/sec or ≈ 20 km/h (e.g., Anderson et al. 1966; Packham 1970; Cheney et al. 1992).

A whole host of models exist for predicting flame angle (e.g., Fons 1940a; Hamada 1952; Anderson and Rothermel 1965; Putnam 1965; Thomas 1965b, 1967; Welker et al. 1965; Rothermel and Anderson 1966; Welker and Sliepcevich 1966; Fang 1969; Lois 1979; Nelson 1980; Albini 1981a; Quintiere et al. 1981; Nelson and Adkins 1986) most of which have derived from laboratory studies and/or theoretical considerations. Not one of them report to extend to the fire plume above the flame zone where the convective heating takes place; some fire modellers have simply assumed that they are one of the same (e.g., Venkatesh and Saito 1992). Thus, at the present time there exists no relationship that has been specifically formulated for predicting the plume angle from surface fire behaviour characteristics and wind velocity. This was considered fundamental to the present efforts.

3.2.3.1 Evaluation of Van Wagner's Formulation

Van Wagner (1973b) derived a relationship based on the earlier work of Taylor (1961) and Thomas (1964) that could be used to give an initial approximation of the plume's angle of inclination, at least for light to moderate winds (perhaps up to 18 km/h according to Figure 3 of his paper). Taylor (1961) originally proposed the following theoretical relation for plume angle on the basis of a "... heuristic argument ..." (Albini 1981a):

$$tan\ A_p = \mathbf{C}\ (\boldsymbol{I}/\boldsymbol{u}^3)^{1/2} \tag{3.5}$$

where A_p is the angle formed between the buoyant plume of a wind-driven surface fire and the horizontal (°), **C** is a proportionality constant, $\boldsymbol{I}$ is the intensity of the line heat source and $\boldsymbol{u}$ is the wind speed (m/sec). Albini (1981a) deduced a similar relationship for flame tilt angle instead of flame angle based on flame height ($\boldsymbol{h_F}$) instead of $\boldsymbol{I}$.

Taylor's (1961) theory was further developed by Thomas (1962, 1964) and Van Wagner (1973b) attributed the following formulation in part to their collective efforts:

$$tan\ A_p \propto (\boldsymbol{bI}/\boldsymbol{u}^3)^{1/2} \tag{3.6}$$

where $\boldsymbol{b}$ is a buoyancy term which "... must be included for dimensional reasons ..." (Van Wagner 1973b) and is comprised of a group of variables defined as follows:

$$\boldsymbol{b} = \boldsymbol{g}/\rho\ \boldsymbol{c_p}\ \boldsymbol{T_o} \tag{3.7}$$

where g, ρ, c_p and T_o are quantities as previously defined in Chapter 2. Given that g and c_p are constants and that ρ can also be considered one as well for practical purposes, b is essentially constant given the very minor effect of a few degrees variation in T_o; Van Wagner (1973b) in fact set T_a = 24.84°C (i.e., T_o = 298°K) in his derivation of b. Using Thomas' (1964) values for g, u, c_p, and T_o = 298°K, Van Wagner (1973b) determined that the numerical value of b = 0.107 in the unit system m-sec-kg-kcal-°K. When Byram's (1959a) fire intensity (I_B) is used in place of I in Equation 3.6, and I_B is expressed in kW/m rather than in kcal/sec-m as Van Wagner (1973b) used, then b = 0.025574 (*cf.* Alexander 1985b); Cheney et al. (1992) on the other hand set b = 0.0265 although they didn't specify what values they used in the derivation of this quantity. Thus, the following equation constitutes the relation that Van Wagner (1973b) used for considering the influence of wind in his model for predicting crown scorch height:

$$A_p = tan^{-1}((0.025574 I_B/(0.27778 U_{1.2})^{3.0})^{0.5}) \qquad U_{1.2} > 0 \qquad (3.8)$$

where $U_{1.2}$ is the wind speed (km/h) measured at a height of 1.2 m above ground within a forest stand (*cf.* Van Wagner 1963b; Van Wagner 1968) or in the "open" if in a logging slash (Chrosciewicz 1975) or grassland (Durre and Beer 1989) fuel complex is involved (Van Wagner 1984); the ratio between the wind speed measured at the international standard height and exposure of 10-m above ground in the "open" U_{10} (km/h) and the in-stand wind varied from about 3:1 to 5:1 (Van Wagner 1984). Because Van Wagner (1973b) did not specify the height above ground and exposure with respect to wind speed measurement in his paper, many authors in the U.S.A. (e.g., Albini 1976a; Norum 1977; Dietereich 1979; Martin et al. 1979; Ryan 1982), for example, have assumed the winds applied to the 6.1 m (20 ft) open exposure standard that is commonly employed for fire danger rating and fire behaviour prediction purposes (Crosby and Chandler 1966; Finklin and Fischer 1990) and as a result, others have in turn followed suit (e.g., de Ronde 1988; de Ronde et al. 1990). On the other hand, some modellers (e.g., Schmidt 1975; Saveland 1982; Kercher and Axelrod 1984: Keane et al. 1989; Andrews and Bradshaw 1990) have assumed that the wind speed was equivalent to the "mid-flame wind speed" (Albini and Baughman 1979; Baughman and Albini 1980; Salazar and Bradshaw 1986; Keane et al. 1996), which is a reasonable "... theoretical interpretation ..." (Van Wagner 1984). Still others have left the wind speed height and exposure unstated (e.g., Soares 1979; Albini 1976b; Peterson and Ryan 1986; Tozzini and Soares 1987; Miller 1994; Reinhardt et al. 1996).

Inspite of Van Wagner's (1973b) adoption in his crown scorch modelling work, the applicability of Equation 3.8 to free-burning, wind-driven surface fires remain to be independently tested. Cheney et al. (1992) recently suggested that the effect of wind on A_p is stronger than the function advocated by Van Wagner (1973b) as represented by Equation 3.8. Their suggestion was based on the observations pertaining to an operational prescribed fire where the air temperature was 15°C, the wind at a 2 m height inside the forest stand averaged 6.5 km/h with gusts to 19 km/h, and I_B was estimated to be $\approx$ 1100 kW/m. The observed crown scorch height was 9 m. However, their own scorch height model predicted 11.5 m (i.e., A_p = 65°) and would have predicted $\approx$ 12.6 m for calm conditions.

The best available basis for evaluating Equation 3.8 comes from the recent research as documented in a compendium prepared by Fendell et al. (1990); *see* also the separate papers published by Carrier et al. (1991) and Wolff et al. (1991) resulting from this pubication. In their study, experimental fires were carried out in fuelbeds comprised of various manufactured materials (e.g., toothpicks) in a wind tunnel (at zero slope steepness) in which particular attention was paid to achieving plume behaviour that matched free-burning conditions in wildland environments (Fleeter et al. 1984). In these experiments (Fendell et al. 1990; Carrier et al. 1991), A_p was deduced from a high density thermocouple grid (Figs. 3.2b and 3.6 a-d). Four power curve fits were plotted based on the following equation form (after Carrier et al. 1991):

$$A_p = \mathbf{c}\ (\mathbf{m}/u)^{\mathbf{p}} \tag{3.9}$$

where **c** is a coefficient term (i.e., 36.8, 38.6, 40.0 and 41.6, respectively), **m** = dry fuel weight per unit area or fuel load (kg/m^2), u = wind speed (m/sec), and **p** is the power term (i.e., 0.15, 0.20, 0.25 and 0.33, respectively). Data pertaining to A_p and associated variables are available for 54 of the 194 or so of the experimental fires (Table 3.2 and Appendix A) carried out in the wind tunnel by Fendell et al. (1990). Of considerable value was the ability to maintain a constant wind velocity. This is a unique data set as it not only provides the opportunity for evaluating Equation 3.8, but other models for predicting A_p as well. It would be extremely difficult if not nearly impossible to replicate this type of effort in a field setting.

Of the 54 observations available on A_p, only one case would be really considered a distinct outlier -- i.e., Fendell et al. (1990) TRW test #154 with an observed $A_p = 62°$. Fendell et al. (1990) conducted various tests "...explicitly to examine fuel-moisture-content and/or substratum-moisture-content effects" on the "... flame-propagation rate". In test #154, fine water droplets were sprayed onto the ceramic trays, that were used to support the vertical fuel elements during the wind tunnel experimental fires, while at the same trying to maintain the pre-application fuel moisture content. Wolff (1995) admits that some of the fuel elements may have absorbed some of the water; this would have violated the assumption of equating **m** to w (Appendix A) to a certain extent, thereby reducing the calculated I_B of 41 kW/m (i.e., the actual value should probably be less). Wolff (1995) observed in cases like test #154, which was conducted at a relatively low u value (1.0 m/sec) compared to the other test fires (Table 3.2), that water vapour rising above the fuelbed was visible during the burning in the wind tunnel which in turn affected the rate of advance. However, for the purposes of model development and testing it's included in the scatter plots presented here in this section.

A comparison of the predicted plume angles by Equation 3.8 with the observed values of Fendell et al. (1990) is presented in Figure 3.7. The simple correlation coefficient (r) between the observed A_p versus the predicted A_p is 0.874. Strictly speaking, if Equation 3.6 were expressed in terms of A_p rather than tanget A_p, this gives the following result:

$$A_p = tan^{-1}\ (K\ (b\ I/u^3)^{1/2}) \tag{3.10}$$

In Van Wagner's (1973b) work, the proportionality constant K was not considered. In other words, it was assumed that $K = 1.0$ or K was simply ignored all together, in which case (K = 1.0 also applies), an assumption that Cheney et al. (1992) have apparently followed as well. A value of 0.345 was derived for K from an analysis of the Fendell et al. (1990) A_p data. The incorporation of this empirical constant would not appear to improve the predictability of A_p by Equation 3.10 as evident by the results displayed in Figure 3.8.

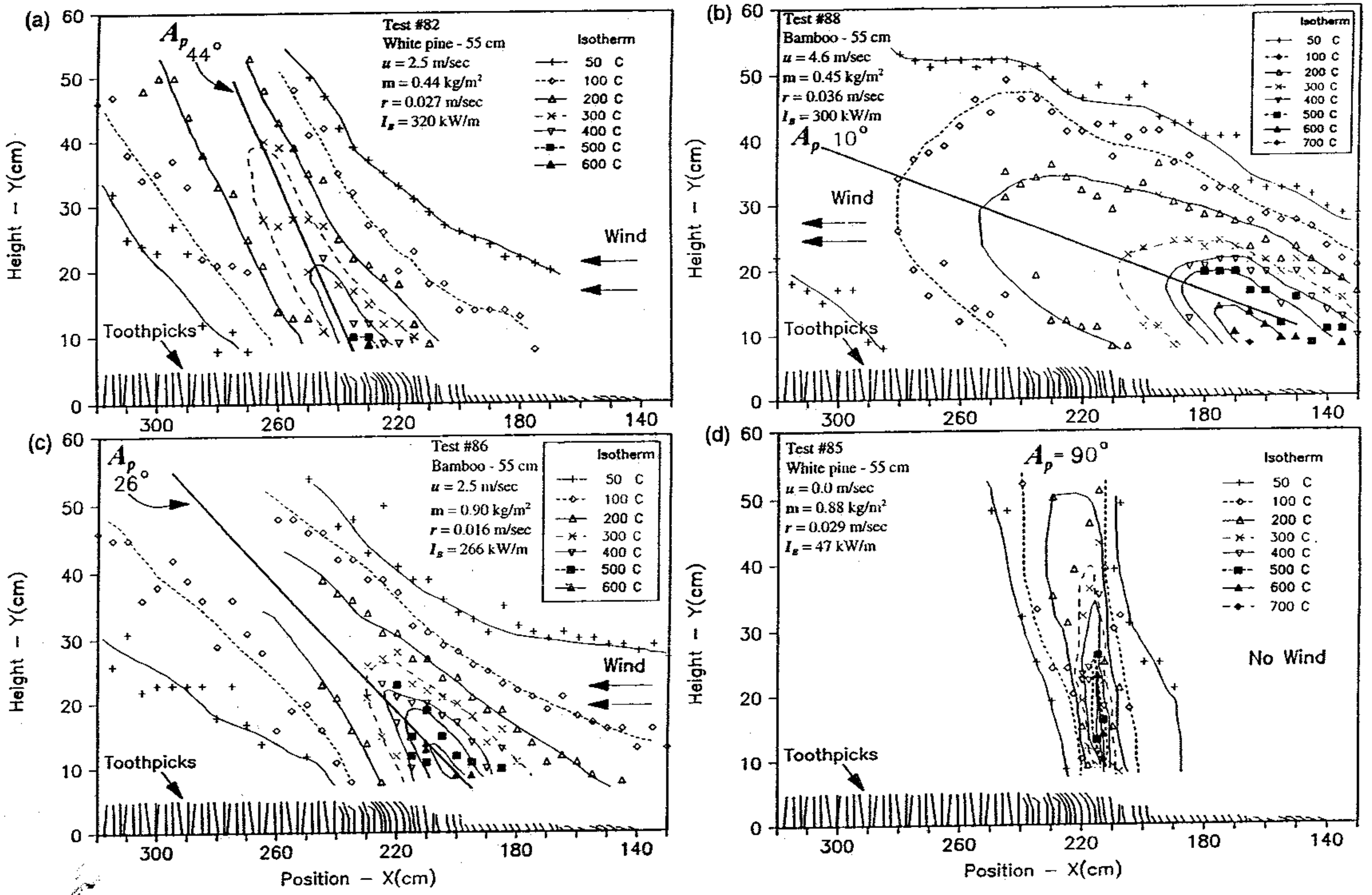


Figure 3.6: Example of isothermal contours inferred from thermocouple data based on experimental fires conducted in a wind tunnel (after Fendell 1988a, 1988b). Note that the x and y axes do not have a 1:1 relationship.

Table 3.2: Descriptive statistics for the fire plume angle data and other pertinent variables associated with the experimental fires carried out in the TRW wind tunnel facility as reported on by Fendell et al. (1990)[a].

Statistic	A_p (°)	u (m/sec)	I_B (kW/m)	m (kg/m^2)	r (m/sec)	T_a (°C)	N_c (dimensionless)
White pine flat toothpicks - 55 cm wide fuelbed (19 fires)[b]							
Mean	33	2.37	180	0.35	0.031	20.4	2.3
SD[c]	10	1.19	105	0.18	0.020	2.3	3.0
Range	21-62	1.00-16.56	41-472	0.11-0.88	0.010-0.091	16.5-27.0	0.2-9.8
White pine flat toothpicks - 100 cm wide fuelbed (7 fires)							
Mean	40	1.73	220	0.33	0.04	20.1	21.5
SD	13	1.60	133	0.28	0.02	1.7	18.6
Range	21-54	0.7-4.6	81-440	0.11-0.88	0.027-0.075	17.0-22.0	0.1-54.0
Birch dowels - 55 cm wide fuelbed (9 fires)							
Mean	27	2.45	241	1.32	0.016	21.2	11.3
SD	10	1.24	104	0.77	0.008	1.6	28.3
Range	10-43	0.7-4.6	108-466	0.50-3.12	0.007-0.036	19.0-23.0	0.2-86.4
Bamboo skewers - 55 cm wide fuelbed (15 fires)							
Mean	27	2.92	298	1.10	0.018	21.0	5.5
SD	10	1.40	162	0.87	0.008	1.9	15.8
Range	10-53	0.7-4.6	108-800	0.45-3.77	0.005-0.036	18.0-24.0	0.2-61.7
Birch dowels/white pine flat toothpicks - 55 cm wide fuelbed (3 fires)							
Mean	27	2.5	217	0.71	0.017	21.5	0.8
SD	8	0.0	82	0.26	0.003	2.0	0.3
Range	17-32	2.5-2.5	129-292	0.41-0.89	0.014-0.019	19.5-23.5	0.5-1.1
White pine sandwich picks - 55 cm wide fuelbed (1 fire)							
Mean	39	2.5	442	1.99	0.012	21.0	1.7
SD	--	--	--	--	--	--	--
Range	--	--	--	--	--	--	--
Total (54 fires)[b]							
Mean	31	2.5	243	0.77	0.025	20.8	7.4
SD	11	1.3	138	0.71	0.017	2.2	16.6
Range	10-62	0.7-4.6	41-800	0.11-3.77	0.005-0.091	15.5-27.0	0.1-86.4

[a] The fuel height and bulk density averaged 14.0 ± 11.5 kg/m^3 (range: 2.39-67.8) and 5.5 ± 3.0 cm (range: 3-20), respectively. Statistics on the individual fuelbed situations is given in Appendix A.

[b] Includes Fendell et al. (1990) TRW test #154.

[c] SD = standard deviation.

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

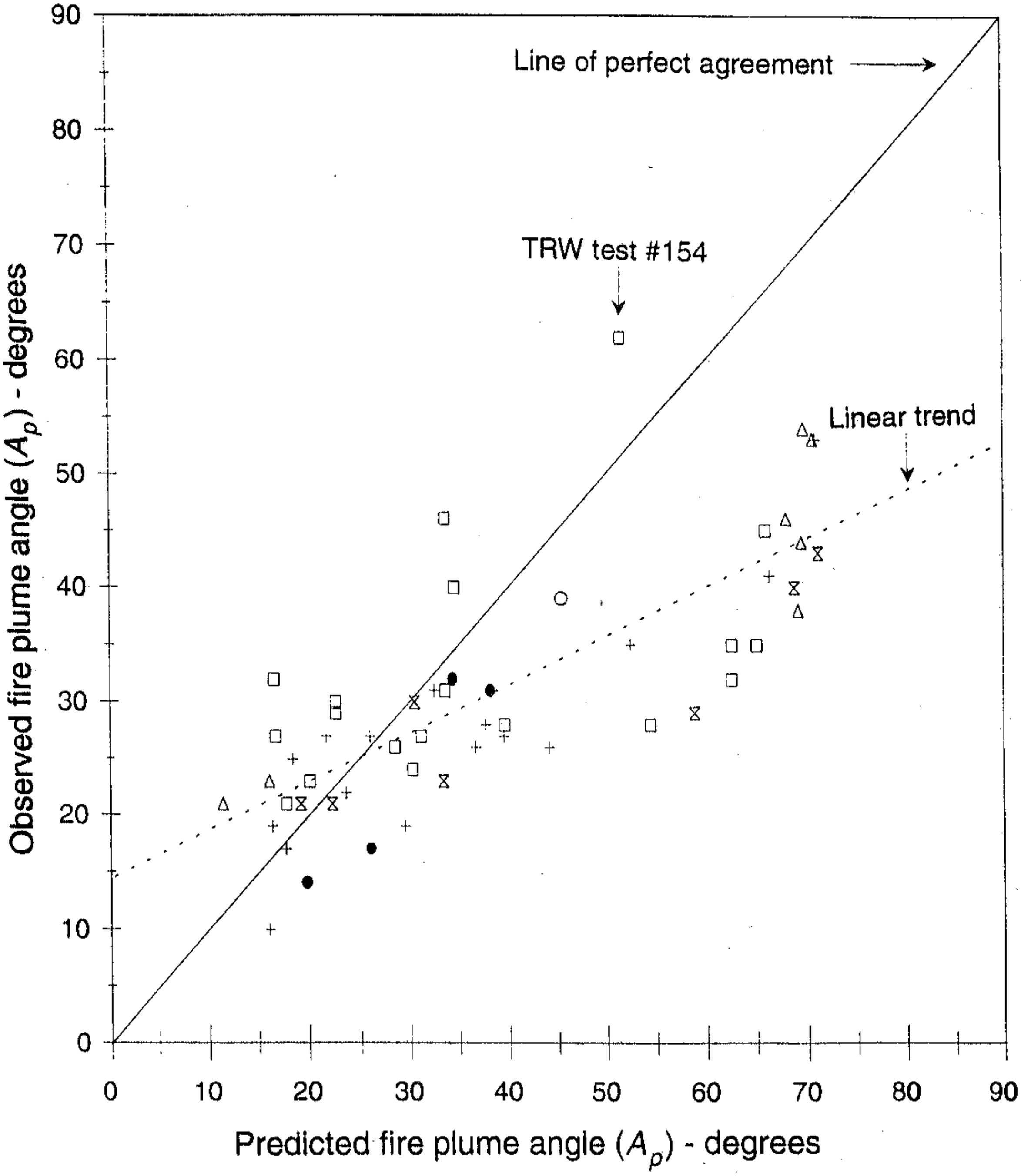


Figure 3.7: Fire plume angle predictions by Equation 3.8 versus actual observed fire plume angles based on experimental fires conducted in a wind tunnel as reported on by Fendell et al. (1990).

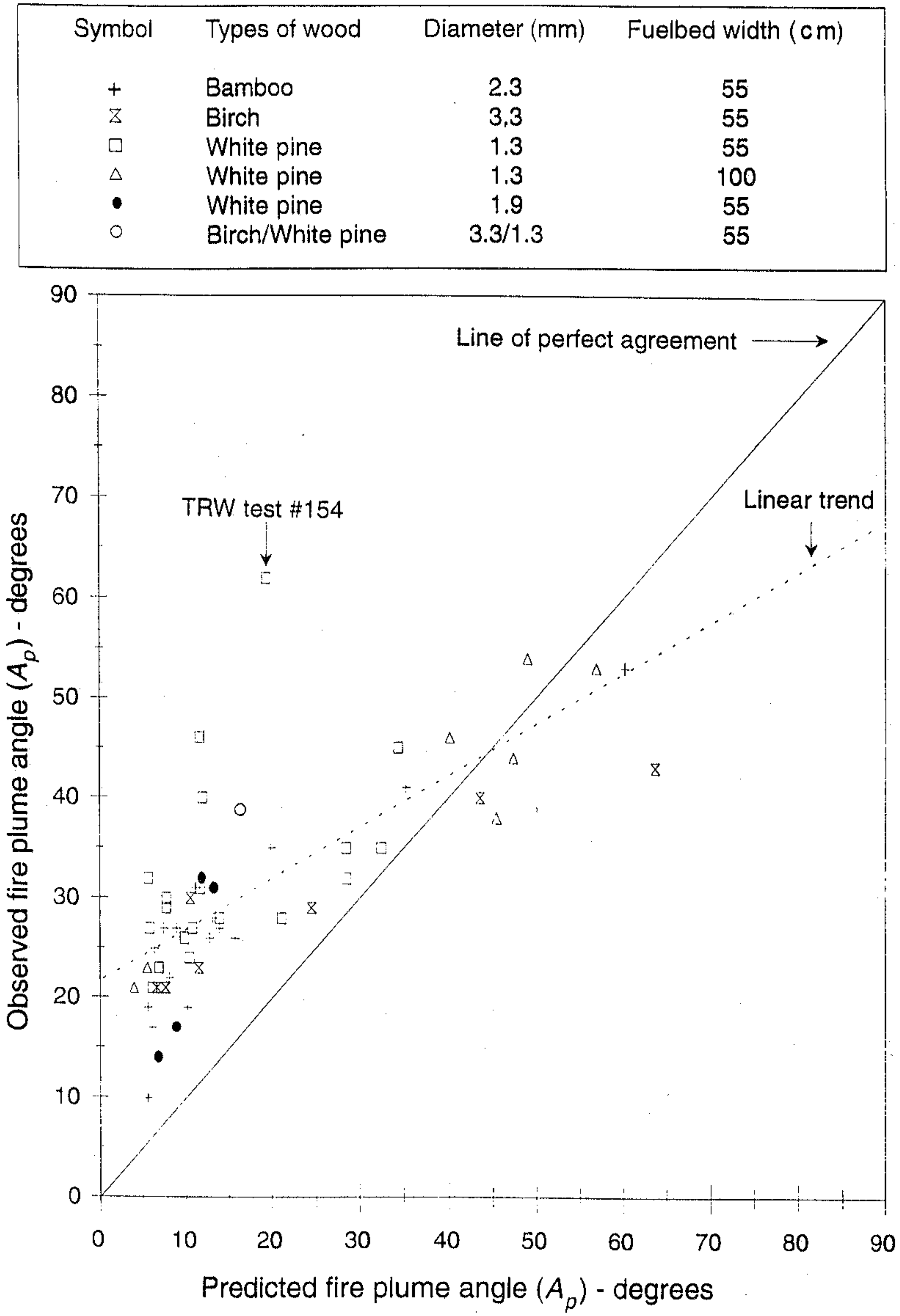


Figure 3.8: Fire plume angle predictions by Equation 3.10 (where $K = 0.344$ and $b = 0.025574$) versus actual observed fire plume angles based on experimental fires conducted in a wind tunnel as reported on by Fendell et al. (1990).

3.2.3.2 Evaluation of Byram's Convection Number as an Independent Variable

Both Martin et al. (1991) and Weise (1993) related Byram's (1959b) P_f/P_w ratio or convection number (N_c) (Nelson 1993a, 1993b) as discussed in Chapter 2, to flame angle and flame tilt angle (*see* Fig. 2.3), respectively; Weise (1993) derived the following equation (Fig. 3.9) based on pooled data for wind-blown head fires carried out in a wind tunnel using white birch (*Betula papyrifera*) sticks at no slope (0°) and at 15° and 30° gradients, both upslope and downslope:

$$A_T = tan^{-1}\,(2.36\ N_c^{\ -0.383}) \tag{3.11}$$

where A_T is the flame tilt angle (°); note that the coefficient in Equation 3.11 has subsequently been changed to 3.08 (Weise and Biging 1996, Equation 10) when it was later learnt that N_c had been inadvertly miscalculated by a factor of two. Martin et al. (1991) on the hand, using liquid pool fires, provided no equation. The results of these two studies were encouraging enough to prompt an analysis of the Fendell et al. (1990) A_p data in relation to N_c. The equation relating N_c to A_p depicted in Figure 3.9 is ($r^2 = 0.57$):

$$A_p = 27.8\ N_c^{0.154} \tag{3.12}$$

The general trend in relationship is certainly logical -- i.e., the plume becomes increasingly more erect as the power of the fire exceeds the power of the wind as reflected in N_c becoming progressively larger. For the 30 experimental fires where N_c was less than 1.0, the mean, standard deviation and range in A_p was 25.2°, 7.3° and 10-46°, respectively. In contrast, when N_c was greater than 1.0, these same statistical measures of A_p for the other 24 experimental fires were 38.3°, 10.2° and 26-62° (this includes TRW test #154), respectively. It's evident in Figure 3.9 that there is a large variation in A_p at N_c values less than about 1.0 and considerably less variation when $N_c > 1$. This would suggest that a separate relationship should be developed for wind-driven fires. For convection-dominated fires (i.e., presumably when $N_c > 1$), A_p could be related to N_c through the following equation:

$$A_p = 29.1\ N_c^{0.129} \tag{3.13}$$

This equation is also presented in Figure 3.9 ($r^2 = 0.50$). However, before such a relation could be implemented, it would be necessary to determine a means of incorporating the effects of slope steepness into the computation of N_c.

3.2.3.3 Development of a New Relationship

According to Taylor (1961), in an unpublished report written by A.O. Rankine in 1945, Rankine had experimentally determined the exponent in Equation 3.5 to be 0.286 instead of 0.5 based on a study he had conducted in a large wind tunnel using butane burners arranged in a line perpendicular to the air flow (Rankine 1950). Taylor (1961) actually quotes both 0.286 and 0.283 on pages 21-22 of his paper, but the weight of the available evidence, suggests that the latter value must be a typographical error.

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

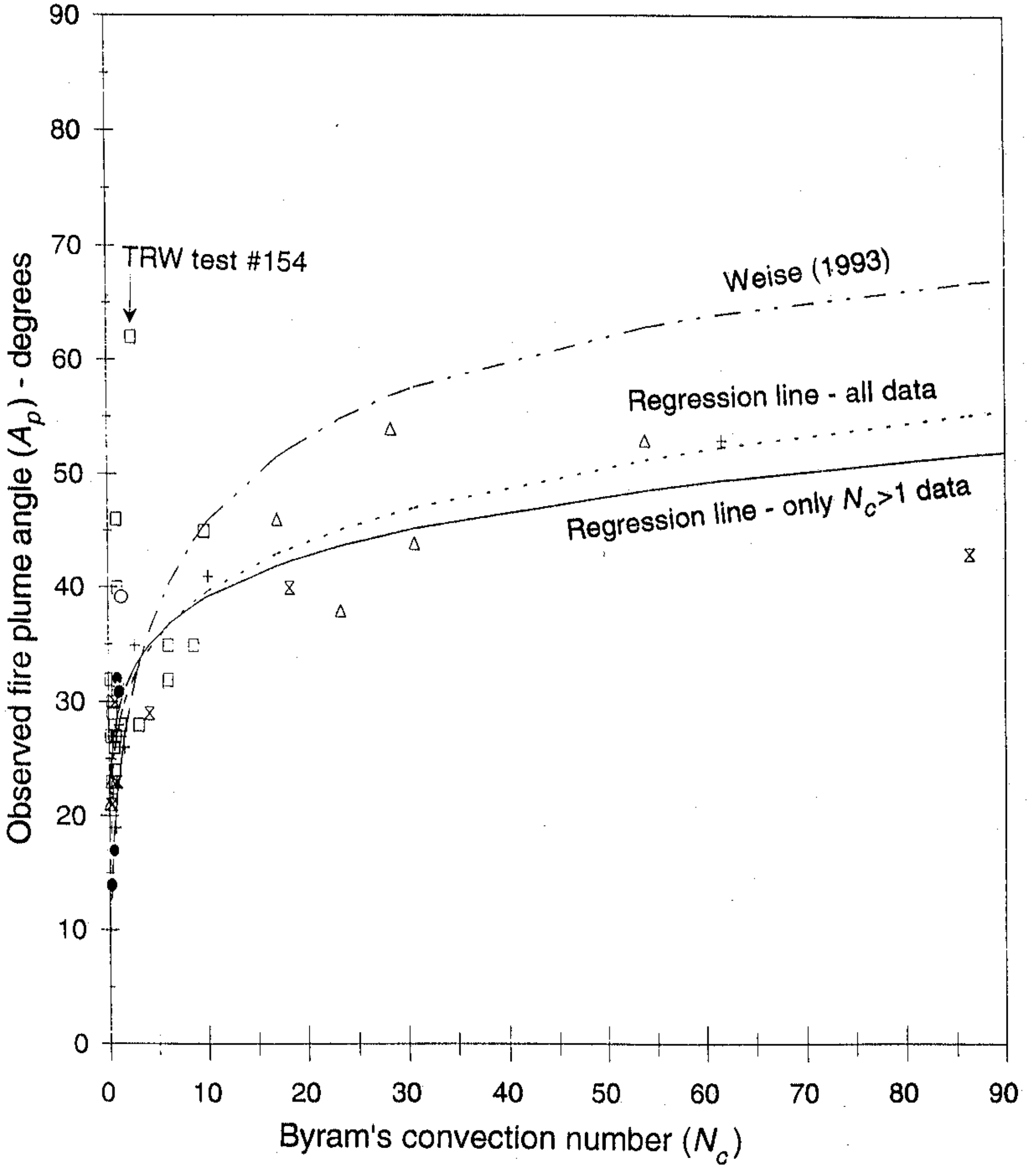


Figure 3.9: Observed fire plume angles based on experimental fires conducted in a wind tunnel as reported on by Fendell et al. (1990) in relation to Byram's convection number.

Nelson and Adkins (1986) found that their laboratory measurements of flame tilt angle in relation to wind speed departed from the buoyant flame theory of Taylor (1961) and Albini (1981). Furthermore, Nelson and Adkins' (1986) empirically obtained almost an identical exponent to what Taylor (1961) reported for Rankine's study. Nelson and Adkins' (1986) Equation 10 can be rewritten in the notation used here as:

$$A = tan^{-1} (0.388 (I_B/u^3)^{0.29}) \qquad (3.14)$$

where A is the flame angle (°) as opposed to the flame tilt angle A_T of wind-driven surface fires (Fig. 2.3). The coefficient 0.388 essentially represents **C** in Equation 3.5 when the exponent 0.5 is replaced by 0.29. Nelson (1991) has speculated that if one is just concerned with the buoyant plume at heights not far above the flame tip of a surface fire -- say a distance equivalent to five or ten flame heights -- and the wind is steady and not too light, then A could serve as an indicator of A_p. A comparison of the predicted A values based on Equation 3.14 in relation to the observed A_p values of Fendell et al. (1990) as presented in Figure 3.10 (r = 0.875) indicates that this might perhaps be a valid argument, but Equation 3.14 could not be used in its current form to predict A_p directly. However, the trend evident in Figure 3.10 proved to be a useful insight into formulating a relation for predicting A_p.

Following the lead of Nelson and Adkins (1986), a constant of 0.209 was derived from the A_p data set of Fendell et al. (1990) by holding the exponent constant at 0.286 (as opposed to 0.29); the coefficient of determination (r^2) was 0.87. A comparison of the predicted versus observed plume angles incorporating this new empirically derived constant is shown in Figure 3.11 and reflects the following formulation:

$$A_p = tan^{-1} (0.209 (I_B/(0.27778\ U_s)^{3.0})^{0.286}) \qquad U_s > 0.0 \qquad (3.15a)$$

where U_s, judged to be the effective within-stand wind speed as measured at roughly "eye-level" (km/h) as discussed in Section 3.1, has been substituted for u (m/sec). Clearly, Equation 3.15a is a noticeable improvement over Equation 3.8 as evident by a comparison of the linear regression trends in Figures 3.7 and 3.11 in relation to the line of perfect agreement. Because Equation 3.15a will result in a zero A_p value when U_s = 0.0, it becomes necessary to include the following qualification:

$$A_p = 90 \qquad U_s = 0 \qquad (3.15b)$$

Although Nelson and Adkins (1986) didn't include this qualifier in their work, it should in reality also be applied to Equation 3.14 as well. In other words, under calm or still air conditions, A = 90° as well. Note that in the case of TRW test #85 (*see* Fig. 3.6d), which was carried out at a no wind condition (i.e., u or U_s = 0.0 and therefore was not included in the derivation of Equation 3.15a), that $A_p \approx 90°$.

Whether the difference in the two coefficients for A (0.388) and A_p (0.209) are real or not is a valid question. Equation 3.14 does incorporate an approximate relationship between I_B versus u and flame height formulated by Nelson and Adkins (1986), whereas I_B was used directly in the derivation of Equation 3.15a. The difference could also be due to the methods used to derive the respective angles, the types of fuelbeds used, the characteristics of the

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

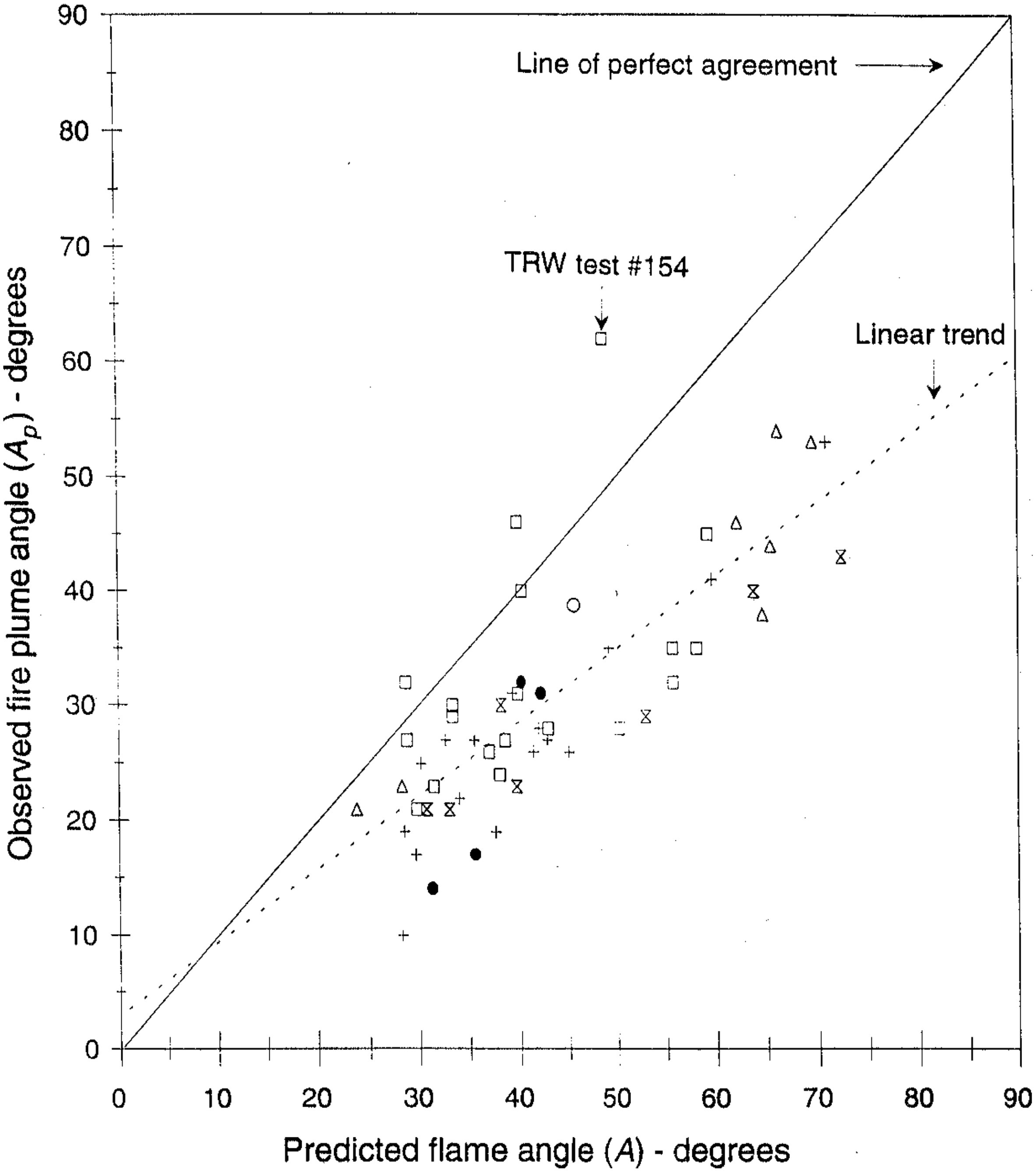
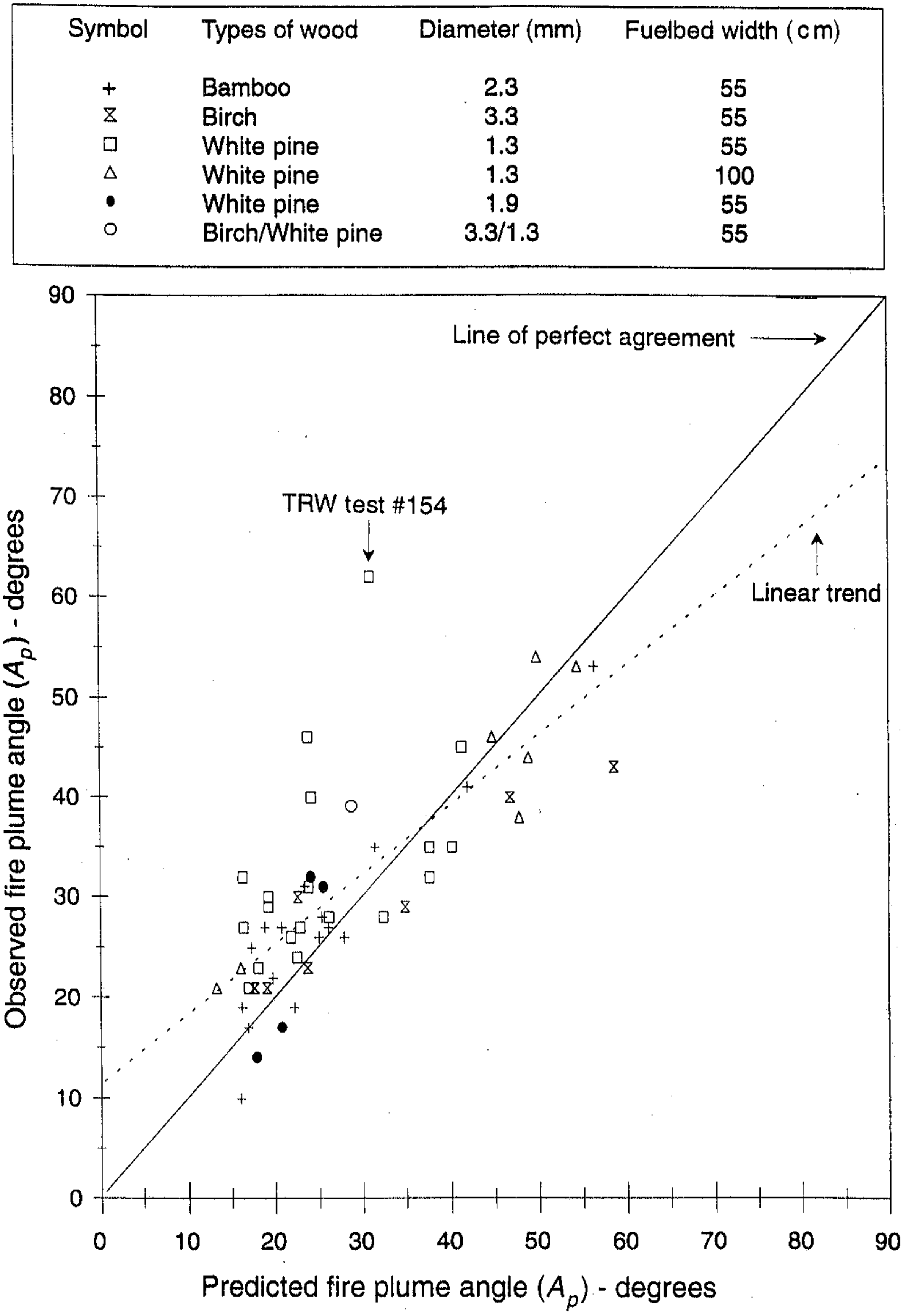


Figure 3.10: Flame angle predictions based on Nelson and Adkins' (1986) relation (Equation 3.14) versus actual observed fire plume angles based on experimental fires conducted in a wind tunnel as reported on by Fendell et al. (1990).



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 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., $\sin 43° = 0.682 \times 12.6 = 8.6$) 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:

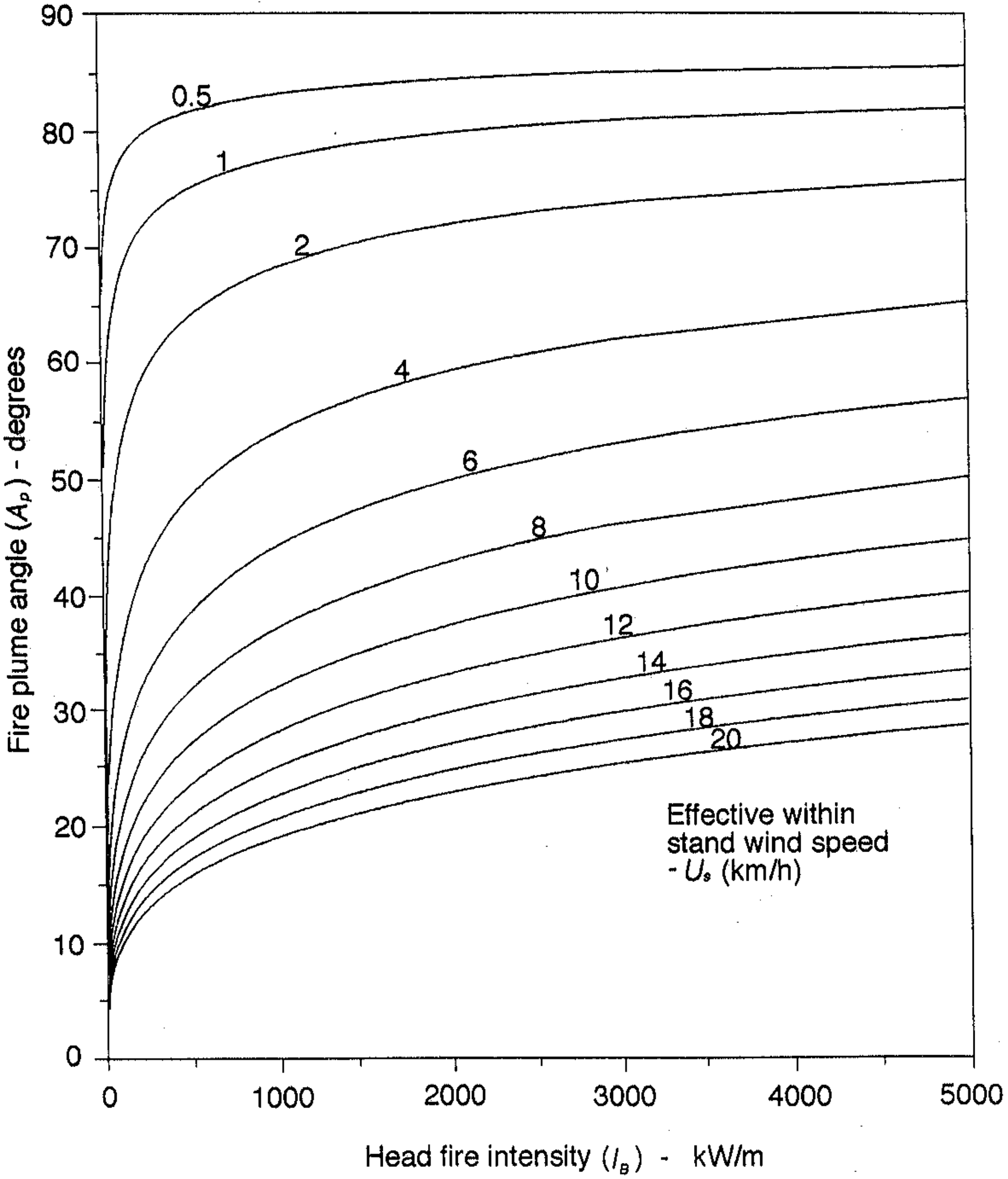


Figure 3.12: Fire plume angle as a function of Byram's fire intensity and wind speed according to Equation 3.15a.

> *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:

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

---

[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:

$$\Delta T = \frac{k_1 I_B^{2/3} \sin A_p}{z} \tag{3.17}$$

where k_1 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_1 in Equations 3.16 and 3.17 are empirical in nature and must be determined from field measurements and observations. A value for k_1 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:

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

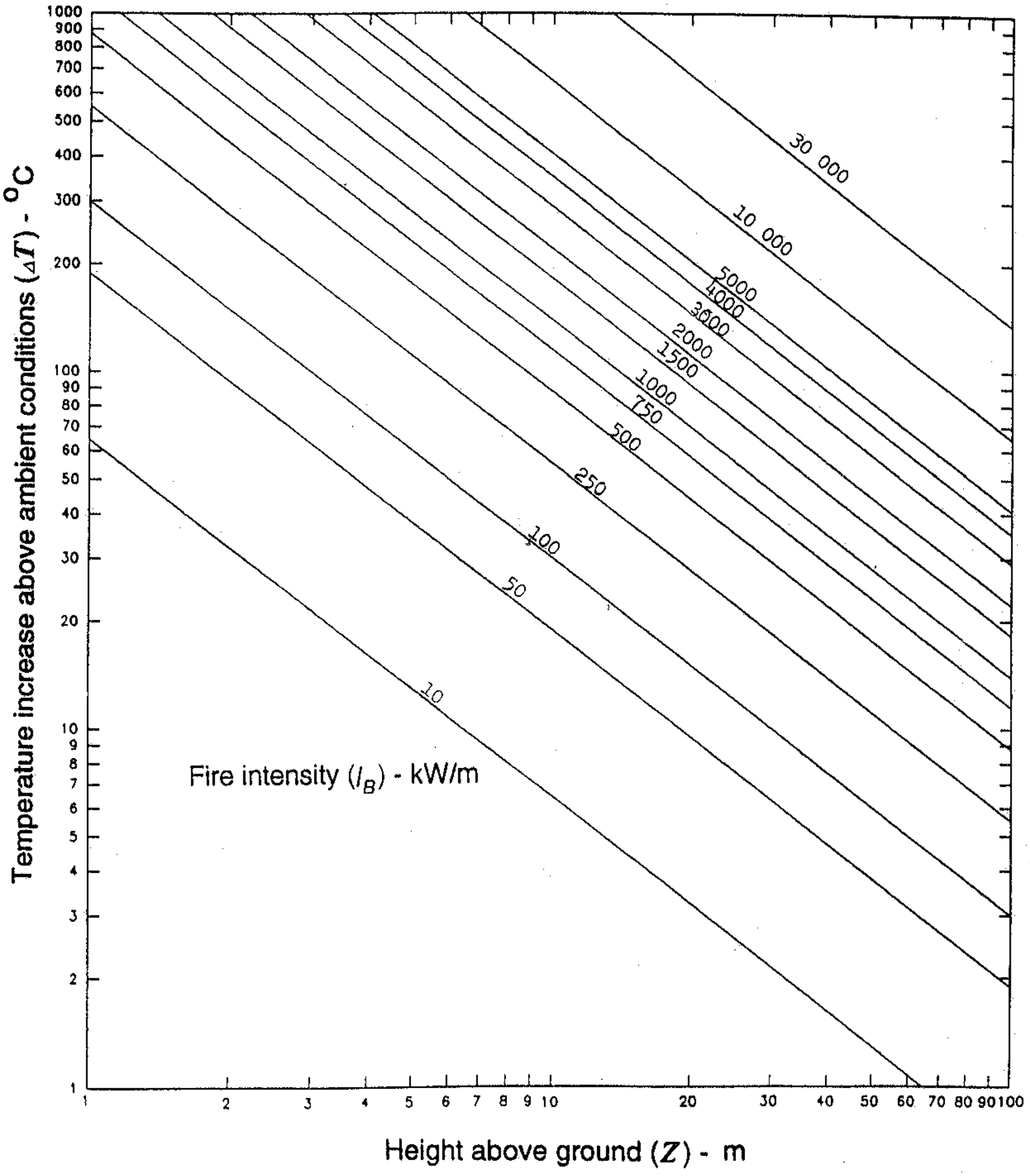


Figure 3.13: Temperature rise above ambient conditions in the convection column above a flame front of a given fire intensity for a "calm" wind situation according to Equation 3.16 where $k = 13.9$ (after Alexander 1991d).

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_l 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 ≈ 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

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[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 $\boldsymbol{k_1}$ 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 $\boldsymbol{k_1}$ 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:

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

$$\boldsymbol{k}_1 = \frac{\Delta \boldsymbol{T}\, z}{\boldsymbol{I}_B^{2/3}\, sin\, \boldsymbol{A}_p} \tag{3.21}$$

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 (m^2)	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/m^2; 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.

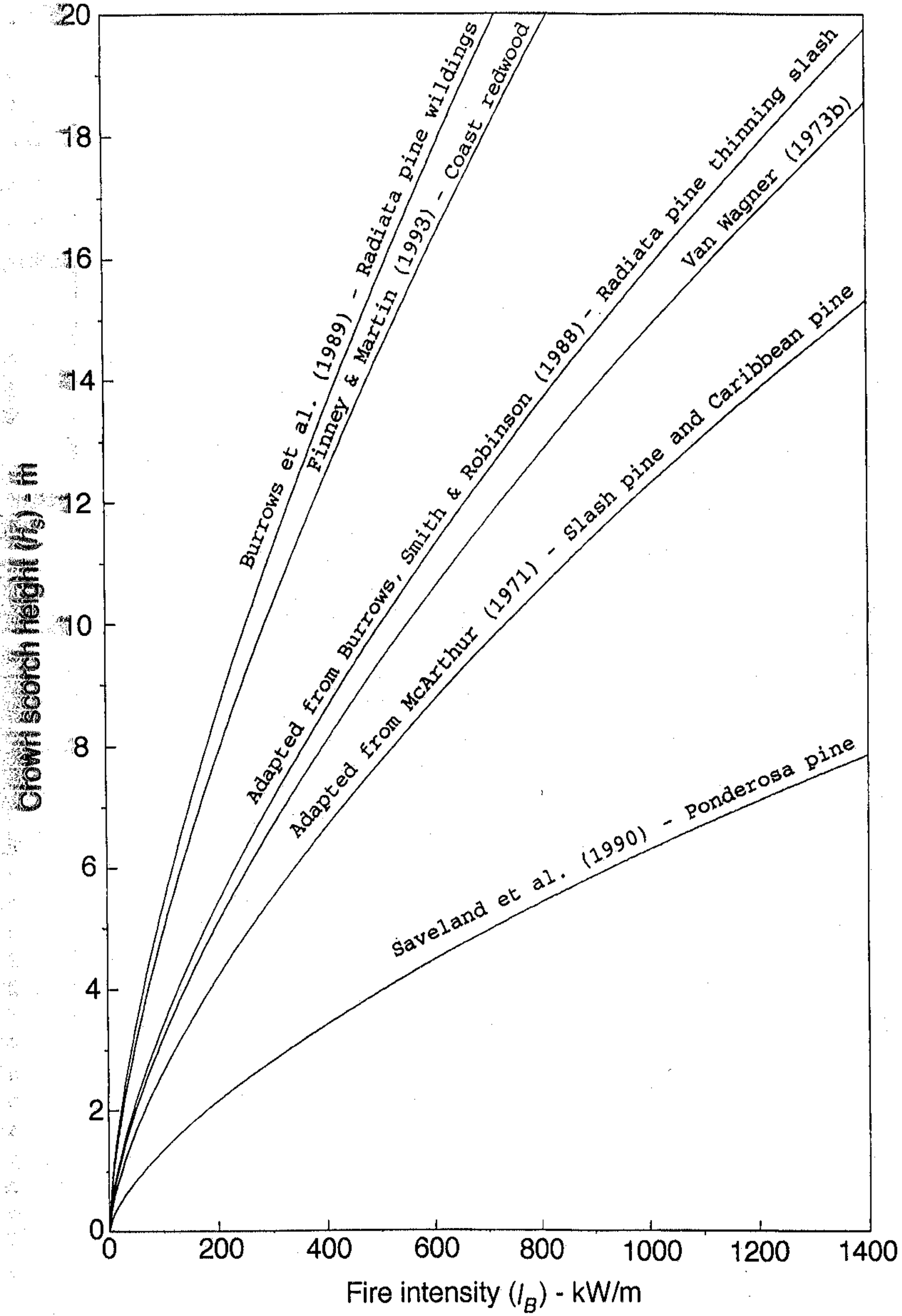

Figure 3.14a: Summary of existing fire intensity-crown scorch height relationships reported on in the literature.

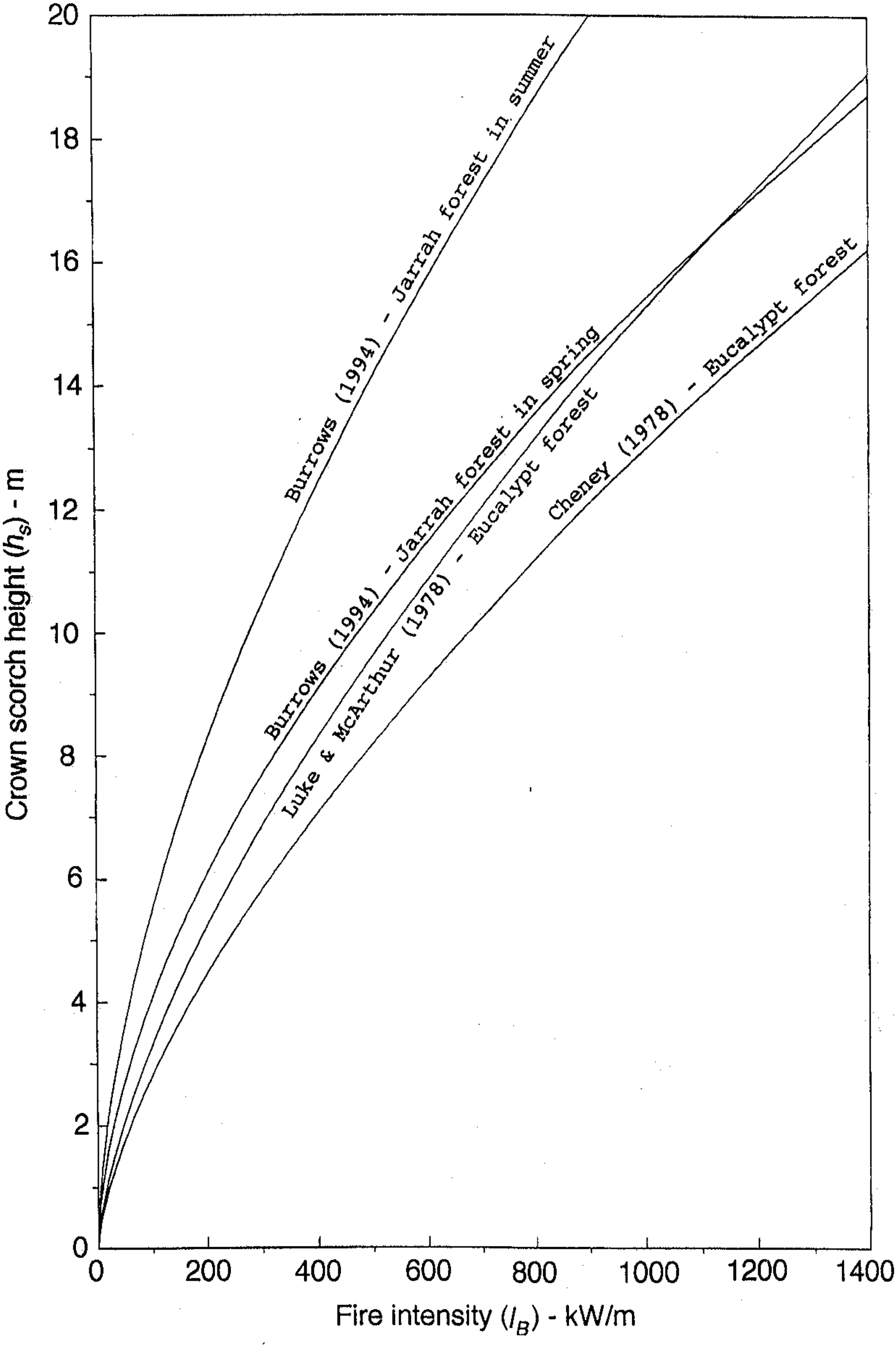

Figure 3.14b: concluded.

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 ($U_{1.2} \approx$ 2.3-4.7 km/h) but under moderate to high temperatures ($T_a \approx$ 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 ≈ 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.

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[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):

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

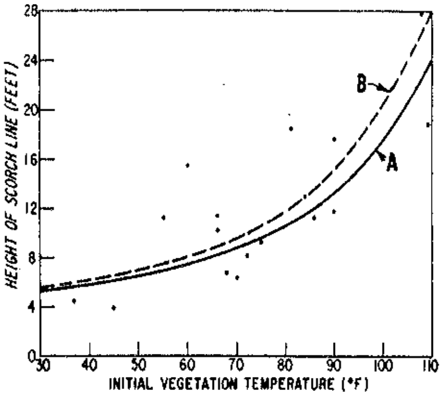
where L is the flame length (m). The range in L reported by Byram (1958) was used to calculate the range in I_B (20-47 kW/m) by this relation that was in turn used in Equation 3.23 to calculate the variation in h_s depicted in Figure 3.15b that was predicted by Van Wagner (1973b); T_a was assumed to 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)

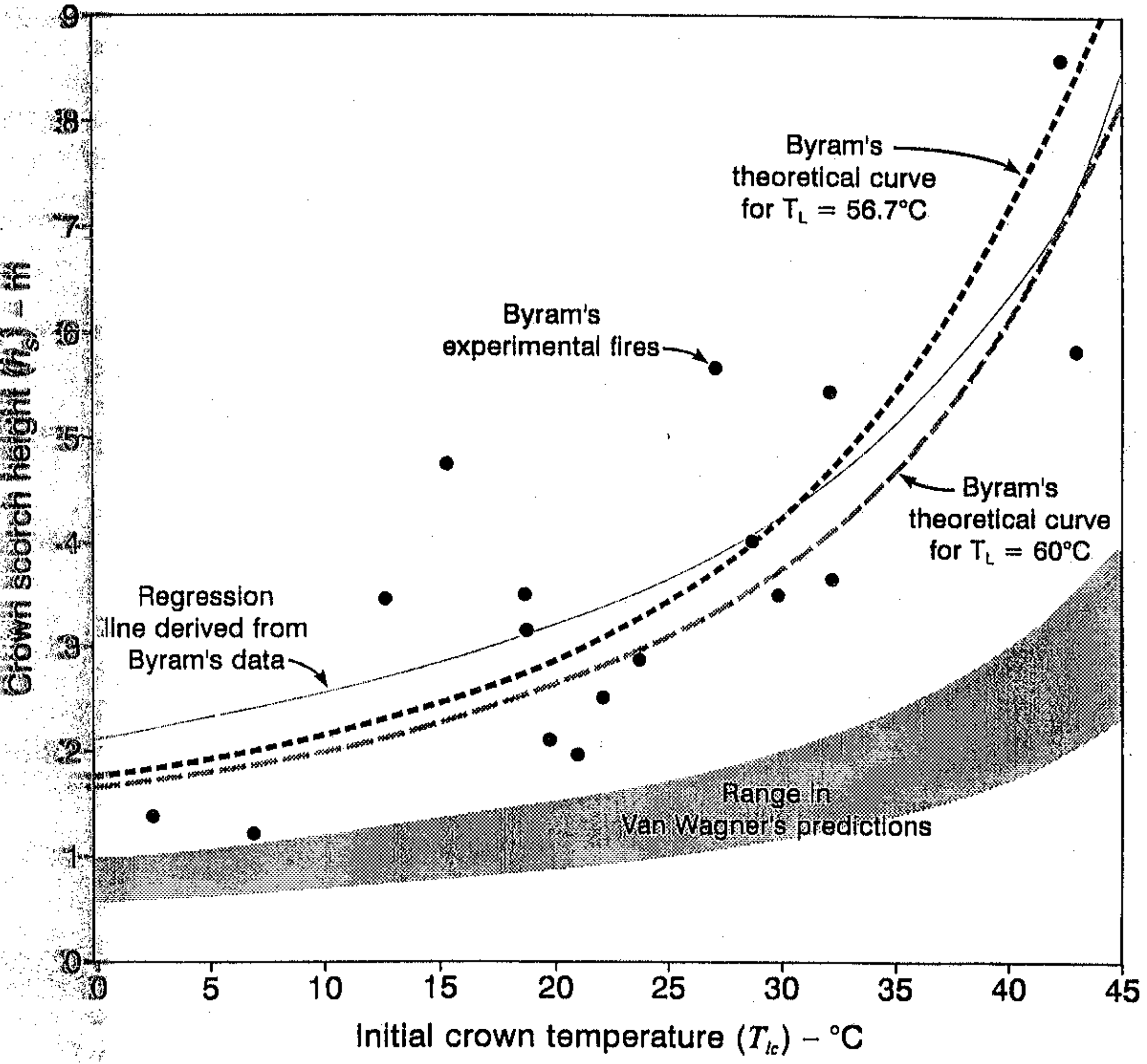


Figure 3.15: Byram's (1958) original presentation of crown scorch height in relation to initial crown temperature at essentially a constant fire intensity of ≃ 32 kW/m (a) and (b) an adapation including a comparison to predictions by Van Wagner's (1973b) relation represented by Equation 3.23 were fire 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_1 without the influence of wind considered (i.e., A_p = 90° or in other words *sin* 90° = 1.0) derived from the following equation:

$$k_1 = \frac{(T_L - T_a)h_s}{I_B^{2/3}\ sin\ A_p} \tag{3.26}$$

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_1 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_1 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:

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

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):

$$T_L = \mathbf{A} + \mathbf{B} \ln t_d \tag{3.28}$$

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:

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

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:

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

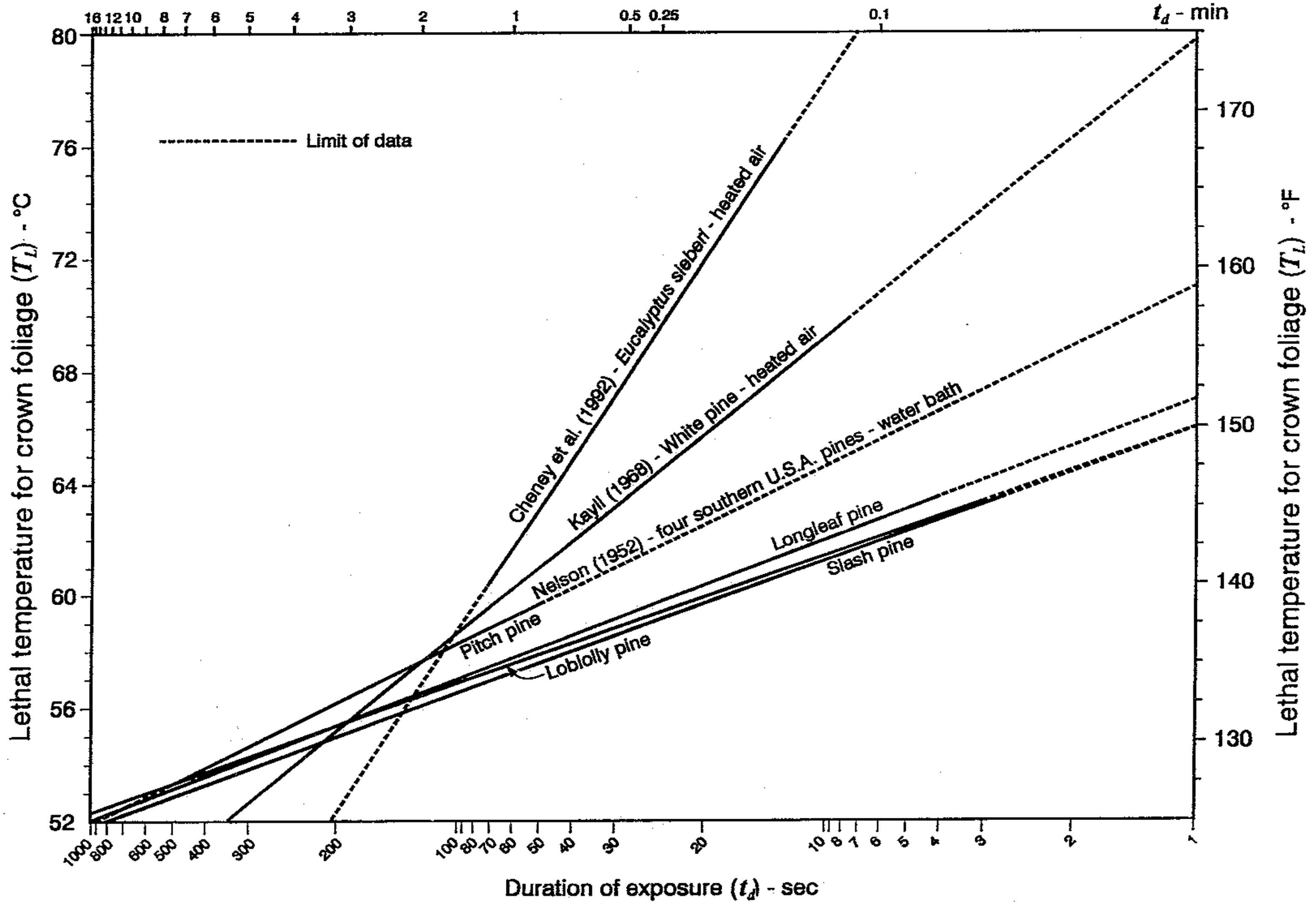


Figure 3.16a: Lethal time-temperature relationships reported for various species using both the water bath technique and heated air treatments.

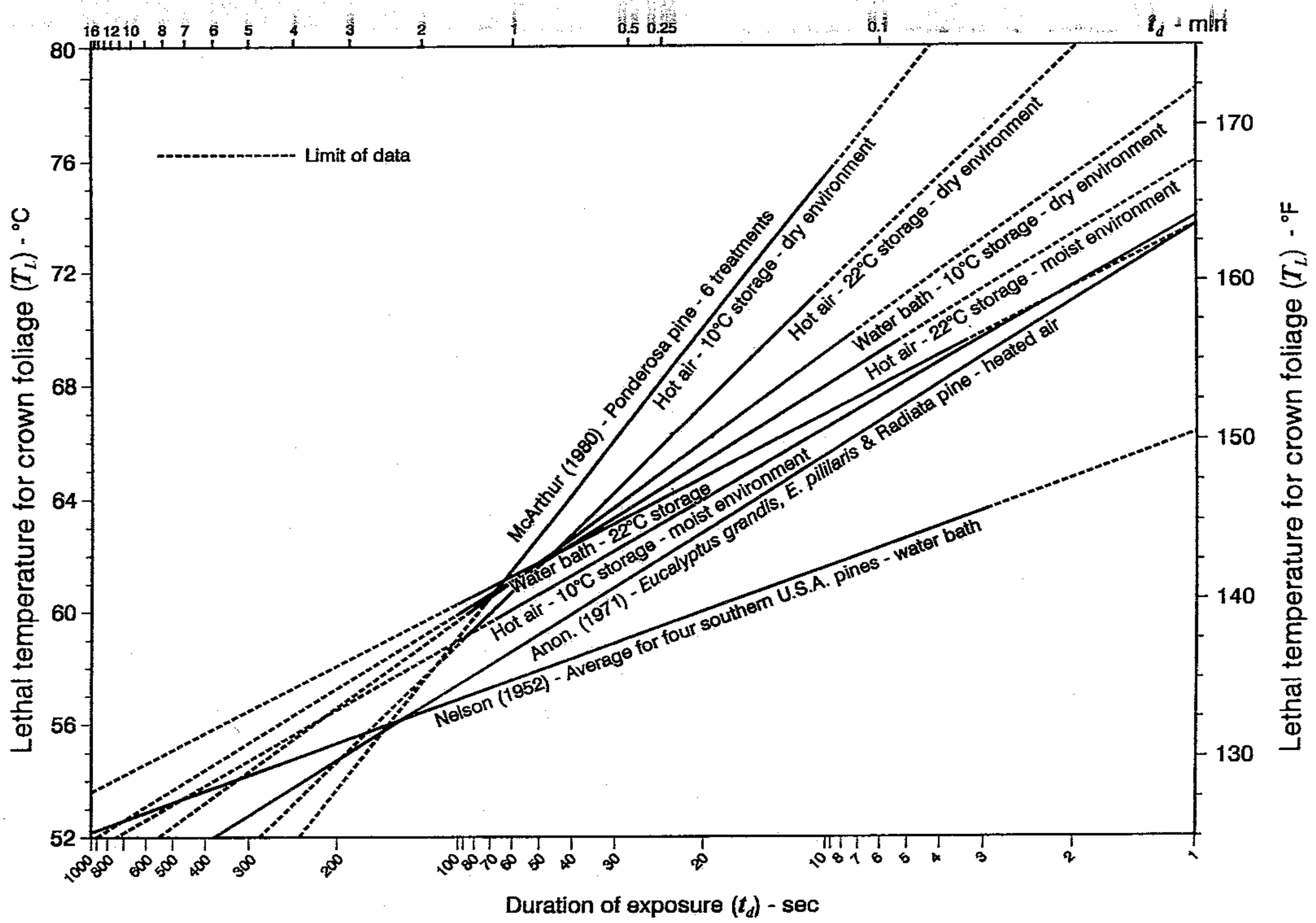


Figure 3.16b: concluded.

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

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

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

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 $T_L = 65°C$:

$$T_L = 73.65 - 3.67 \ln t_d \qquad (3.44)$$

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:

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

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_{ic} 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_{ic} 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 ($r^2 = 0.84$):

$$T_L = 96.54 - 8.34 \ln t_d \qquad (3.46)$$

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_l, 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 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/m^2)								Hw^b (kJ/m^2)
							Aerated needles		Forest floor		Roundwood[a]		Total		
				Aerated[c]	Surface	Profile	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 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., k_1, k_2 and 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) I_B - L relationship (i.e., Equation 3.24 to infer the I_B for each experimental fire (*cf.* Burrows 1984c) rather than using the observed r and measured w to calculate I_B by Equation 2.1 (Tables 3.6a and 3.6b). The h_s - 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:

$$h_s = 0.1579\, I_B^{2/3} \tag{3.47}$$

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

Unfortunately no D or t_r data is available in order to estimate 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 U_s would be substituted for u):

$$D = 0.39\, w^{0.25}\, u^{1.51} \tag{3.48}$$

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 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:

$$D = 1.5\, h_F \tag{3.49}$$

In contrast to the computations for t_r obtained usng Nelson and Adkins' (1988) model for predicting D, Leicester's (1985) simplistic relationship resulted in 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 D from the observed h_F and L and was felt to yield quite reasonable estimates of 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):

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

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.*

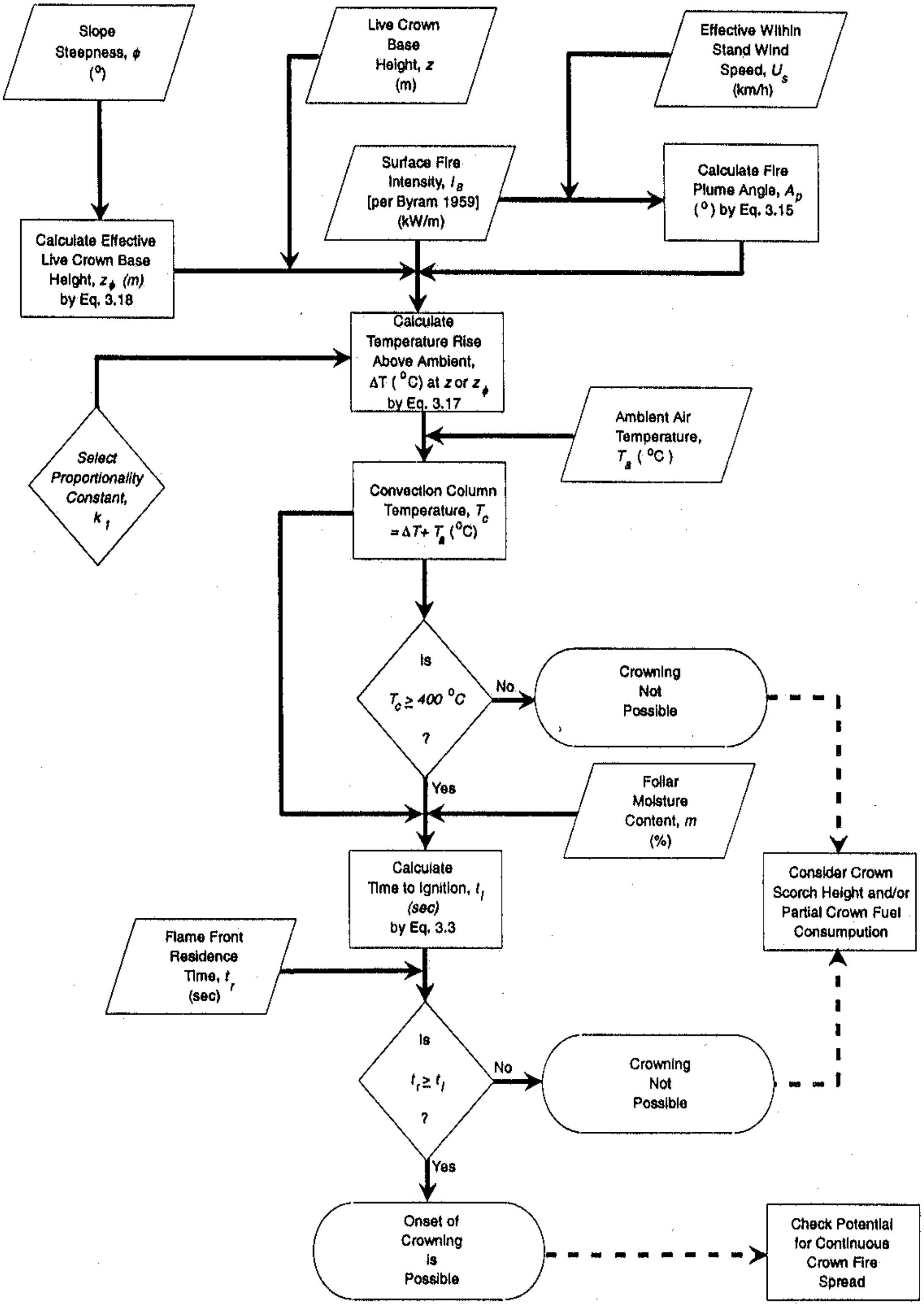


Figure 3.17: Flow diagram for the onset of crowning predictive model and related considerations.

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

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

$A_p = 47°$ 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 $\Delta T = 453°\text{C}$ according to Equation 3.17. Thus, $(\Delta T + T_a) = 473°\text{C}$ meets the minimum T_c criteria of $\geq 400°\text{C}$. It therefore follows that $t_i = 36$ sec from Equation 3.3 and because the observed t_i 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, $\Delta T = 112°\text{C}$ 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° ($T_c = 199°\text{C}$) and 192° ($T_c = 212°\text{C}$), respectively which also doesn't meet the minimum criteria of $T_c \geq 400°\text{C}$. 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_l = 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_l for m = 145% (*cf.* Gill and Pook 1991; Pook and Gill 1993) and T_c = 400 °C is 59 sec.

FSG = 10 ~
RH = 33
Ta = 21
Us = 7.9 km/h
U10 = 24.3 km/h

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/m^2)	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 $k_l = 16$. 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_1 to be used in analyzing the Plot A2 fire of Van Loon and Love (1973). However, the value (k_1 = 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

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[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, $\boldsymbol{\theta}$ 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

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[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	Forest fire danger[a]		Head fire rate of spread (m/h)[b]		Head fire flame height (m)		Maximum spotting distance (m)[c]	
(hrs)	Index value	Class level	12.5 t/ha	20.0 t/ha	12.5 t/ha	20.0 t/ha	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		Size	Planting date	Initial stem spacing	Pruning history		Thinning history[a]		Prescribed burn history
Cpt. no.	Unit no.	(ha)	(month/yr)	(m)	Height (m)	Date (month/yr)	Density (no./ha)	Date (month/yr)	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.

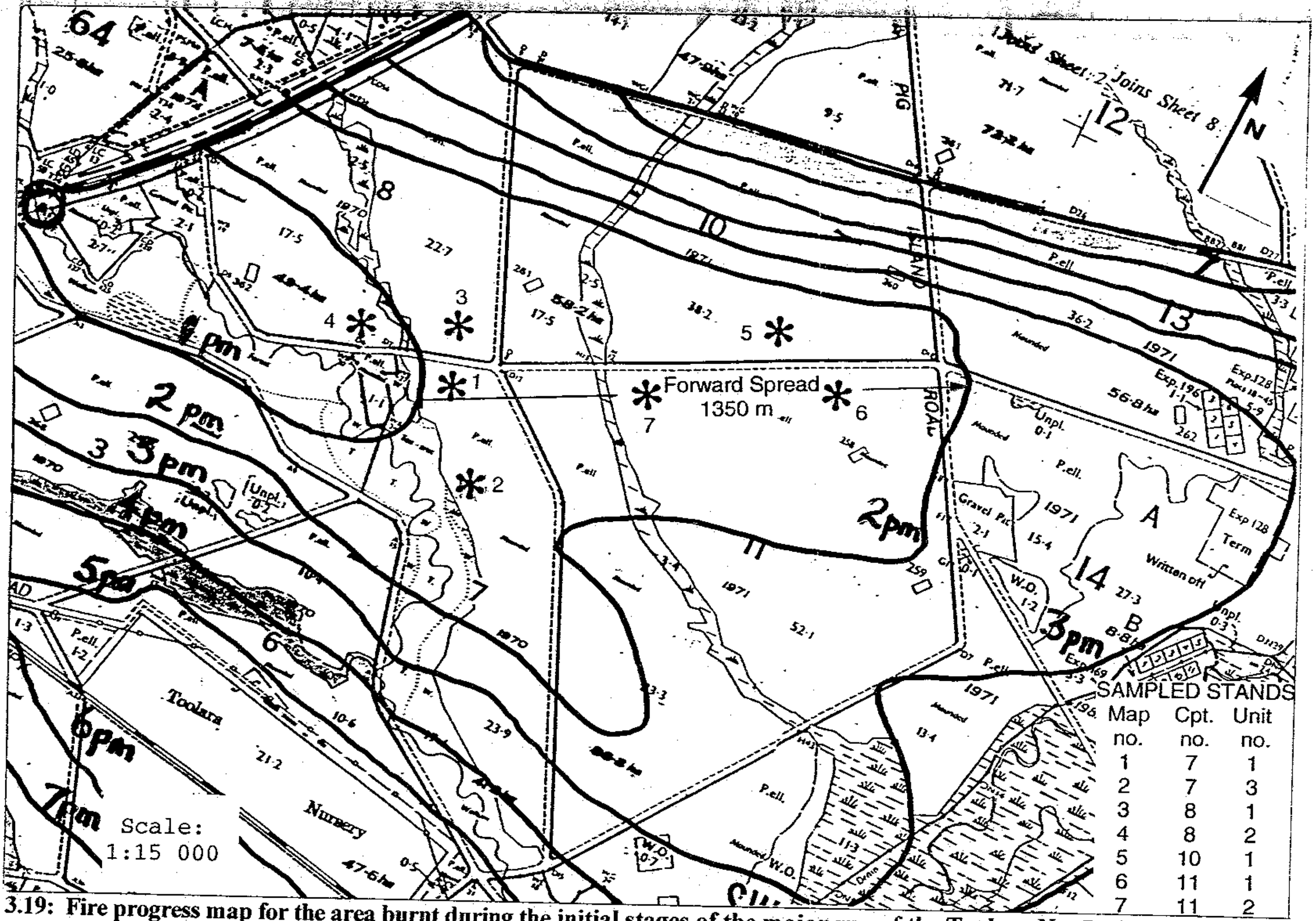
Table 3.10: Preburn stand characteristics/crown fuel properties and post-fire observations of sampled Pinus slash pine plantation stands burnt during the initial stages of the major run of the Toolara No. 7 wildfire in southeastern Queensland, Australia on 22 September 1991.

Logging Swampy Area		DBHOB[a]	SH[a]	BA	z	m_F	CD	d	HFC[a]	HSF[a, b]
Cpt. no.	Unit no.	(cm)	(m)	(m^2/ha)	(m)	(kg/m^2)	(m)	(kg/m^3)	(m)	(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.



SAMPLED STANDS

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.

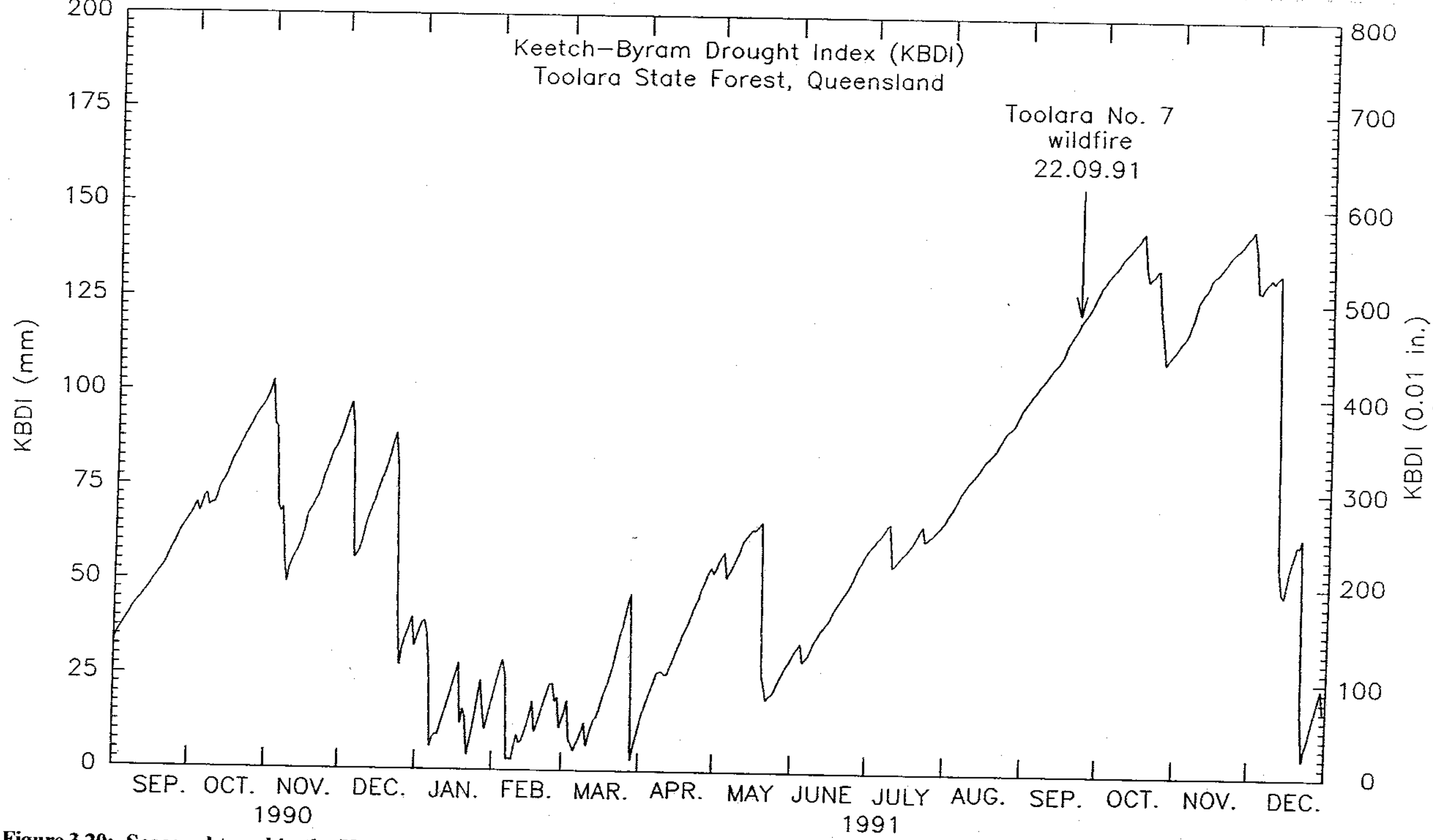


Figure 3.20: Seasonal trend in the Keetch-Byram Drought Index at the Toolara Forest Station in southeastern Queensland, Australia, during 1990-91.

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):

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

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 (%), $\boldsymbol{T_a}$ is the ambient air temperature (°C), and $\boldsymbol{U_{10}}$ 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):

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

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):

$$\boldsymbol{R_\theta} = \mathbf{FFDI}\ 1.2\ \mathbf{W}e^{0.069\boldsymbol{\theta}} \tag{3.53}$$

$$\boldsymbol{h_F} = 0.013\ \boldsymbol{R} + 0.24\ \mathbf{W} - 2.0 \tag{3.54}$$

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

where $\boldsymbol{R_\theta}$ is the head fire rate of spread on a slope (m/h), **W** is the total available fuel load (t/ha), $\boldsymbol{\theta}$ is the slope steepness (°), $\boldsymbol{h_F}$ is the head fire flame height (m), $\boldsymbol{R}$ 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 $\boldsymbol{I_B}$ 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):

$$\boldsymbol{I_B} = \mathbf{FFDI}\ 0.6\ \mathbf{W}^2 e^{0.069\boldsymbol{\theta}} \tag{3.56}$$

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:

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

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):

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

where **BA** is the stand basal area (m^2/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 m^2/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:

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

For U_{10} = 28 km/h, U_s = 12 km/h based on **BA** = 27 m^2/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 $U_s \simeq 10$ 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

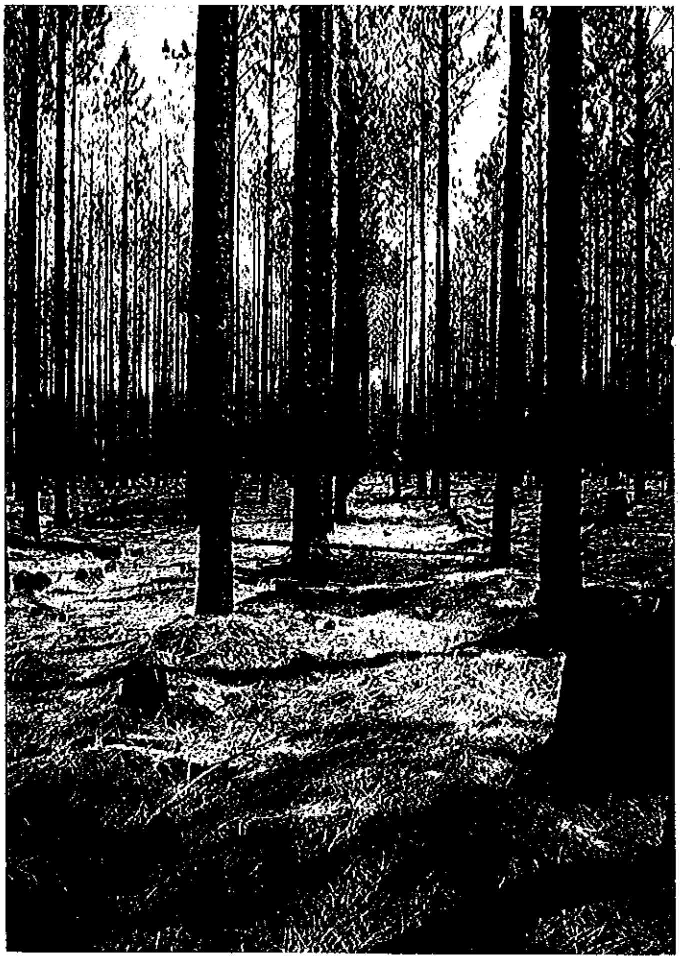


Figure 3.21: Post-burn interior ground views of sampled stands burnt during the initial stages of the major run of the Toolara No. 7 wildfire in southeastern Queensland, Australia, on 22 September 1991. Photo dates: 9 October 1991. In Cpt. 7, Unit 3 and Cpt. 8, Unit 2 note the lack of scorched needles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

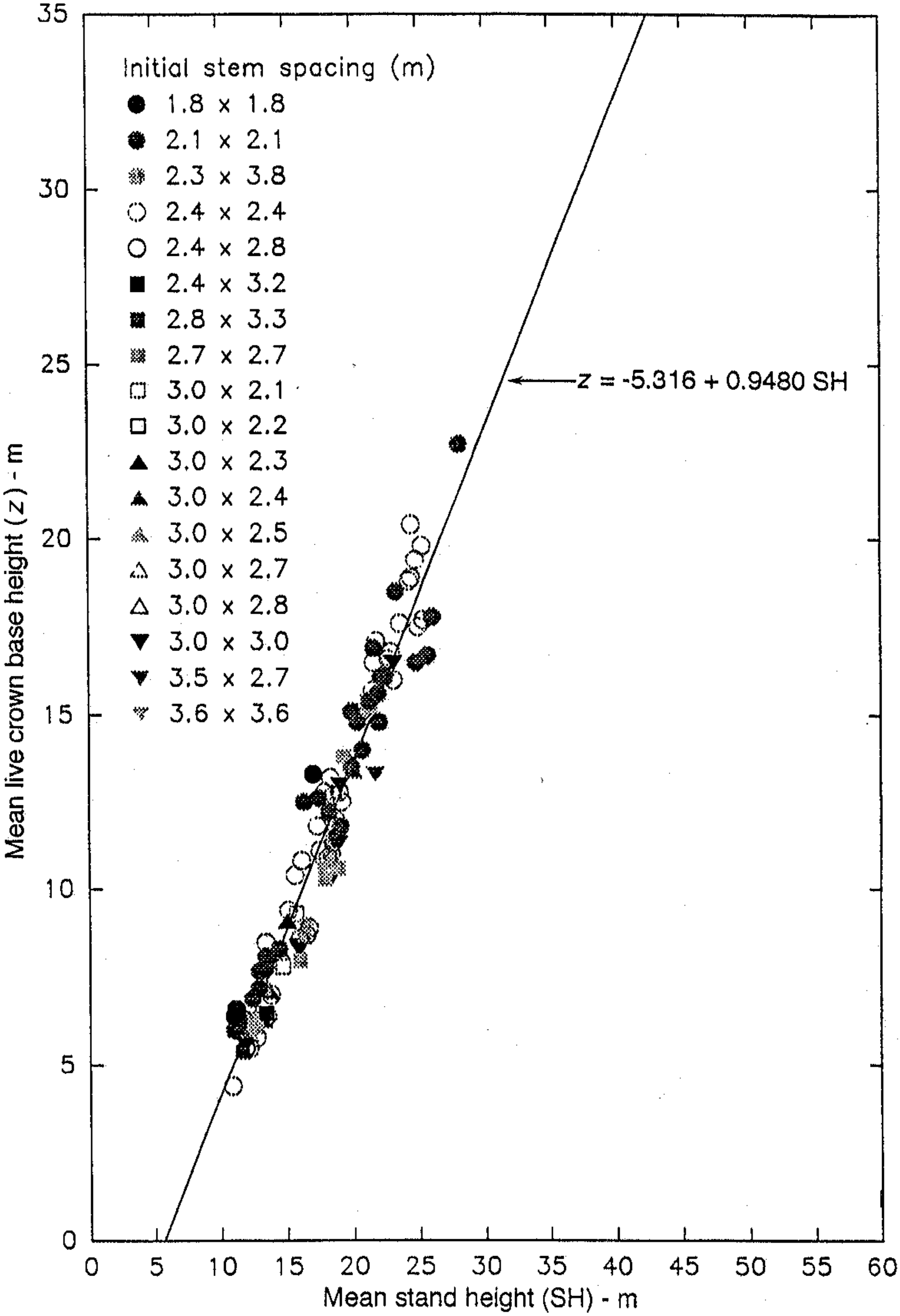


Figure 3.22: Relationship between mean stand height and live crown base height in slash pine plantations of southeastern Queensland, Australia.

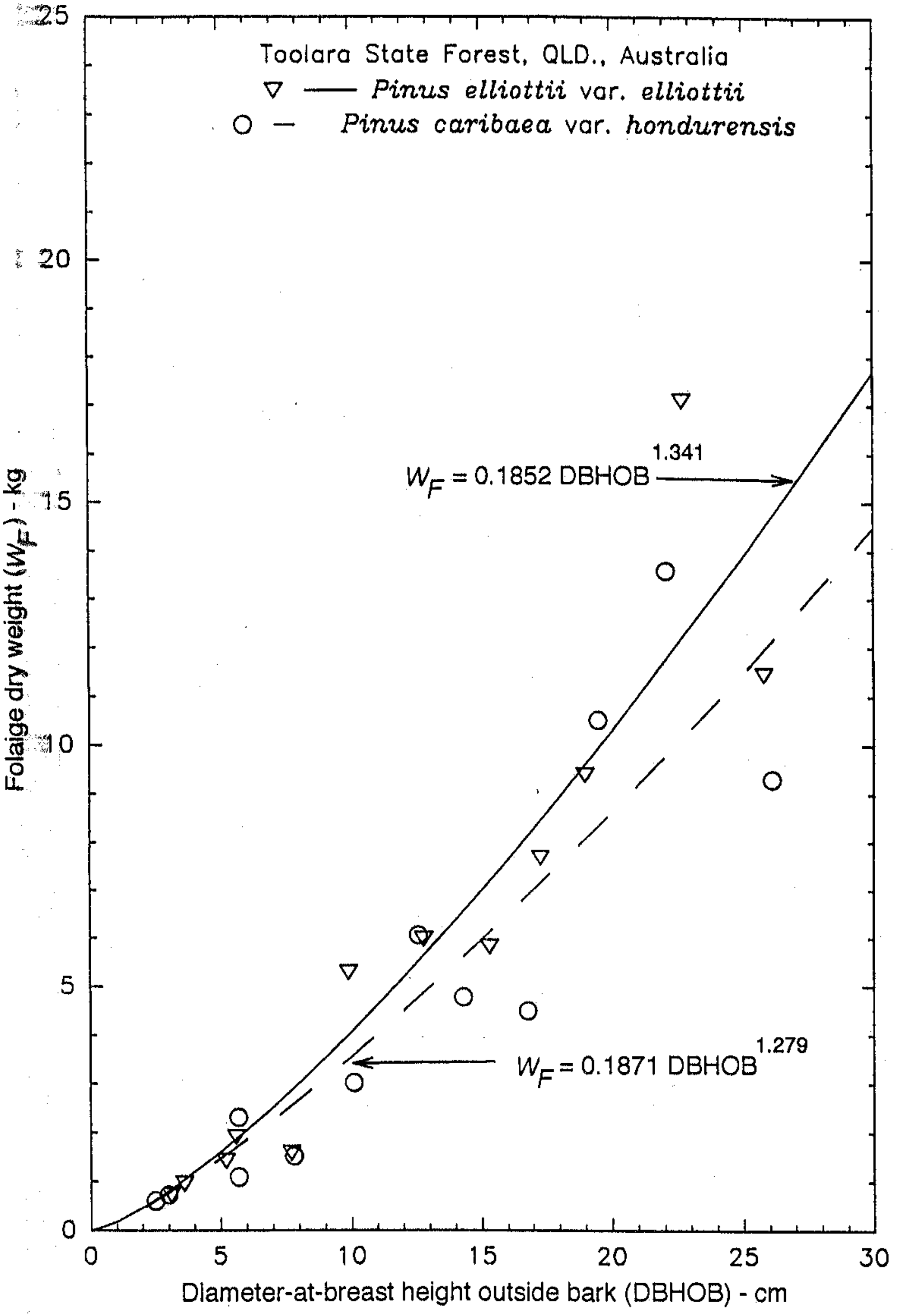


Figure 3.23: Relationships between diameter at breast height outside bark and the dry weight of needle foliage for slash pine and Honduras Caribbean pine in the Toolara State Forest of southeastern Queensland, Australia.

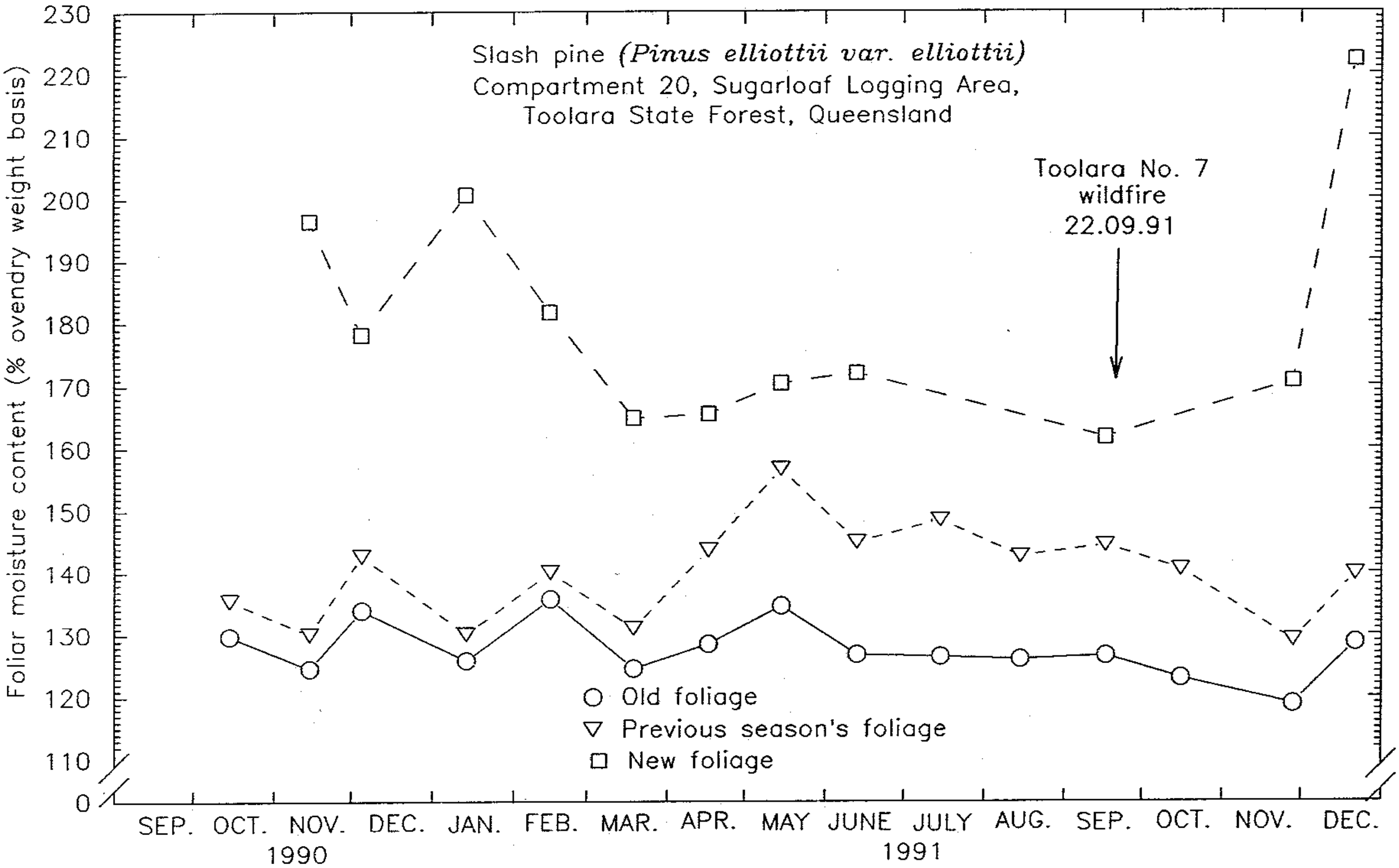


Figure 3.24: Seasonal trends in the moisture content of slash pine foliage in the Toolara State Forest of southeastern Queensland, Australia, during 1990-91.

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	 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 $\geq t_l$, 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_l 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., $\boldsymbol{I_B}$, $\boldsymbol{T_a}$, and $\boldsymbol{U_s}$ 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 $\boldsymbol{I_B}$ and equivalent $\boldsymbol{U_s}$ 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 $\boldsymbol{t_i}$ is based on simulated $\boldsymbol{T_c}$ conditions spanning a range in $\boldsymbol{m}$ (≈ 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 ø, 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

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[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 coefficents 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)			Fuelbed bulk density (kg/m^3)		
			mean	SD	range	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/m^2)	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)	$\mathbf{m}$ (kg/m^2)	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 $\mathbf{m}$ 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

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[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

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[a] Implies complete flame defoliation of all foliage.

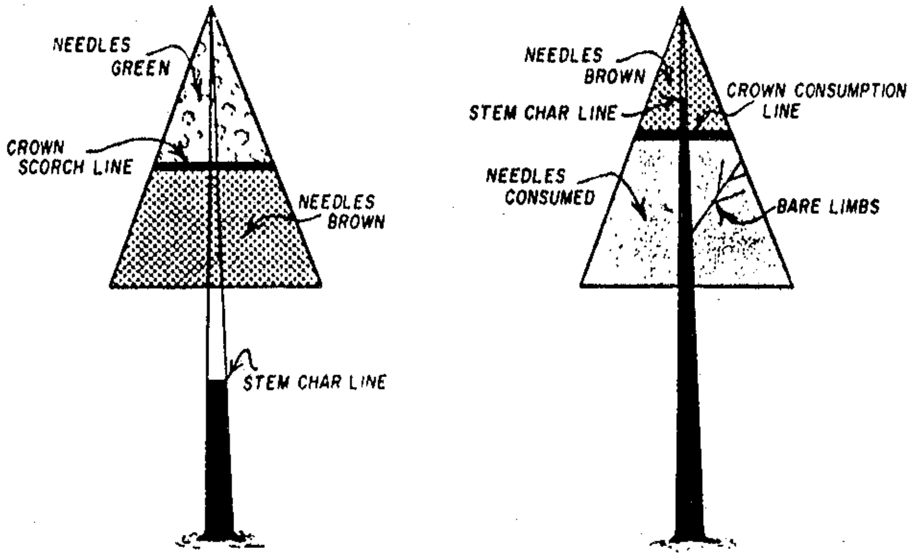

Figure B-1: Variation in readily evident impacts of fire on coniferous tree crowns and stems (from Storey and Merkel 1960).

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		Oven-dry weights (kg)					
				Needle foliage	Twigs and branches by condition/roundwood diameter				Female cones
		Cpt.	Logging area		Live <6 mm	Live >6 mm	Dead <6 mm	Dead >6 mm	
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		**DGLOB** (cm)	**DCBOB** (cm)	Silvicultural history			
									Pruning		Thinning	
					Length (m)	Width (m)			Ht. (m)	Year	Sph	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.