Fire behaviour as a factor in forest and rural fire suppression

Martin E. Alexander

Forest Research Bulletin No. 197
Forest and Rural Fire Scientific and Technical Series
Report No. 5

Other reports printed in the *Forest and Rural Fire Scientific and Technical Series* (Forest Research Bulletin No. 197) include:

1. Fogarty, L.G. 1996. Two rural/urban interface fires in the Wellington suburb of Karori: assessment of associated burning conditions and fire control strategies.
2. Rasmussen, J.H.; Fogarty, L.G. 1997. A case study of grassland fire behaviour and suppression: the Tikokino Fire of 31 January 1991.
3. Fogarty, L.G.; Jackson, A.F.; Lindsay, W.T. 1997. Fire behaviour, suppression and lessons from the Berwick Forest Fire of 26 February 1995.
4. Pearce, H.G.; Hamilton, R.W.; Millman, R.I. 2000. Fire behaviour and firefighter safety implications associated with the Bucklands Crossing Fire burnover of 24 March 1998.

Cover Photographs:
Upper left – Fire behaviour during the 1995 Berwick Forest Fire, Otago.
Upper right – Whakamaru lookout in Kinleith Forest, Central North Island.
Lower left – Aerial suppression during the 1994 Montgomery Crescent Fire, in the suburb of Karori, Wellington.
Lower right – Fire suppression during a simulated fire exercise in Kinleith Forest, March 1993.

Paper Reprint

Fire behaviour as a factor in forest and rural fire suppression[*]

Martin E. Alexander
(Senior Fire Research Officer, Canadian Forest Service, Northern Forestry Centre, Edmonton, Alberta, Canada)

This paper was originally presented at the Forest and Rural Fire Association of New Zealand (FRFANZ) 2nd Annual Conference, 5-7 August 1992, Christchurch, when the author was a Visiting Fire Research Scientist on a 12 month secondment to the New Zealand Forest Research Institute, Rotorua, New Zealand.

This research report is a product of the *Forest Research* (formerly NZ FRI) forest and rural fire research programme. Funding and "in kind" support for this project is jointly provided by the following organisations:

- **Foundation for Research, Science and Technology**
- **New Zealand Fire Service Commission**
- **National Rural Fire Authority**
- **New Zealand Forest Owners Association**
- **Department of Conservation**
- **New Zealand Defence Force**
- **members of Local Government New Zealand**

[*] Correct citation: Alexander, M.E. 2000. Fire behaviour as a factor in forest and rural fire suppression. Forest Research, Rotorua, in association with the National Rural Fire Authority, Wellington. Forest Research Bulletin No. 197, Forest and Rural Fire Scientific and Technical Series, Report No. 5. 30 p.

Published with the assistance of:

Forest and Rural Fire Association of New Zealand

New Zealand Fire Service Commission
Contestable Research Fund

National Rural Fire Authority

Disclaimer:

The contents of this publication are not intended to be a substitute for specific specialist advice on any matter and should not be relied on for that purpose. The New Zealand Forest Research Institute Ltd. and the authors of this publication shall not be liable for any loss, damage or liability incurred as a direct or indirect result of reliance by any person upon information contained, or opinions expressed in this work.

Additional copies of this publication are available from:

Publications Officer
Forest Research
Private Bag 3020
Rotorua
New Zealand

National Rural Fire Authority
PO Box 2133
Wellington
New Zealand

ISSN: 1174-5096

Contents

Tables

Abstract

This paper provides an overview on the fundamental characteristics associated with the behaviour of free-burning fires as it influences fire control operations, based primarily on a review of the overseas literature and current developments in the field of wildland fire management. Particular emphasis is placed on the critical importance of fast, aggressive initial attack in relation to elapsed time since ignition as the severity of burning conditions increases in order to avert the potential for large, costly fires in forest and rural areas. The threat of wildfires can probably never be entirely eliminated, but hopefully a larger percentage of future occurrences can be suppressed at much smaller sizes than at present by more fully incorporating considerations of fire behaviour into training, planning and operations than is currently the case in New Zealand fire protection.

Introduction

All forest and rural fire management organizations, regardless of the land-use objectives, have as their basic tenet to keep the area burned by unwanted fires to a minimum in order to eliminate the threat to life and property, reduce the potential damages to renewable resources and to prevent fire fighting expenditures from escalating unduly, commensurate with sociopolitical, economic and ecological realities (Wilson 1975; Burrows *et al*. 1989; Anon 1991). The best prospect for alleviating major wildfire problems, taking into account an area's fire climatology (e.g., the frequency of critical fire weather conditions), is to create fuel situations that will reduce the energy output rate of such fires to a point where conventional fire fighting methods will be effective (Wilson and Dell 1971; Countryman 1974; Cheney 1985b, 1989; Wilson 1992). This approach to mitigating the likelihood of conflagrations through the application of prescribed fire at regular intervals in a mosaic pattern is epitomized by the broad-scale programmes of fuel reduction burning which have been developed for the eucalypt forests in southeastern Western Australia (Underwood and Peet 1981) and pine forests of the southeastern U.S.A. (Wade and Lundsford 1989). Certain forest and vegetation types don't necessarily lend themselves to using fire as a means of hazard reduction, for example, thin barked species which succumb even to very mild fires (Johnson 1992). However, other forms of managing fuels which don't involve burning are potentially available, for example, fuelbreaks comprised of relatively non-flammable vegetation (Johnson 1975; Green 1977), although they haven't achieved the same degree of implementation as prescribed underburning. Losses due to wildfire occurrences in commercial forests can be minimised to a certain extent by harvest scheduling (Dempster and Stevens 1987), plantation design (Cheney and Richmond 1980), and by other forms of fuel and/or vegetation management (Burrows 1981; Cheney 1985a).

Regardless of how intensive and effective fuel/vegetation management practices become, any fire management organisation must still maintain its initial attack fire supression capability. In his book on *An Introduction to Fire Dynamics*, Drysdale (1985) made the following statement:

> *... further major advances in combating wildfire are unlikely to be achieved simply by continued application of the traditional methods. What is required is a more fundamental approach which can be applied at the design stage ... Such an approach requires a detailed understanding of fire behaviour ...*

It's on the basis of this premise that the present paper has been prepared with respect to the forest and rural fire scene in New Zealand, utilising the literature primarily from Canada, Australia and the U.S.A. The economics of fire protection in relation to the values-at-risk from wildfire (Cooper and Ashley-Jones 1987; Robertson 1989) will not be dealt with here. Terminology follows Merrill and Alexander (1987). The "anatomy" of a forest or rural fire is depicted in Figure 1.

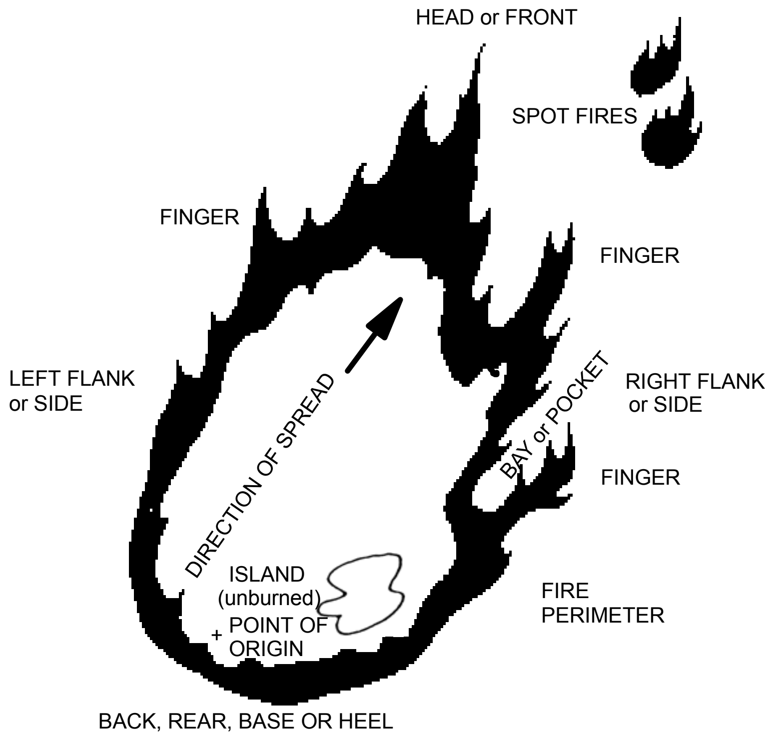

Figure 1. The anatomical parts of a wildland fire (after Moberly *et al*. 1979).

Fire Behaviour Characteristics

Fire behaviour is generally defined as the manner in which fuel ignites, flame develops, fire spreads and exhibits other related phenomena such as firewhirls (Countryman 1971) as determined by the interaction of fuels, weather and topography (Countryman 1972). In certain instances, the fire suppression operations can in fact adversely affect wildfire behaviour (Shields 1969; Haines 1989).

The probability that an ignition will occur is dependent primarily on the firebrand size and type (i.e., glowing or flaming) and whether the fuels are receptive or not based on their moisture content, temperature, bulk density, etc. at the point of origin (Parrott and Donald 1970; Blackmarr 1972; Stockstad 1979; Countryman 1983). Assuming a firebrand lands on fuels favourable for ignition the possibility of whether a fire start will sustain itself and spread outwards from the immediate vicinity of the initial point source will depend on the continuity, quantity and moisture content of the fine fuels, and the wind speed at the ground surface (Wilson 1985, 1987).

The more important fire behaviour characteristics from the practical standpoint of fire suppression are:

- forward rate of spread
- fire intensity
- flame front dimensions
- spotting pattern (density and distances)
- fire size and shape
- rate of perimeter increase
- burn-out time

Head fire spread rates can range from about 1.5 m/hour (lower limit of fire spread in surface fuels) up to 14 km/h for forest fires and greater than 20 km/h for grass fires. The intensity of a free-burning fire, as determined by Byram's (1959a) formula, is probably the most commonly accepted measure of rating fire severity. For practical purposes, Byram's (1959a) fire intensity (kW/m) = [available fuel load (t/ha) × rate of spread (m/hour)] ÷ 2 (Burrows 1984)[1]. Fire intensity can vary over four orders of magnitude from about 10 kW/m (threshold for fire spread by flaming combustion) to in excess of 100 000 kW/m (major conflagrations).

Fire intensity is directly related to flame size (Fig. 2). Flame heights associated with high-intensity fires generally average about 15-45 m with occasional flashes up to 185 m or more (Byram 1959b). Although many fuel type-specific empirical fire intensity/flame length relationships exist, a simple approximation is $I = 300 \times L^2$ (after Newman 1974), where I = fire intensity (kW/m) and L = flame length (m). Note that flame length should not be confused with flame height which is the maximum vertical extension of the flame front (Fig. 2); they are equal only in still air conditions (i.e., no wind) on level ground. For example, an average flame front one metre in height and oriented at a 45° angle would by simple geometry have a flame length of about 1.4 m. A firefighter standing 2 metres away from a 1 m high flame front would find the

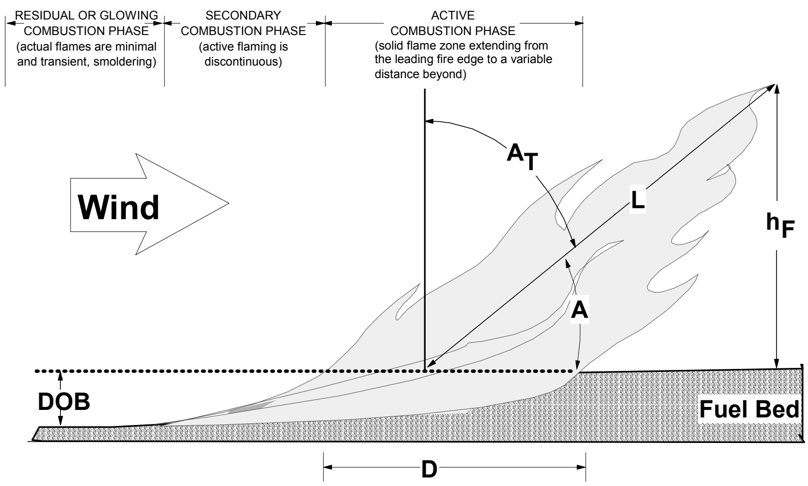

Figure 2. Cross-sectional view of a stylized head fire on level terrain illustrating the energy or heat-release stages during and following passage of the flame front, flame length (L), flame height (h_F), flame angle (A), flame tilt angle (A_T), horizontal flame depth (D), and the resulting depth of burn (DOB) (from Alexander 1982).

[1] This formulation is based on the assumption that the net low heat of combustion = 18 000 kJ/kg (*cf.* Forestry Canada Fire Danger Group 1992).

pain on exposed skin (e.g., bare hands) unbearable after 30 seconds; this would be reduced to less than 10 seconds if the person was within a metre of the flames (Vines 1981). If the flames were greater than 15 m in height firefighters would have to be more than 35 m away to avoid disabling burns from the radiant heat (Green and Schinke 1971).

Fire intensity or flame length is a major determinant of the difficulty of containing a wildfire (Fig. 3). A rough rule of thumb is that the minimum width of a fireguard should be, in the absence of spotting, at least one to one-and-a-half times the flame length (Byram 1959a; Albini 1976).

Spot fires occur when burning embers or sparks are lofted above the flame zone as a result of thermal updrafts created by the fire's convective activity, that are then deposited some distance ahead of the advancing fire front (Clements 1977; Albini 1979, 1983). A single spot fire may occur tens of kilometers downwind or alternatively many firebrands may literally "shower" unburned fuels just a few meters away from the fire edge. Assuming a firebrand(s) is capable of igniting the fuel it has landed upon (as determined by moisture content and structural properties), spot fire distance is related primarily to fire intensity and wind speed (Anon. 1960; Morris 1987), whereas spot fire density is largely a function of the characteristics of the potential firebrands for a given fuel type (quantity, particle density, shape, size, etc.). In the case of surface fires, the onset of significant spotting activity from the standpoint of control problems in terms of an upper limit of intensity is generally acknowledged to be around 1500-2000 kW/m (Taylor and Wendel 1964; Hough and Albini 1978; Hirsch *et al.* 1979). Crown fires inevitably spawn spot fires (Hesterberg 1959). A fire intensity of about 4000 kW/m is commonly recognised as a threshold for active crowning although this certainly depends on the stand and crown structure (Alexander 1988).

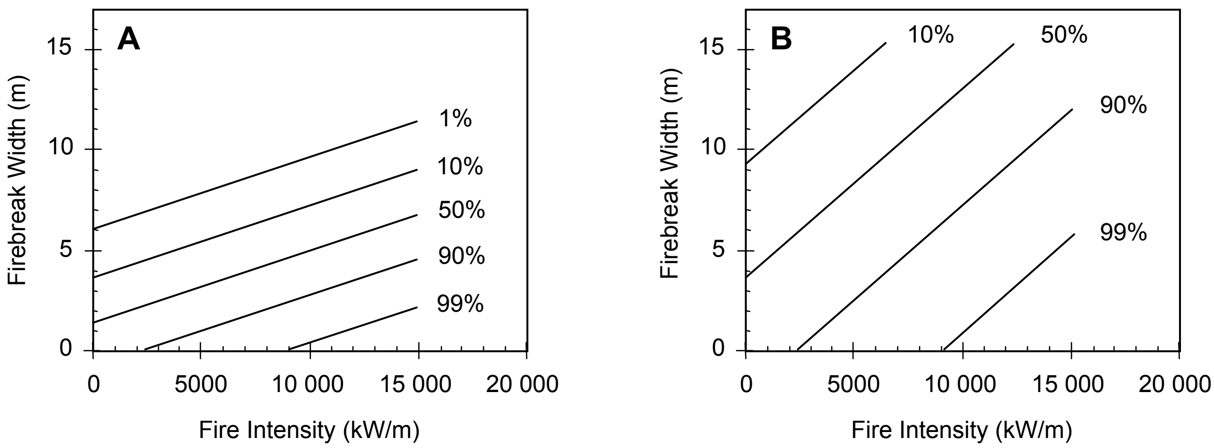

Figure 3. Probability of a grass fire breaching a mineralized firebreak as a function of fire intensity, firebreak width and the absence (**A**) or presence (**B**) of trees within 20 m of the upwind side of the firebreak (e.g., in the former case, there's a 90% probability of a grassland fire with an intensity of 5000 kW/m will be stopped by a 1.0 m wide firebreak). These nomograms are based on research carried out in the Northern Territory of Australia involving eucalypt trees (after Wilson 1988).

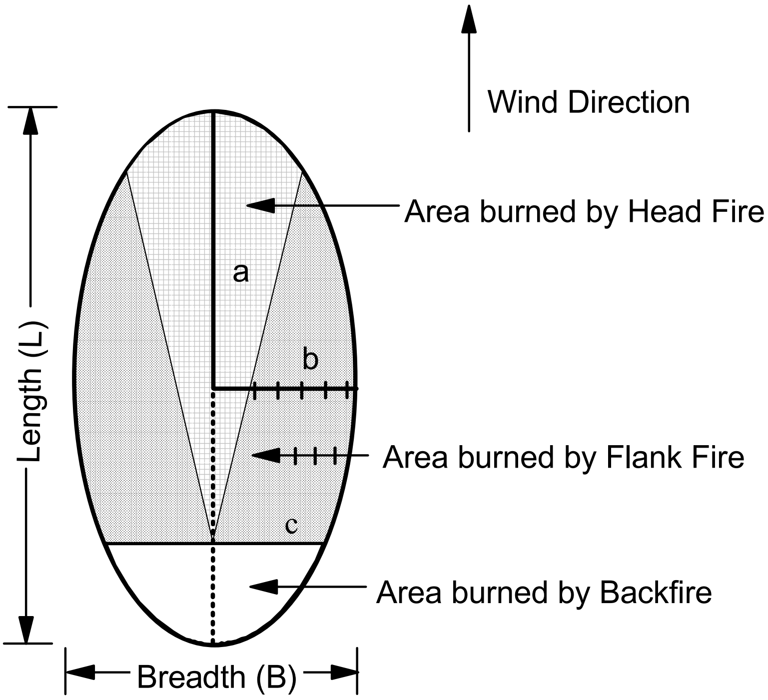

Figure 4. Simple elliptical fire growth model (from Alexander 1985).

The general shape of wind-driven fires originating from a point ignition tend to resemble an ellipse provided the wind direction remains relatively constant (Fig. 4). Assuming this elliptical fire shape, the rate of spread and intensity are the greatest at the head and gradually diminish from the flanks to the back of the fire (Catchpole *et al*. 1992). Elliptical fire area and length of the perimeter can be calculated on the basis of the head and back fire spread rates, wind speed and elapsed time since ignition (e.g., Forestry Canada Fire Danger Group 1992). The simple elliptical fire growth model employed to predict area burned and perimeter length can also be used to calculate a fire's rate of perimeter growth or increase. Alternatively, the rate of perimeter increase (m/hour) is approximately = head fire rate of spread × 2.5 (e.g., 150 m/h × 2.5 = 375 m/h). The total length of the fire perimeter could also be quickly estimated by multiplying the forward spread distance (i.e., head fire rate of spread × elapsed time since ignition) using this simple rule of thumb (*cf.* Sneeuwjagt and Peet 1985).

Burn-out time represents the duration of active flaming and smouldering combustion. Ground or subsurface fires will remain burning provided there is sufficient fuel of appropriate dryness left after passage of the main fire front (Henderson and Muraro 1968), in which cases mop-up may be exceedingly time consuming and in turn costly (González-Cabán 1984). Thus, fuel complexes exhibiting heavy fuel loads, especially deep organic layers, such as found in peat bogs and old growth forests, and large decaying logs are especially prone to such fire persistence following major dry spells or droughts (Kiil 1971; Brady 1988).

Fire Suppression Effectiveness and Resource Productivity

Fire suppression involves all the activities concerned with controlling and finally extinguishing a wildfire following its ignition. The fire triangle is commonly used to illustrate the basic principles of fire suppression (Fig. 5). To stop a free-burning fire you must either: (1) remove the fuels ahead of the spreading combustion zone, (2) reduce the temperature of the burning fuels, or (3) exclude oxygen from reaching the combustion zone by smothering. In practical terms this generally means creating a physical barrier in front of the fire by removing the fuels or cooling/smothering the flames with water, covering them with mineral soil, suppressants (e.g., foam) or chemical fire retardants by various means from either the ground or the air (Mactavish 1960; Welsh 1965; Hardy 1977; Lieskovsky and Newstead 1980; Ingoldby and Smith 1982; Ogilvie *et al*. 1989; French 1990). In almost every fuel type it is necessary to physically separate the burnt from the unburnt fuels along the fire perimeter in order to prevent re-kindling and "breakaways" from occurring even after the fire has been initially extinguished with water or stopped by the application of chemical fire retardants (Cheney 1986).

The various kinds of resources commonly employed in forest and rural fire fighting each have an upper limit to their effectiveness. These limits, taking into account radiation levels and the "breaching" potential by spotting and direct flame contact or radiation, can be related to fire intensity (Table 1). Direct attack on fire perimeters with intensities in excess of 4000 kW/m is generally not possible. Backfiring is sometimes possible but not necessarily always successful up to intensities of around 10 000 kW/m, although this depends to a large extent on the prevailing wind velocity, the fire's spotting potential and forward rate of spread as well as other considerations such as the availability of anchor points (DeCoste *et al*. 1968; Cooper 1969; Hodgson and Cheney 1969; Deeming and Wade 1974; Moore *et al*. 1976; Burrows 1986). Aerial devices such as the helitorch or flying drip torch (Muraro 1976) have certainly enabled backfiring to be undertaken more effectively and safely than by ground ignition (Quintilio *et al*. 1985).

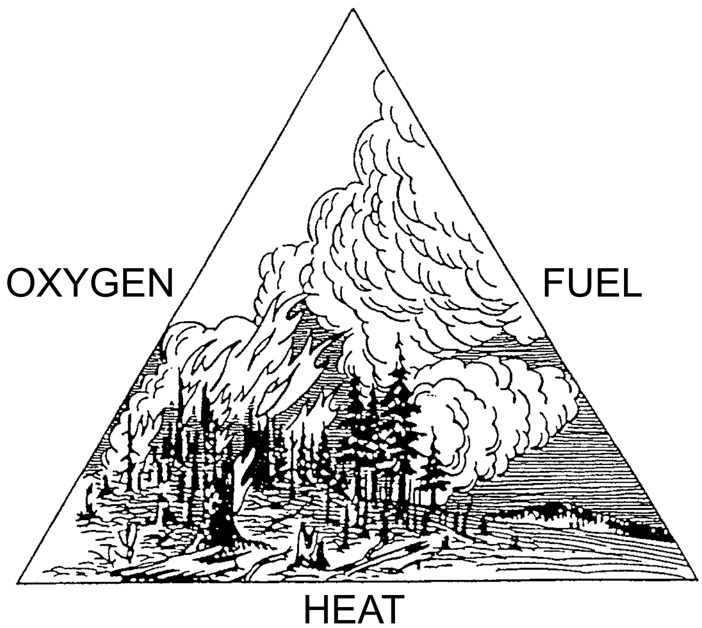

Figure 5. The wildland fire triangle (after Barrows 1951).

Table 1. Generalised limits of fire suppression effectiveness in relation to fire intensity (after Alexander and De Groot 1988; Alexander and Lanoville 1989).

Fire Intensity (kW/m)	Control Requirements
< 500	Ground crews with hand tools
500-2000	Water under pressure and/or heavy machinery
2000-4000	Helitanks and airtankers using chemical fire retardants
> 4000	Very difficult if not impossible to control

Resource production rates or the productivity of fire suppression forces are commonly compared against the fire size (i.e., perimeter length) at the time of initial attack and the rate of perimeter increase to determine the time until containment is achieved (Riebold 1959; Pirsko 1961; Douglas 1973; Cheney 1975; Barney 1983). Production rates are most often given in terms of m/person-hours for individual crew members using hand tools, power equipment or other devices (Ovchinnikov and Grumans 1988; Murphy *et al*. 1989, 1991) or in m/hour for various sized ground crews, ground tankers, bulldozers (Table 2), ploughs and other heavy machinery (Crosby *et al*. 1963; Moore *et al*. 1976; Barney and Peters 1983; Sneeuwjagt and Peet 1985; Anon. 1988; Phillips *et al*. 1988; Ponto 1989). Unless otherwise stated, production rates imply a certain minimum width. For example, the blade width of medium and large bulldozers is generally about 3-4.5 metres whereas ground crews using hand tools commonly construct fireguard around one metre wide.

Table 2. An example of fireguard production rates by fuel type for three commonly used fire suppression resources (adapted from Schmidt and Reinhart 1982).

Generalised Fuel Type	Crew with Hand Tools (m/person-hour)	5-person Pumper Crew* (m/hour)	Medium-sized Bulldozer (m/hour)
Short Grass	80	805	1509
Tall Brush	13	402	734
Conifer Stand	40	463	694
Logging Slash	20	402	785

* 946-litre (250 U.S. gallons) tank capacity (R.G. Schmidt, personal communication).

Commonly, a mixture of resources are engaged in a wildfire suppression operation. For example, in South Australian exotic pine plantations, a 5-person Woods and Forests Department crew can "knock down" the fire edge by direct attack using water (see Table 3) from canvas hose lays (run off pumper trucks and/or supply tankers located on roads or firebreaks). This is immediately followed up with the construction of a fireguard to mineral soil by a ground crew using McLeod tools or a John Deere 350 bulldozer fitted with a V-blade plough. The overall production rate is about 500-700 m/hour (Geddes and Pfeiffer 1981).

Table 3. Variation of nozzle size and pressure for performing common forest and rural fire suppression tasks (after Luke and McArthur 1978).

Type of Fire or Fire Situation	Nozzle Working Arrangements		Performance			
	Size (mm)	Pressure (kPa)	Velocity at nozzle (km/h)	Vertical jet throw (m)	Horizontal jet throw (m)	Discharge rate (ℓ/min)
Mop up; attacking low intensity fires	3.2	200	75	9	10	10
	3.2	350	100	11	13	13
Attacking moderate intensity fires; reaching into crowns of low trees	3.2	500	115	12	13	15
	6.3	200	75	12	13	40
	6.3	350	100	14	17	50
Standing off from high intensity fires	6.3	500	115	15	20	60
	6.3	700	135	15	22	70
Reaching into crowns of moderately tall trees	9.5	700	135	22	29	160
Standing off from very high intensity fires	12.7	350	100	24	25	200
Reaching into the crowns of high trees	12.7	500	115	27	29	240
	12.7	700	135	30	33	290
	12.7	1000	145	32	35	340

When it comes to the delivery of water, it is instructive to examine a pumper truck's tank capacity with respect to its capability in terms of available operational time before it has to be refilled. The time taken to empty a 450-litre tanker has been worked out for various nozzle pressures and sizes (Anon. 1987b) but what is really needed is an assessment in relation to the fire fighting task (Table 3). For example, Forestry Corporation of New Zealand Limited has a fleet of seven 4WD appliances available for call out in the Kaingaroa Forest. Each unit is capable of holding 3600 litres of water and carrying 860 metres of hose. Thus, an individual unit could sustain an initial attack for about one hour on a high intensity fire before refilling would be required. However, this would be reduced to 18 minutes for a very high intensity fire.

Resource production rates will naturally vary according to the type of suppression technique employed (e.g., "hot spotting" vs. continuous fireguard construction), fuel type characteristics, slope steepness, soil conditions, fire intensity or flame length (Fig. 6) and cumulative time engaged in the fire suppression operation (e.g., breakdowns in heavy machinery). Several studies have shown that fireguard production rates are subject to considerable variation (e.g., Haven *et al*. 1982; Barney *et al*. 1992), probably because many factors are difficult to adequately quantify (e.g., an individual's motivation, training and experience). The relative efficiency of fire suppression crews gradually decreases with time owing to the fatigue factor (Budd *et al*. 1991). For example, crews after the first five hours of work may only be 60% as effective as during the first few hours (Anon. 1988).

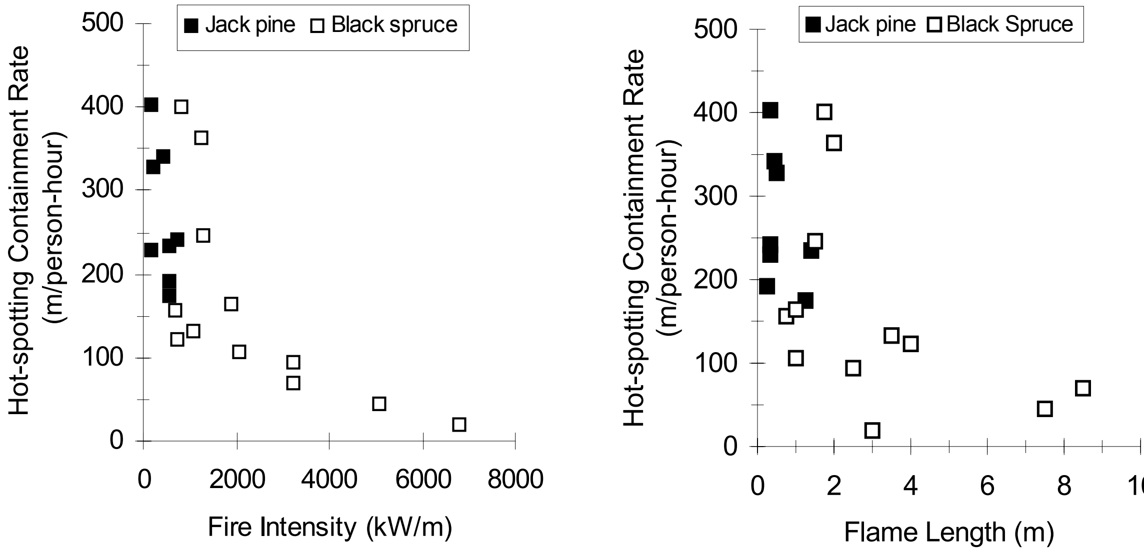

Figure 6. Hot-spotting production rate for initial attack crews using hand and power tools as a function of head fire intensity and flame length in two broad fuel types commonly found in the boreal forest of central Alberta, Canada (adapted from Quintilio *et al.* 1990 and Murphy *et al.* 1991).

The productivity of airtankers and helitankers is generally thought of in terms of simply the linear length (m) per drop as determined from an analysis of drop pattern characteristics (e.g., Storey *et al.* 1959; Grigel *et al.* 1974; Rawson 1977; Rees 1983; Stechishen and Halicki 1984; Newstead and Lieskovsky 1985) such as presented in Figure 7. Of course not all of the gross drop pattern is equally effective (Storey *et al.* 1959). Thus, partial penetration of the drop zone is to be expected (Stechishen 1976; Newstead and Alexander 1983). In certain fuel types, particularly dense forests, a considerable amount of liquid can be intercepted by the tree canopy (Anderson 1974). The net effective length and width is determined by the "coverage level" (George 1981) or depth of the liquid that actually reaches the critical fuels to be treated at the ground surface. This is a function of a host of factors, including fuel type and topographic characteristics, drop height and

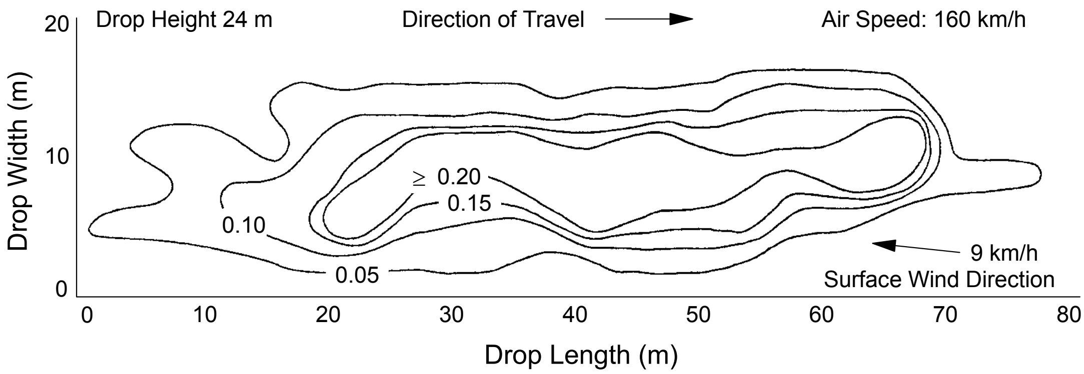

Figure 7. An example of a drop pattern or "footprint" for a Dromader M-18 airtanker delivering water in an open field (after Stechishen and Halicki 1984). Contour lines indicate the depth or thickness of the water concentration.

speed, tank size/configuration or bucket capacity/design, and the atmospheric conditions (especially wind velocity) at the time of the drop (Hardy 1977; Howard 1980; George and Johnson 1990). The amount required to impede a fire's progress varies according to intended use (i.e., direct or indirect application), type of substance (water, foam or chemical retardant), fire intensity and the physical properties of the surface fuel bed (Stechishen 1970; Stechishen and Little 1971; Loane and Gould 1986). For example, the depth of water required to stop a fire in cured grass or in pine needle litter with an intensity of 2000 kW/m would be 0.06 cm and 0.53 cm, respectively; the corresponding required depths using a long-term chemical fire retardant, such as FIRETROL 936, would be 0.03 cm and 0.22 cm (Loane and Gould 1986).

Fire containment with a helitanker or an airtanker depends on the ability to perform at a pace in excess of the fire's rate of perimeter increase (Fig. 8). However, at least for a single land-based airtanker, the "one strike concept" would be the more typical scenario (Hodgson and Newstead 1978). The effective drop lengths of "light" helicopters such as the Hughes 500 and Bell Jet Ranger using a monsoon bucket are considerably shorter than those of airtankers (*cf*. Quintilio and Anderson 1976) because of the limitations determined by their maximum sling load (Anon. 1987a). For this reason and because of their manoeuvrability and capacity to make multiple sorties before refuelling is required, the greatest role of helitankers is in "hot spotting" along the fire perimeter (Grigel 1974; Murray 1986; Anon. 1987a).

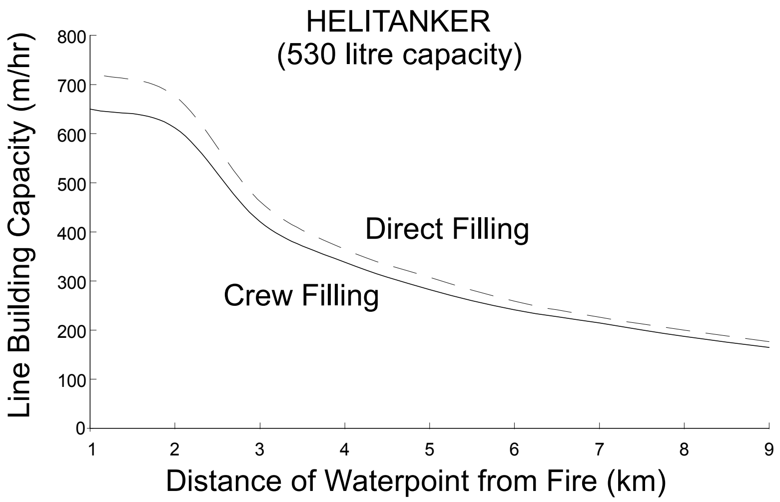

Figure 8. An example of the simulated productivity of a "light" helicopter with a 530-litre capacity bucket dropping water in the exotic pine plantation fuel types of southeastern Queensland (after Hunt 1986).

Aircraft can be an extremely efficient fire suppression resource, especially when used during the incipient phase of fire growth when immediate access by ground suppression crews is not possible (Storey *et al*. 1959; McArthur 1969). They are also very expensive to maintain and operate (even on a contractual basis), let alone purchase. Helitankers and airtankers have in many instances been credited with enormous savings (e.g., Countryman 1969). They are nevertheless not a universal "cure all" for wildfire suppression problems. Even low or moderate intensity fires can spread around (Fig. 9), burn through/under (Alexander 1989) and/or spot over (George *et al*. 1989) a retardant, foam or water drop.

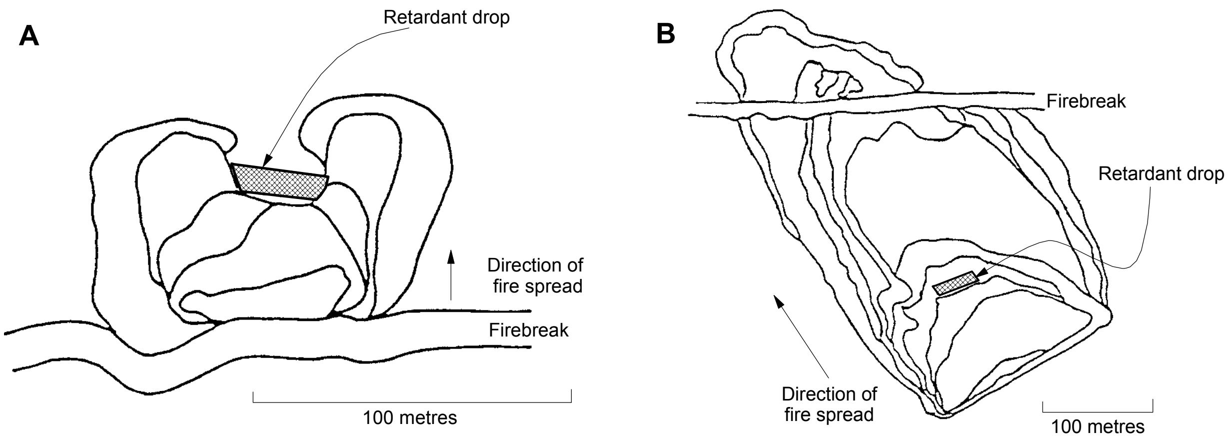

Figure 9. Two examples of the relative effectiveness of chemical retardant drops delivered from a helitanker in the temporary containment of a free-burning fire based on experimental studies carried out in the eucalypt forest fuel type of eastern Victoria, Australia (after Cheney and Hutchings 1986); the contours represent the fire perimeter at successive time intervals. In the first case (**A**), the head fire intensity was 1760 kW/m and spot fire activity ahead of the flame front was minimal. The retardant line, which was about 30 m long and 10 m wide, extinguished the head fire for about one hour until the flank flames burnt around the extremities of the drop and formed a new head fire. In the second case (**B**), the head fire intensity was 2670 kW/m and this more vigorous, rapidly spreading fire produced spot fires 25 to 300 m ahead of the main flame front. The retardant drop zone offered little resistance to the spread of this fire and the head fire intensity was halved for a 15-minute period in the vicinity of the drop and the surface fuels within the drop zone remained unburnt. The head fire later resumed an intensity of 2700 kW/m and spotted across a 30 m wide firebreak.

The cost-effectiveness of aerial fire suppression for a particular area needs to be critically examined in relation to the use of water versus chemical fire retardants (Owen 1984) and in terms of other types of resources (Quintilio and Anderson 1976; Loane and Gould 1986; Bell 1987; Gould 1987). Even large airtankers, such as the Canadair CL-215 or CL-415 and the C-130 Hercules MAFFS, are effective over a fairly narrow range of the fire intensity spectrum (Cheney *et al*. 1982; George 1985); furthermore, their efficiency is dependent to a great extent on the pilot's skill and the capability of the "bird dog" officer (Murray 1988). In using helitankers and airtankers it must be remembered that the primary purpose of aerial attack "… is to retard the progress of the fire and hold it until ground crews can move in and are able to complete the suppression job" (Haggarty *et al*. 1983).

Revelations Concerning Elapsed Time Since Ignition

The general pattern of a fire's growth with suppression action is illustrated in Figure 10. The fire is not detected until some time after ignition takes place. Because of the delay in mobilising and transporting personnel and equipment to the fire site, the actual attack on the fire does not begin until an even later time. The size of the fire, which has been growing steadily or even accelerating in rate of growth up to this time, still continues to grow after the initial attack but its rate of growth is slowly decreased until the fire is brought under control (Fig. 11).

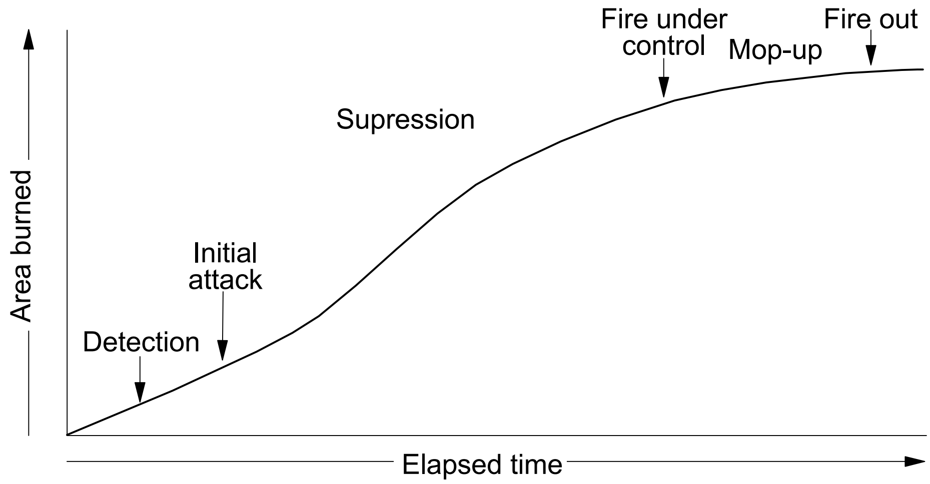

Figure 10. Schematic diagram illustrating the various activities involved in controlling and extinguishing a wildfire as a function of cumulative area burned and elapsed time since ignition (after Parks 1964).

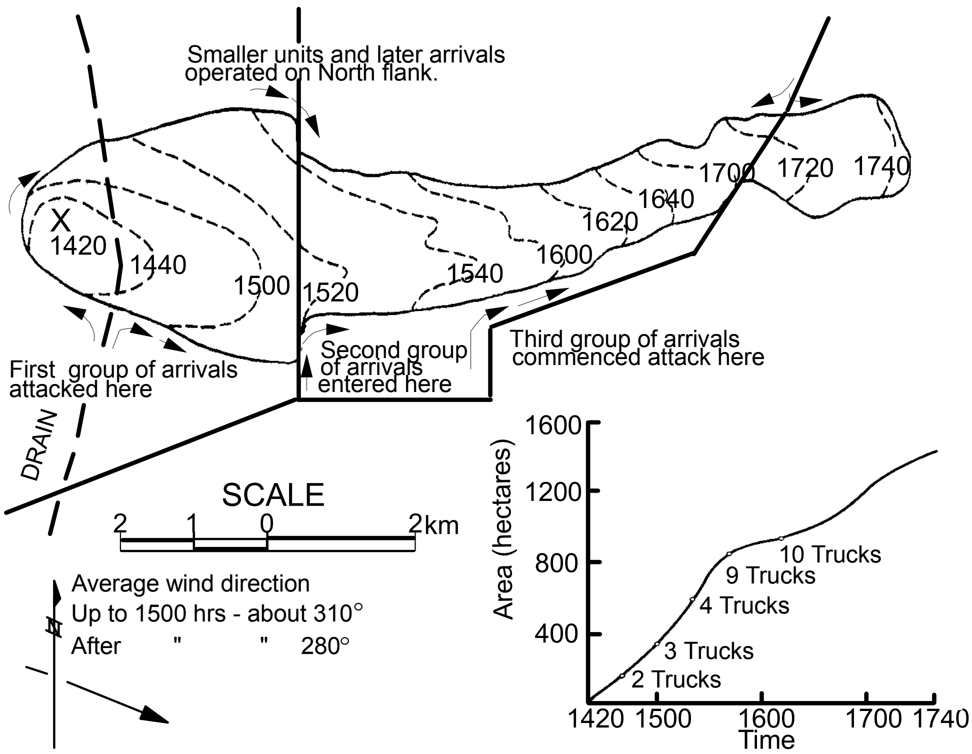

Figure 11. An example of the typical growth pattern exhibited by wildland fires that are affected by fire suppression action, which tends to limit the area burned significantly below their free-burning potential size. This particular example is of the 1966 Monbulla Fire which occurred in the pasture lands of the southeastern region of South Australia (after Douglas 1966). Suppression forces consisted exclusively of pumper-truck units.

Inspite of our best fire prevention efforts, the simple fact of the matter is that wildfires will continue to occur; the necessity of controlling wildfires is the result of the failure of the fire prevention program (Gaylor 1974). As Joe Taylor stated at the 1989 Prevent Rural Fires Convention held in Wellington, “You cannot prevent fires. You can only prevent small fires becoming big ones”. It’s generally acknowledged that the key to reducing area burned and in turn damages and suppression costs is fast and effective initial attack. Yet, in my opinion not enough attention is paid in initial attack preparedness planning to the critical importance of time in relation to initiating fire behaviour and in turn fire suppression problems; in this regard McArthur’s (1968) paper on *The Effect of Time on Fire Behaviour and Fire Suppression Problems* should be required reading for all forest and rural firefighters. Valuable time can be lost between the moment of ignition and the start of effective work on the fire perimeter, meanwhile an initiating fire is gradually expanding in area (Fig. 12). In this regard, four elapsed time intervals or stages are generally recognized (also see Fig. 13):

Discovery period of time from the start of a fire until it is first seen by someone who reports it.

Report period of time from discovering the fire until the first person charged with initiating suppression action is notified of its existence and location, etc.

Get-Away period of time taken between reporting of the fire until the departure of the initial attack forces.

Travel period of time between departure of the initial attack forces and their arrival at the fire.

Within the limits of 24 km, which is usually accepted as the maximum effective radius of vision for lookout observers (Show and Kotok 1937), average discovery time has been determined from experimental fires to be about 10-11 minutes (Buck 1938; Bickford and Bruce 1939) (Fig. 14). It generally takes perhaps 1-3 minutes for a lookout observer to determine a fire’s location and to note other features (e.g., colour of smoke, angle of the convection column, apparent size of the fire, estimate of current wind speed and direction) and then to communicate this information to a dispatcher (Anon. 1971a, 1971b, 1986). If the general public is relied upon for fire detection, generally the fire sizes at initial attack are considerably larger; this of course depends on the population density and the proximity of a fire in relation to the populace.

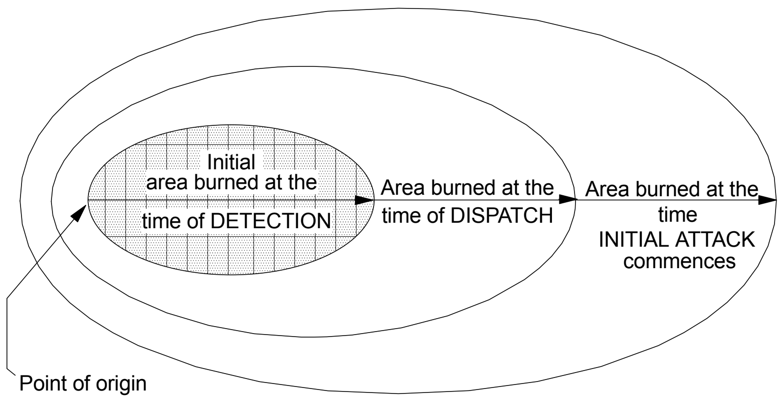

Figure 12. Conceptualisation of free-burning fire growth with the passage of time since ignition before containment action begins.

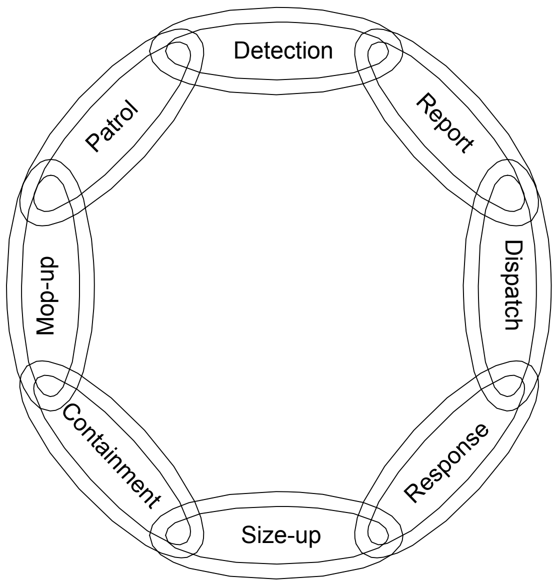

Figure 13. The chain of actions required to control a wildfire (from Gaylor 1974).

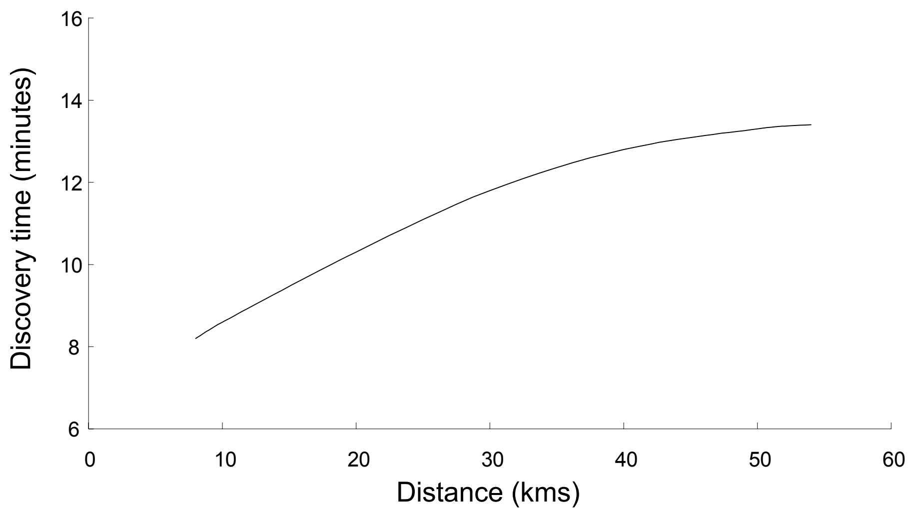

Figure 14. Discovery time of incipient fires by lookout observers under favourable atmospheric visibility as a function of distance in the mature ponderosa pine fuel type of northern California, U.S.A. (after Buck 1938).

When a wildfire is reported, a dispatcher must make several key decisions (the impact of these decisions become especially acute on multiple fire days). How many resources should be sent, which ones and from where? This could easily take another 1-3 minutes or longer depending on the procedures involved and the time taken to contact the initial attack forces by phone or radio. Dispatching is organised in various ways (Chase 1980; Kourtz 1987a). It may take the form of threat analysis (Bratten *et al*. 1981) in which a knowledgeable and experienced dispatcher's response (Chandler *et al*. 1983) follows from an assessment of the fire's location and current behaviour whereas automated or preplanned dispatching (e.g., Geddes and Pfeiffer 1981) relies upon predetermined criteria (e.g., fire danger class).

The get-away or response time must also consider the time involved in loading up men and equipment and/or the time taken for rotary- or fixed-wing aircraft to warm up before proceeding to the fire area. A minimum get-away time would probably be an additional 1-5 minutes depending on whether aircraft were involved or not. For example, the time taken for helicopters to become airborne and headed to a fire averages about five minutes (Hart 1977).

Most fire management organisations have established elapsed time standards for discovery, reporting and get-away (e.g., Gray and Janz 1985; Anon. 1986; De Groot 1990) which generally are not subject to such wide variation as travel times, which are determined to a large extent by the distances involved with respect to the fire location. Francis (1972), for example, has suggested as a general rule of thumb that rural land owners should be capable of reaching any part of their property within 10-15 minutes from the time an "alarm" is raised. Minimising travel time to a wildfire is an important criterion when suppression resources are dispatched and for that reason, travel time is one of the most important measures used in evaluating alternative arrangements of initial attack locations (Mees 1986). In order to minimise travel times during critical fire danger periods, fire suppression personnel and their equipment may on a daily basis be temporarily located at strategic points rather than being stationed at a central depot (Gray and Janz 1985). Travel times can also have bearing on decisions as to where permanent fire control facilities should be located (Hodgson and Newstead 1978; Martell 1982).

The time taken to reach the fire area can be determined rather precisely for helicopters and airtankers based on their cruise speeds (Anon. 1975, 1991) and the distance involved (Anon. n.d.; Preece *et al*. 1989); for example, the cruising speeds of a Hughes 500 and a Bell Jet Ranger are nominally about 200 km/h. For ground suppression forces and equipment travelling by vehicle, road conditions must be considered (Sneeuwjagt and Peet 1985; Anon. 1988). Finally, firefighters may have to walk some distance to reach the fire from a helispot or road.

Some time will also probably be taken for "size-up". This initial attack reconnaissance or "triage" (Pyne 1984) represents the most crucial time in the entire fire fighting operation (Chandler *et al*. 1983). Sizing up a fire shouldn't be rushed for as Gaylor (1974) has emphasised, "A correct size-up often means the difference between success and failure." The pocket-size handbook *Planning For Initial Attack* (Moberly *et al*. 1979) is an excellent reference on this subject area.

The fire's behaviour will determine whether direct or indirect attack is possible; excellent summaries on fire suppression strategy and tactics can be found in a variety of textbooks and other sources dealing with wildland fires (e.g., Anon 1973; Brown and Davis 1973; Luke and McArthur 1978; Chandler *et al*. 1983; Barney *et al*. 1984; Pyne 1984; Perry 1990). If the intensity at the fire's head and its rate of perimeter increase is sufficiently low enough for the type and number of initial attack forces dispatched to the fire, then containment at a small size will be achieved relatively quickly, otherwise an escaped fire must be contended with and the possibility of a large project or campaign fire in turn exists (Perry 1989).

Once the fire has been contained, the essential job of mopping up begins and afterwards the area must be patrolled before it's declared truly "out". Infrared scanning equipment can be of immense value during these later stages in the life history of wildfire, especially if large areas must be searched (Ogilvie 1981, 1982).

A successful initial attack is based on the principle of what Gaylor (1974) considers as one of the "seven secrets of wildfire control" – *hit 'em hard and keep 'em small!* The questions of "how much" and "how soon" manpower and equipment should be committed to a newly reported fire can be approximated with some degree of certainty based on the characteristics of the fire's environment (e.g., slope steepness, soil conditions, fuel types, wind velocity) and probable behaviour (i.e., head fire spread rate and intensity). The extreme alternative of sending "everything you have as soon as possible" is, from economic and strategic (e.g., multiple fires at opposite ends of a fire protection area) points of view, just as irresponsible as the other alternative of sending too little or the wrong kind of resources – "the optimal strategy lies somewhere in between" (Jewell 1963).

All fires originating from a single ignition point undergo a period of acceleration in their forward rate of spread (and intensity) until such time as they reach a plateau or steady-state condition (McAlpine and Wakimoto 1991) for the prevailing burning conditions (Fig. 15). This may take only about 10 minutes in grasslands but perhaps 30 minutes or more in forests (Brown and Davis 1973) depending on the variations in wind direction. Table 4 has been prepared on the basis of an available surface fuel load of 15 t/ha which would be typical for most forest fires; in exotic pine plantations this would most likely occur according to the Buildup Index component of the Fire Weather Index (FWI) System (Van Wagner 1987) at a value of around 60 (Forestry Canada Fire Danger Group 1992). Forward spread rates of 150, 300, 600 and 1200 m/hour for surface fires in mature stands (where the height to the base of the green crown layer would be greater than 10 metres) would in all likelihood occur according to the Initial Spread Index (ISI) component of the FWI System at values of 7, 10, 15 and 26, respectively (Forestry Canada Fire Danger Group 1992); ISIs of 2, 3, 5 and 7, respectively, would be required to achieve equivalent rates of spread in grasslands assuming a 100% degree of curing. The formation of crown fires in exotic pine plantations pruned to 2.4, 4 and 6 metres would take place at intensities of 1065, 2291 and 4209 kW/m, respectively (Alexander 1988). For grass fires, maximum surface fuel loads would be considerably lower (*c.* 3.5 t/ha) but potential spread rates would generally be much higher for a given set of burning conditions, assuming a high degree of curing. For example, to achieve an intensity of 4000 kW/m or greater, a surface fire in grasslands would have to advance at a rate of at least 2286 m/hour whereas in an exotic pine plantation this same level of intensity could be achieved at a rate of spread of 533 m/hour.

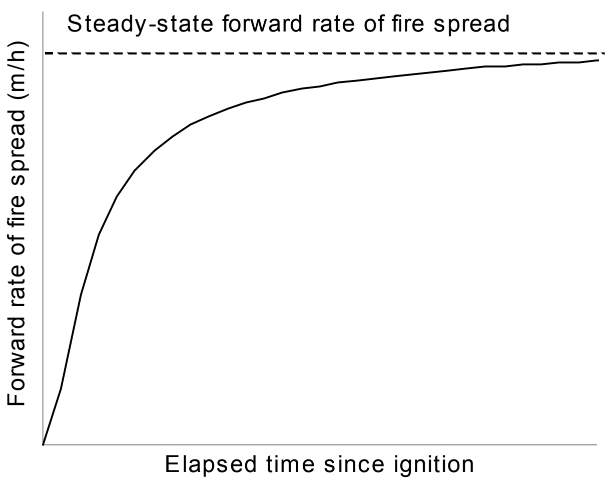

Figure 15. Mathematical representation for the theoretical acceleration in forward rate of fire spread, $R = R_{SS}e^{-aT}$ (after Cheney 1981).

Table 4. Simulation of the buildup in fire intensity with elapsed time since ignition for free-burning fires originating from a single ignition source.

Elapsed Time-" T" (minutes)	" Steady State" Head Fire Rate of Spread (m/h)			
	150	300	600	1200
" T"	Head Fire Intensity at time " T" (kW/m)*			
5	492	984	1968	3936
10	769	1538	3075	6150
20	1012	2024	4049	8098
40	1114	2227	4455	8910
Maximum	1125	2250	4500	9000

* Assuming the head fire attains 90% of its final steady-state rate of spread after 30 minutes.

Some Suggestions for Forest and Rural Fire Managers

The opportunities for managing wildland fuels in New Zealand to reduce the chances of a wildfire disaster are somewhat more limited in comparison to say Australia where, in many areas, fuel reduction burning is designed to keep fuel loads at a certain level based on potential spread rates as determined from an analysis of fire danger records (e.g., Gill 1986). Regardless of this fact, the necessity for establishing and maintaining the capability for detection of wildfires at the earliest possible moment and prompt, effective initial attack constitutes the cornerstone of any fire management organisation (Byram 1948; Macleod 1964); a proper balance must obviously be struck between these two activities in terms of cost effectiveness (Martell 1982; Kourtz 1987b).

In my view, the application of fire behaviour knowledge to improving forest and rural fire protection in New Zealand has for far too long lagged behind what might be considered a preoccupation with equipment development. In the following section, I offer some possible courses of action designed to remedy this situation.

An awareness or appreciation of fire behaviour should form an integral part of the training programme at all levels of an organisation from the firefighter up through to the fire boss, as well as principal rural fire officers and contractors (e.g., helicopter and fixed-wing pilots, bulldozer operators). In addition to conventional classroom instruction, controlled burns, simulated fire exercises and Wajax pump competitions are frequently cited as valuable forms of training (Cooper 1986a, 1986b). However, as Cooper (1986a) notes, "Training is best done live." Lookouts should be tested periodically with unscheduled smoke "bombs". Fire suppression training, particularly for the initial attack fire boss and supporting crews, needs to be more realistic with respect to the urgency of time and initiating fire behaviour. I favour the idea of finding areas where free-burning point source fires could be ignited and allowed to grow to perhaps 0.1-0.5 hectares in size before forces would arrive on the scene (e.g., Burrows *et al.* 1988). These situations would also afford the opportunity to document resource production rates in relation to actual wildfire conditions (e.g., Quintilio *et al.* 1990; Murphy *et al.* 1991). This concept of real simulated wildfires is very appropriate in areas which have a low fire incidence in general and/or in specific fuel types. In such cases, especially after a succession of very mild fire seasons, complacency sets in and it's very difficult to maintain the "edge" in regards to initial attack efficiency.

All rural fire authorities in New Zealand are required to prepare a fire control plan and to update them annually (Anon. 1991b). A cursory look at a few plans indicates that they could possibly benefit from preattack planning (Dell 1972; Anon. 1978). Preattack planning is the process of collecting, evaluating, and recording fire intelligence data in advance of fire occurrence for decision-making purposes to increase the chances of successful fire suppression in initial attack and large fire situations consistent with the fire management objectives for a given protection area. A preattack plan would include information on fuel types and topographic conditions including access routes and travel times, and water supply sources. It would also include information on existing and/or proposed developments or improvements (e.g., helispots, forward command posts). The preparation of travel time maps (*cf.* Van Wagner 1965) would be an extremely valuable aid for fire control planning.

It should be obvious from Table 4 that in certain instances fire suppression forces are incapable of controlling wildfires until burning conditions ameliorate, unless they just happen to be in the vicinity of an initiating fire. It's in these situations where fire prevention efforts should be at their maximum. A very good example of this is the media blitz associated with a "total fire ban" day in southeastern Australia (Luke and McArthur 1978; Dawson 1991) or a "red flag" day in the U.S.A. (National Fire Weather Advisory Group 1990). Anticipating these days of extreme fire behaviour potential as occurred, for example, in the Nelson region on February 5, 1981 when the Hira Forest Fire made a major run (Cooper 1986b), depends on using a fire danger rating system, such as the FWI System, and having a daily fire weather forecasting service (Pouliot 1991). To my knowledge, fire danger forecasting isn't practised in New Zealand. It's readily acknowledged that even with an adequate network of fire weather stations and a computer-based information system with fuel and terrain data (Barrows 1969; Kourtz 1984; Beck and Muller 1991; Lee and Anderson 1991) coupled with fire weather forecasts, near real-time prediction of potential fire behaviour is still inherently difficult (Cheney 1985c; Alexander and Andrews 1989). Furthermore, it must always be borne in mind that such tools are designed to support operational decision-making – "A person, not the model, will make the decision" (Andrews 1989).

Table 5. Fire presuppression guidelines suggested for Fijian exotic pine plantations (adapted from McArthur 1971).

Action	Fire Danger Class				
	Low	Moderate	High	V. High	Extreme
Primary lookouts manned	-	+	+	+	+
Secondary lookouts manned	-	-	-	+	+
Crews working on "close call"	-	-	+	+	+
Water tanker crews at H.Q.	-	-	-	+	+
All personnel and equipment available for immediate call	-	-	-	-	+
Weekend personnel requirements for standby or patrol	-	-	+	+	+

Although guidelines for presuppression readiness (Table 5) have been formulated by most fire authorities, rules for initial attack dispatching (Table 6) are virtually non-existent in New Zealand; existing fire control plans should be periodically reviewed in light of new knowledge. Sufficient information from operational experience and research elsewhere presently exists (e.g., Quintilio and Anderson 1976; Potter *et al*. 1981; Martell *et al*. 1984a, 1984b; Gray and Janz 1985; Fried and Gilless 1989; Kourtz 1989; De Groot 1990; Lanoville and Mawdsley 1990; Hirsch 1991) to begin modelling the process (Fig. 16), including considerations of cost-effectiveness (Fried and Gilless 1988; Wiitala 1992), that will suit New Zealand's needs. Certainly more refined guides to the quantitative prediction of fire behaviour and resource productivity would be desirable; however, this should not deter someone from applying what is currently known! For example, a relationship linking the ISI and BUI components of the FWI System to head fire rate of spread and fuel consumption in old man's gorse is desperately needed. Some rudimentary study of drop patterns involving the Cresco 600 airtanker have been undertaken (R.M. Edwards, personal communication) but much more work remains to be done on aerial fire suppression. The future of research on forest and rural fire behaviour and its relation to fire suppression productivity in New Zealand will require the financial support and cooperation of all concerned parties on a continuing basis.

Table 6. An example of a dispatcher's guide for fires starting in radiata pine plantations in southern New South Wales, Australia (adapted from Luke 1962).

Item	Fire Danger Class				
	Low	Moderate	High	V. High	Extreme
Probable Maximum Fire Behaviour					
Head fire spread rate (m/hour)	80	160	302	704	1509+
Elliptical fire perimeter @ 1 hour (m)	282	543	805	1609	3520+
Elliptical fire area @ 1 hour (ha)	0.8	2.4	6.1	24.3	101+
Minimum Suggested Requirements for Earliest Possible Initial Attack					
Number of personnel	2	4	6	12	30+
Water tankers	0	0	1	2	3+
Bulldozers	0	0	0	1	2
Expected containment time (hours)	0.5	0.5	0.5	1-2	2-5

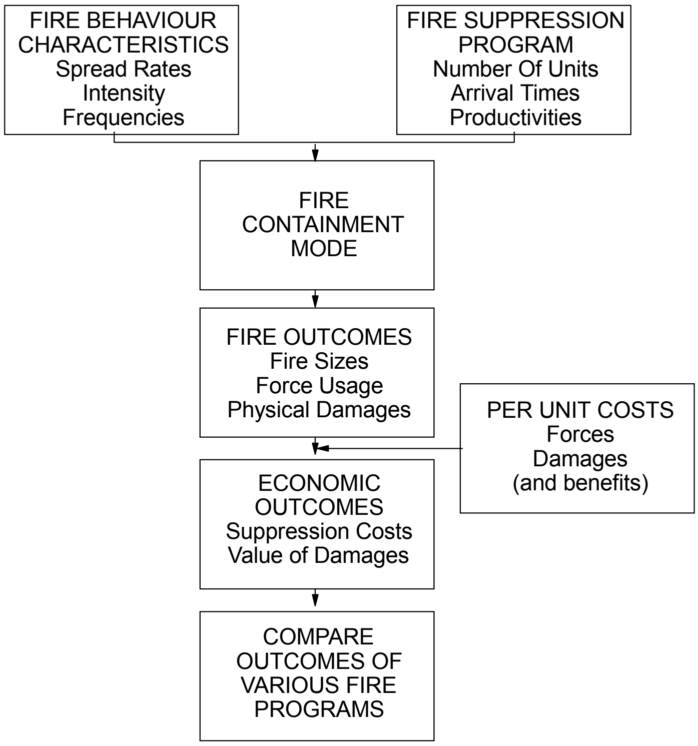

Figure 16. The fire suppression simulation model process (from Smith 1984).

Conclusions

Fire intensity or in turn flame size will dictate the limits of effectiveness for the various kinds of resources employed in wildland fire fighting. Rate of fire spread will determine the quantities of men and/or equipment required to contain a wildfire at a certain size or within a specified period of time based on their individual production rates. The planning of an initial attack fire suppression system should be based on the knowledge that all free-burning fires accelerate from the time flame first appears until they reach their maximum rate of spread and intensity for the particular combination of fuel, topography and weather conditions under which they are burning. In this respect, any unnecessary delay between the detection of a fire and the commencement of initial attack operations represents a crucial stage. Forest and rural fire authorities in New Zealand should be considering ways of saving time between the moment of ignition and the start of effective work on the fire perimeter.

Acknowledgements

Special thanks are extended to M. Casey for word processing and to H.G. Pearce for preparation of Figure 6.

References

Albini, F.A. 1976. Estimating wildfire behavior and effects. U.S. Department of Agriculture, Forest Service, General Technical Report INT-30. Intermountain Forest and Range Experiment Station, Ogden, Utah. 92 pages.

Albini, F.A. 1979. Spot fire distance from burning trees – a predictive model. U.S. Department of Agriculture, Forest Service, General Technical Report INT-56. Intermountain Forest and Range Experiment Station, Ogden, Utah. 73 pages.

Albini, F.A. 1983. Potential spotting distance from wind-driven surface fires. U.S. Department of Agriculture, Forest Service, Research Paper INT-309. Intermountain Forest and Range Experiment Station, Ogden, Utah. 27 pages.

Alexander, M.E. 1982. Calculating and interpreting forest fire intensities. Canadian Journal of Botany 60(4): 349-357.

Alexander, M.E. 1985. Estimating the length-to-breadth ratio of elliptical forest fire patterns. Pages 287-304 *in* Donoghue, L.R. and R.E. Martin (Editors). Proceedings of the Eighth Conference on Fire and Forest Meteorology. April 29-May 2, 1985, Detroit, Michigan. SAF Publication 85-04. Society of American Foresters, Bethesda, Maryland.

Alexander, M.E. 1988. Help with making crown fire hazard assessments. Pages 147-156 *in* Fischer, W.C. and S.F. Arno (Compilers). Protecting People and Homes from Wildfire in the Interior West: Proceedings of the Symposium and Workshop. October 6-8, 1987, Missoula, Montana. U.S. Department of Agriculture, Forest Service, General Technical Report INT-251. Intermountain Research Station, Ogden, Utah.

Alexander, M.E. 1989. Foam effectiveness in relation to quantified fire behavior. Foam Applications for Wildland and Urban Fire Management 2(2): 4-5.

Alexander, M.E. and P.L. Andrews. 1989. Wildland fire occurrence and behavior analysis in the year 2000 and beyond. Fire Management Notes 50(4): 35-37.

Alexander, M.E. and W.J. De Groot. 1988. Fire behavior in jack pine stands as related to the Canadian Forest Fire Weather Index (FWI) System. Poster (with text). Canadian Forestry Service, Northern Forestry Centre, Edmonton, Alberta.

Alexander, M.E. and R.A. Lanoville. 1989. Predicting fire behavior in the black spruce-lichen woodland fuel type in western and northern Canada. Poster (with text). Forestry Canada, Northern Forestry Centre, Edmonton, Alberta and Government of Northwest Territories, Department of Renewable Resources, Territorial Forest Fire Centre, Fort Smith, Northwest Territories.

Anderson, H.E. 1974. Forest fire retardants: transmission through a tree crown. U.S. Department of Agriculture, Forest Service, Research Paper INT-153. Intermountain Forest and Range Experiment Station, Ogden, Utah. 20 pages.

Andrews, P.L. 1989. Application of fire growth simulation models in fire management. Pages 317-321 *in* MacIver, D.G.H. Auld and R. Whitewood (Editors). Proceedings of the 10th Conference on Fire and Forest Meteorology. April 17-21, 1989, Ottawa, Ontario. Forestry Canada and Environment Canada, Ottawa, Ontario.

Anon. No date. Air speed wheel. Circular slide-rule. National Wildfire Coordinating Group, NFES 0097. National Fire Equipment System, Boise Interagency Fire Center, Boise, Idaho.

Anon. 1960. Ember-lifting power of convection column updrafts. Pages 42-43 *in* Annual Report, 1959. U.S. Department of Agriculture, Forest Service, Southeastern Forest Experiment Station, Asheville, North Carolina.

Anon. 1971a. Lookout man's handbook. Alberta Department of Lands and Forests, Alberta Forest Service, Forest Protection Branch, Edmonton, Alberta. 199 pages.

Anon. 1971b. Handbook for lookout men. British Columbia Department of Lands, Forests and Water Resources. Forest Protection Handbook No. 6. British Columbia Forest Service, Forest Protection Division, Victoria, British Columbia. 69 pages.

Anon. 1973. Forest fire suppression. New Zealand Forest Service, Wellington, New Zealand. 110 pages.

Anon. 1975. Air operations for forest, brush, and grass fires. Second edition. National Fire Protection Association, Boston, Massachusetts. 57 pages.

Anon. 1978. Preattack planning guide. U.S. Department of Agriculture, Forest Service, Northern Region, Missoula, Montana. Non-paged.

Anon. 1986. Firefighters guide. National Wildfire Coordinating Group, NFES 1571. National Fire Equipment System, Boise Interagency Fire Center, Boise, Idaho. Non-paged.

Anon. 1987a. Helicopters in forest fire operations. Ministry of Forestry, Wellington, New Zealand. 28 pages.

Anon. 1987b. Handbook on pumping and delivering water to fires. Ministry of Forestry, Wellington, New Zealand. 28 pages.

Anon. 1988. Fire school notes. Department of Forestry, Brisbane, Queensland. 126 pages.

Anon. 1991a. Standard for wildfire control. 1991 edition. NFPA 295. National Fire Protection Association, Quincy, Massachusetts. 48 pages.

Anon. 1991b. Rural fire management code of practice. Three-ring binder. National Rural Fire Authority, Wellington, New Zealand. Non-paged.

Barney, R.J. 1983. Fireline production: a conceptual model. U.S. Department of Agriculture, Forest Service, Research Paper INT-310. Intermountain Forest and Range Experiment Station, Ogden, Utah. 7 pages.

Barney, R.J., G.R. Fahnestock, W.G. Herbolsheimer, R.K. Miller, C.B. Phillips and J. Pierovich. 1984. Section 5: Fire management. Pages 189-251 *in* Wenger, K.F. (Editor). Forestry Handbook. Second edition. John Wiley and Sons, New York, New York.

Barney, R.J., C.W. George, and D.L. Trethewey. 1992. Handcrew fireline production rates – some field observations. U.S. Department of Agriculture, Forest Service, Research Paper INT-457. Intermountain Research Station, Ogden, Utah. 25 pages.

Barney, R.J. and J.W. Peters. 1983. Jeep-mounted fireline plow unit. Fire Management Notes 44(3): 18-19.

Barrows, J.S. 1951. Fire behavior in northern Rocky Mountain forests. U.S. Department of Agriculture, Forest Service, Station Paper No. 29. Northern Rocky Mountain Forest and Range Experiment Station, Missoula, Montana. 123 pages.

Barrows, J.S. 1969. Intelligence systems for forest fire control. Pages 1934-1940 *in* Proceedings of the Sixth World Forestry Congress, Volume II. June 6-18, 1966, Madrid, Spain. Spanish Ministry of Agriculture, Madrid, Spain.

Beck, J.A. and C. Muller. 1991. The inception and development of decision support systems for forest fire management in Western Australia. Pages 94-100 *in* Daniel, T.C. and I.S. Ferguson (Editors). Proceedings of the U.S.-Australia Workshop Integrating Research on Hazards in Fire-Prone Environments: Reconciling Biological and Human Values in the Wildland/Urban Interface. June 12-16, 1989, Melbourne, Victoria. The United States Man and the Biosphere Program, Washington, D.C.

Bell, A. 1987. Water bombing of fires: no magic solution. Ecos 50: 19-23.

Bickford, C.A. and D. Bruce. 1939. Fire-discovery time in the longleaf pine-slash pine type. U.S. Department of Agriculture, Forest Service, Occasional Paper No. 88. Southern Forest Experiment Station, New Orleans, Lousiana. 5 pages.

Blackmarr, W.H. 1972. Moisture content influences ignitability of slash pine litter. U.S. Department of Agriculture, Forest Service, Research Note SE-173. Southeastern Forest Experiment Station, Asheville, North Carolina. 7 pages.

Brady, M.A. 1988. A note on the Sumatra peat swamp forest fires of 1987. Journal of Tropical Forest Science 1(3): 295-296.

Bratten, F.W., J.B. Davis, G.T. Flatman, J.W. Keith, S.R. Rapp and T.G. Storey. 1981. FOCUS: a fire management planning system – final report. U.S. Department of Agriculture, Forest Service, General Technical Report PSW-42. Pacific Southwest Forest and Range Experiment Station, Berkeley, California. 34 pages.

Brown, A.A. and K.P. Davis. 1973. Forest Fire: Control and Use. Second edition. McGraw-Hill, New York, New York. 686 pages.

Buck, C.C. 1938. Factors influencing the discovery of forest fires by lookout observers. Journal of Agriculture Research 56(4): 259-268.

Budd, G.M., J.R. Brotherhood, A.L. Hendrie, M.P. Dawson, F.A. Beasley, B.P. Costin, S.E. Jeffery, W. Zhien and M.M. Baker. 1991. Stress, strain, and productivity in Australian wildfire-suppression crews. Pages 119-123 *in* Pacific Rim Forestry – Bridging the World. Proceedings of the 1991 Society of American Foresters National Convention. August 4-7, 1991, San Francisco, California. SAF Publication 91-05. Society of American Foresters, Bethesda, Maryland.

Burrows, N.D. 1981. Fire hazard reduction by grazing cattle in *Pinus radiata* D. Don plantations in the Blackwood Valley. Research Paper 67. Forests Department, Perth, Western Australia. 5 pages.

Burrows, N.D. 1984. Describing forest fires in Western Australia: a guide for fire managers. Technical Paper No. 9. Forests Department, Perth, Western Australia. 29 pages.

Burrows, N.D. 1986. Backburning in forest areas. Landnote 6/86. Department of Conservation and Land Management, Perth, Western Australia. 6 pages.

Burrows, N., L. McCaw and G. Friend. (Editors). 1989. Fire management on nature conservation lands. Proceedings of a National Workshop, Busselton, Western Australia, October 1987. Occasional Paper 1/89. Department of Conservation and Land Management, Perth, Western Australia. 186 pages.

Burrows, N., B. Ward and A. Robinson. 1988. Aspects of fire behaviour and fire suppression in a *Pinus pinaster* plantation. Landnote 2/88. Department of Conservation and Land Management, Perth, Western Australia. 4 pages.

Byram, G.M. 1948. Some principles of visibility and their application to forest fire detection. Technical Bulletin No. 954. U.S. Department of Agriculture, Washington, D.C. 61 pages.

Byram, G.M. 1959a. Forest fuels. Pages 61-89 *in* Davis, K.P. (Editor). Forest Fire: Control and Use. McGraw-Hill, New York, New York.

Byram, G.M. 1959b. Combustion of forest fuels. Pages 90-123 *in* Davis, K.P. (Editor). Forest Fire: Control and Use. McGraw-Hill, New York, New York.

Catchpole, E.A., M.E. Alexander and A.M. Gill. 1992. Elliptical-fire perimeter and area-intensity distributions. Canadian Journal of Forest Research 22(7): 968-972.

Chandler, C., P. Cheney, P. Thomas, L. Trabaud and D. Williams. 1983. Fire in Forestry, Volume II: Forest Fire Management and Organization. John Wiley and Sons, New York, New York. 298 pages.

Chase, R.A. 1980. FIRESCOPE: a new concept in multiagency fire suppression coordination. U.S. Department of Agriculture, Forest Service, General Technical Report PSW-40. Pacific Southwest Forest and Range Experiment Station, Berkeley, California. 17 pages.

Cheney, N.P. 1975. Industrial forestry plantations, Turkey: Forest fire protection. FO: DP/TUR/71/521 Working Document No. 14. United Nations Development Programme and Food and Agriculture Organization of the United Nations, Rome, Italy. 59 pages.

Cheney, N.P. 1981. Fire behaviour. Pages 151-175 *in* Gill, A.M., R.H. Groves and I.R. Noble (Editors). Fire and the Australian Biota. Australian Academy of Science, Canberra, Australian Capital Territory.

Cheney, N.P. 1985a. Fire protection of small private forests. Paper presented at the Institute of Foresters of Australia and New Zealand Joint Conference, May 20-24, Hobart, Tasmania. 11 pages.

Cheney, N.P. 1985b. Forest Fire Management in Australia. Pages 75-83 *in* Dubé, D.E. (Compiler). Proceedings of the Intermountain Fire Council 1983 Fire Management Workshop. October 25-27, 1983, Banff, Alberta. Canadian Forestry Service, Information Report NOR-X-271. Northern Forest Research Centre, Edmonton, Alberta.

Cheney, N.P. 1985c. New approaches to fire danger and fire behaviour. *In* Proceedings of Fire Weather Services Conference, May 13-14, 1985, Adelaide, South Australia. Department of Science, Bureau of Meteorology, Melbourne, Victoria. pp 12.1-12.9.

Cheney, N.P. 1986. Fire: its impact, and methods and equipment used in its control. *In* FIME '86 International Logging Conference Papers, April 12-13, 1986, Sydney, New South Wales. Australian Forest Industries Journal and Logger Magazine, Sydney, New South Wales. 4 pages.

Cheney, N.P. 1989. Bushfires: their threat to life and property. Pages 60-70 *in* Oliver, J. and N.R. Britton (Editors). Natural Hazards and Reinsurance. Proceedings of a Conference Sponsored by Sterling Offices (Australia) Ltd. Cumberland College of Health Sciences, Lidcombe, New South Wales.

Cheney, N.P., R. Fenwick, P.T. Hutchings and A.J. Nicholson. 1982. Aerial suppression of bushfires – assessment of MAFFS/Hercules operations – Victoria, January - March, 1982. CSIRO Division of Forest Research, Canberra, Australian Capital Territory. 17 pages + appendices.

Cheney, N.P. and P.J. Hutchings. 1986. Project Aquarius. Pages 51-53 *in* Biennial Report, CSIRO Division of Forest Research 1983-1985. Commonwealth Scientific and Industrial Research Organisation, Melbourne, Victoria.

Cheney, N.P. and R.R. Richmond. 1980. The impact of extensive forest management on fire protection with special regard to plantations of eucalypts. Paper prepared for Eleventh Commonwealth Forestry Conference, September 7-25, 1980, Trinidad and Tobago. 22 pages.

Clements, H.B. 1977. Lift-off of forest firebrands. U.S. Department of Agriculture, Forest Service, Research Paper SE-159. Southeastern Forest Experiment Station, Asheville, North Carolina. 11 pages.

Cooper, A.N. 1986a. Forest fire control in New Zealand. Pages 40-42 *in* Levack, H. (Editor). 1986 Forestry Handbook. New Zealand Institute of Foresters (Inc.). Wellington, New Zealand.

Cooper, A.N. 1986b. Training using simulated forest fires. Commonwealth Forestry Review 65(2): 131-139.

Cooper, A.N. and C. Ashley-Jones. 1987. Economics of fire prevention in New Zealand plantations. New Zealand Forestry 31(4): 14-18.

Cooper, R.W. 1969. Preliminary guidelines for using suppression fires to control wildfires in the Southeast. U.S. Department Agriculture, Forest Service, Research Note SE-102. Southeastern Forest Experiment Station, Asheville, North Carolina. 2 pages.

Countryman, C.M. 1969. Use of air tankers pays off ... a case study. U.S. Department of Agriculture, Forest Service, Research Note PSW-188. Pacific Southwest Forest and Range Experiment Station, Berkeley, California. 4 pages.

Countryman, C.M. 1971. Fire whirls ... why, when, and where. U.S. Department of Agriculture, Forest Service, Pacific Southwest Forest and Range Experiment Station, Berkeley, California. 11 pages.

Countryman, C.M. 1972. The fire environment concept. U.S. Department of Agriculture, Forest Service, Pacific Southwest Forest and Range Experiment Station, Berkeley, California. 12 pages.

Countryman, C.M. 1974. Can southern California wildland conflagrations be stopped? U.S. Department of Agriculture, Forest Service, General Technical Report PSW-7. Pacific Southwest Forest and Range Experiment Station, Berkeley, California. 11 pages.

Countryman, C.M. 1983. Ignition of grass fuels by cigarettes. Fire Management Notes 44(3): 3-7.

Crosby, J.S., R.W. Johansen and R.W. Cooper. 1963. The model II Michigan sand caster. U.S. Department of Agriculture, Forest Service, Research Paper CS-2. Central States Forest Experiment, Columbus, Ohio. 30 pages.

Dawson, M.P. 1991. Fire bans and public perception of fire danger. Pages 33-41 *in* Cheney, N.P. and A.M. Gill (Editors). Proceedings, Conference on Bushfire Modelling and Fire Danger Rating Systems. July 11-12, 1988. Canberra, Australian Capital Territory. CSIRO Division of Forestry, Yarralumla, Australian Capital Territory.

DeCoste, J.H., D.D. Wade and J.E. Deeming. 1968. The Gaston Fire. U.S. Department of Agriculture, Forest Service, Research Paper SE-43. Southeastern Forest Experiment Station, Asheville, North Carolina. 36 pages.

Deeming, J.E. and D.D. Wade. 1974. A clarification ... wildfire suppression terminology. Fire Management Notes 35(2): 10-11.

De Groot, W.J. 1990. Development of Saskatchewan's fire preparedness system. Pages 23-50 *in* Hirsch, K.G. (Compiler and Editor). Proceedings of the Sixth Central Region Fire Weather Committee Scientific and Technical Seminar. April 4, 1989, Winnipeg, Manitoba. Forestry Canada, Study NOR-36-03-1 File Report No. 5. Northern Forestry Centre, Edmonton, Alberta.

Dell, J.D. 1972. R-6 preattack guide … area planning and development for forest fire protection in the Pacific Northwest region. U.S. Department of Agriculture, Forest Service, Region 6, Portland, Oregon. 67 pages.

Dempster, W.R. and N.A. Stevens. 1987. Risk management in forest planning. Canada–Alberta Forest Resource Development Agreement Project #B31444-18 Report. Forestry Canada and Alberta Department of Forestry, Lands and Wildlife, Edmonton, Alberta. 38 pages + appendices.

Douglas, D.R. 1966. Minimum needs for effective suppression of grass fires. Australian Forest Research 2(3): 54-57.

Douglas, D.R. 1973. Initial attack on fires in radiata pine plantations. Australian Forestry Council Research Working Group No. 6 Newsletter 4: 1-8.

Drysdale, D. 1985. An Introduction to Fire Dynamics. John Wiley Sons, Chichester, England. 424 pages.

Forestry Canada Fire Danger Group. 1992. Development and structure of the Canadian Forest Fire Behavior Prediction System. Forestry Canada, Information Report ST-X-3. Science and Sustainable Development Directorate, Ottawa, Ontario. 63 pages.

Francis, B.J. 1972. A guide to farm fire units. Journal of Agriculture of South Australia 75(6): 164-167.

French, T. 1990. A power backpack pump with foam capability. Fire Management Notes 51(4): 16-17.

Fried, J.S. and J.K. Gilless. 1988. The California fire economics simulator initial attack module (CFES-IAM): Version 1.11 User's Guide (MS-DOS). University of California, Bulletin 1925. Division of Agriculture and Natural Resources, Berkeley, California. 83 pages.

Fried, J.S. and J.K. Gilless. 1989. Expert opinion estimation of fireline production rates. Forest Science 35(3): 870-877.

Gaylor, H.P. 1974. Wildfires: Prevention and Control. Robert J. Brady Company, Bowie, Maryland. 319 pages.

Geddes, D.J. and E.R. Pfeiffer. 1981. The Caroline Forest Fire, 2nd February, 1979. Bulletin 26. Woods and Forests Department, Adelaide, South Australia. 52 pages.

George, C.W. 1981. Developing airtanker delivery performance using a simple slide chart-retardant coverage calculator. U.S. Department of Agriculture, Forest Service, General Technical Report INT-113. Intermountain Forest and Range Experiment Station, Ogden, Utah. 7 pages.

George, C.W. 1985. An operational retardant evaluation study. Fire Management Notes 46(2): 18-23.

George, C.W., G.F. Ewart and W.C. Friauf. 1989. FLIR: a promising tool for air-attack supervisors. Fire Management Notes 50(4) 26-29.

George, C.W. and G.M. Johnson. 1990. Developing air tanker performance guidelines. U.S. Department of Agriculture, Forest Service, General Technical Report INT-268. Intermountain Research Station, Ogden, Utah. 96 pages.

Gill, A.M. 1986. Research for the fire management of Western Australian state forests and conservation reserves. Technical Bulletin No. 12. Department of Conservation and Land Management, Perth, Western Australia. 82 pages.

González-Cabán, A. 1984. Costs of firefighting mopup activities. U.S. Department of Agriculture, Forest Service, Research Note PSW-367. Pacific Southwest Forest and Range Experiment Station, Berkeley, California. 5 pages.

Gould, J.S. 1987. The cost-effectiveness of airtankers in the south-east region of South Australia and the south-west region of Victoria. Commonwealth Scientific and Industrial Research Organization, DFR User Series Number 9. Division of Forest Research, Canberra, Australian Capital Territory. 45 pages.

Gray, H.W. and B. Janz. 1985. Initial-attack initiatives in Alberta: a response to the 1980s. Pages 25-36 *in* Dubé, D.E. (Compiler). Procedings of the Intermountain Fire Council 1983 Fire Management Workshop. October 25-27, 1983, Banff, Alberta. Canadian Forestry Service, Information Report NOR-X-271. Northern Forest Research Centre, Edmonton, Alberta.

Green, L.R. 1977. Fuelbreaks and other fuel modification for wildland fire control. Agriculture Handbook No. 499. U.S. Department of Agriculture, Forest Service, Washington, D.C. 79 pages.

Green, L.R. and H.E. Schinke. 1971. Guides for fuel-breaks in the Sierra Nevada mixed-conifer type. U.S. Department of Agriculture, Forest Service, Pacific Southwest Forest and Range Experiment Station, Berkeley, California. 14 pages.

Grigel, J. 1974. Role of the helitanker in forest fire control. Canadian Forestry Service, Information Report NOR-X-123. Northern Forest Research Centre, Edmonton, Alberta. 41 pages.

Grigel, J.E., R.J. Lieskovsky and R.G. Newstead. 1974. Air drop tests with helitankers. Canadian Forestry Service, Information Report NOR-X-77. Northern Forest Research Centre, Edmonton, Alberta. 77 pages.

Haggarty, D., R. Newstead and E. Stechishen. 1983. Evaluation of fire bombing aircraft. Canadian Forest Industries 103(8): 21-24.

Haines, D.A. 1989. Air tanker vortex turbulence – revisited. Fire Management Notes 59(2): 14-15.

Hardy, C.E. 1977. Chemicals for Forest Fire Fighting. Third edition. National Fire Protection Association, Boston, Massachusetts. 106 pages.

Hart, P. 1977. Helicopter rappelling. Fire Management Notes 38(4): 13-16.

Haven, L., T.P. Hunter and T.G. Storey. 1982. Production rates for crews using hand tools on firelines. U.S. Department of Agriculture, Forest Service, General Technical Report PSW-62. Pacific Southwest Forest and Range Experiment Station, Berkeley, California. 8 pages.

Henderson, R.C. and S.J. Muraro. 1968. Effect of organic layer moisture on prescribed burning. Canada Department of Forestry and Rural Development, Information Report BC-X-14. Forest Research Laboratory, Victoria. British Columbia. 10 pages.

Hesterberg, G.A. 1959. Controlling fires in the Lake States timber types with sodium-calcium borate. Michigan College of Mining and Technology, Technical Bulletin No. 4. Ford Forestry Centre, L'Anse, Michigan. 21 pages.

Hirsch, K.G. 1991. Development of an initial attack preparedness system for Manitoba. Pages 81-89 *in* Andrews, P.L. and D.F. Potts (Editors). Proceedings of the 11th Conference on Fire and Forest Meteorology. April 16-19, 1991, Missoula, Montana. SAF Publication 91-04. Society of American Foresters, Bethesda, Maryland.

Hirsch, S.N., G.F. Meyer and D.L. Radloff. 1979. Choosing an activity fuel treatment for southwest ponderosa pine. U.S. Department of Agriculture, Forest Service, General Technical Report RM-67. Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colorado.

Hodgson, A. and N.P. Cheney. 1969. Aerial ignition for backburning. Australian Forestry 33(4): 268-274.

Hodgson, M.J. and R.G. Newstead. 1978. Location-allocation models for one-strike initial attack of forest fires by airtankers. Canadian Journal of Forest Research 8(2): 145-154.

Hough, W.A. and F.A. Albini. 1978. Predicting fire behavior in palmetto-gallberry fuel complexes. U.S. Department of Agriculture, Forest Service, Research Paper SE-174. Southeastern Forest Experiment Station, Asheville, North Carolina. 44 pages.

Howard, C.W. 1980. Considerations in selecting fire retardants for aerial application in the suppression of forest fires. Chemonics Industries, Phoenix, Arizona. 49 pages.

Hunt, S.M. 1986. Fire manual for helicopter operations. Department of Forestry, Brisbane, Queensland. 56 pages.

Ingoldby, M.J.R. and R.O. Smith. 1982. Forest fire fighting with foam. Forestry Commission, Leaflet 80. Research Station, Surrey, England. 18 pages.

Jewell, W.S. 1963. Forest fire problems – a progress report. Operations Research 11(5): 678-692.

Johnson, E.A. 1992. Fire and Vegetation Dynamics: Studies from the North American Boreal Forest. Cambridge University Press. 129 pages.

Johnson, V.J. 1975. Hardwood fuel-breaks for northeastern United States. Journal of Forestry 73(9): 588-589.

Kiil, A.D. 1971. Prescribed fire effects in subalpine spruce-fir slash. Canadian Forestry Service, Information Report NOR-X-3. Northern Forest Research Centre, Edmonton, Alberta. 30 pages.

Kourtz, P. 1984. Decision-making for centralized forest fire management. Forestry Chronicle 60(6): 320-327.

Kourtz, P. 1987a. Expert system dispatch of forest fire control resources. AI Applications in Natural Resource Management 1(1): 1-8.

Kourtz, P. 1987b. The need for improved forest fire detection. Forestry Chronicle 63(4): 272-277.

Kourtz, P. 1989. Two dynamic programming algorithms for forest fire resource dispatching. Canadian Journal of Forest Research 19(1): 106-112.

Lanoville, R.A. and W.M. Mawdsley. 1990. Systematic assessment of daily fire preparedness planning. Pages 253-261 *in* Alexander, M.E. and G.F. Bisgrove (Technical Coordinators). The Art and Science of Fire Management. Proceedings of the First Interior West Fire Council Annual Meeting and Workshop. October 24-27, 1988, Kananaskis, Alberta. Forestry Canada, Northwest Region, Information Report NOR-X-309. Northern Forestry Centre, Edmonton, Alberta.

Lee, B.S. and K.R. Anderson. 1991. An overview of IFMIS: the Intelligent Fire Management Information System. Pages 58-70 *in* Grewal, H. (Compiler). Forest Canada Modeling Working Group. Proceedings of the Fifth Annual Workshop. December 13-14, 1990, Kananaskis, Alberta. Forestry Canada, Northwest Region, Northern Forestry Centre, Edmonton, Alberta.

Lieskovsky, R. and R. Newstead. 1980. Forest fire flame-inhibiting (long term) retardants used in Canada. Canadian Forestry Service, Forest Management Note No. 2. Northern Forest Research Centre, Edmonton, Alberta. 4 pages.

Loane, I.T. and J.S. Gould. 1986. Project Aquarius: Aerial suppression of bushfires – cost-benefit study for Victoria. Commonwealth Scientific and Industrial Research Organization, Division of Forest Research, National Bushfire Research Unit, Canberra, Australian Capital Territory. 213 pages + appendices.

Luke, R.H. 1962. Meeting protection objectives in difficult years. Pages 971-978 *in* Proceedings of the Fifth World Forestry Congress, Volume 2. August 29 - September 10, 1960, Seattle, Washington. U.S. Department of Agriculture, Forest Service, Washington, D.C.

Luke, R.H. and A.G. McArthur. 1978. Bushfires in Australia. Australian Government Publishing Service, Canberra, Australian Capital Territory. 359 pages. [reprinted with corrections 1986.]

Macleod, J.C. 1964. Planning for forest fire control. Canada Department of Forestry, Publication No. 1048. Forest Research Branch, Ottawa, Ontario. 8 pages.

McAlpine, R.S. and R.H. Wakimoto. 1991. The acceleration of fire from point source to equilibrium spread. Forest Science 37(5): 1314-1337.

McArthur, A.G. 1968. The effect of time on fire behaviour and fire suppression problems. Pages 3-6, 8, 10-13 *in* E.F.S. Manual 1968. South Australia Emergency Fire Services, Keswick, South Australia.

McArthur, A.G. 1969. The role of water bombing aircraft in the control of forest fires in Australia. Paper presented to the Symposium on the Use of Aircraft in Fire Control organized by the Royal Aeronautical Society of Australia - New South Wales Branch. February 28, 1969, Sydney, New South Wales, 18 pages.

McArthur, A.G. 1971. Aspects of fire control in the *P. caribaea* and *P. elliottii* plantations of north western Viti Levua, Fiji Islands. Report prepared for Fiji Pine Scheme. Forestry and Timber Bureau, Forest Research Institute, Canberra, Australian Capital Territory. 38 pages + appendices.

Mactavish, J.S. 1960. Characteristics of back-pack pumps used in forest fire suppression. Canada Department of Northern Affairs and National Resources, Forestry Branch, Technical Note No. 85. Forest Research Division, Ottawa, Ontario. 23 pages.

Martell, D.L. 1982. A review of operational research studies in forest fire management. Canadian Journal of Forest Research 12(2): 119-140.

Martell, D.L., R.J. Drysdale, G.E. Doan and D. Boychuk. 1984a. An analysis of the Ontario Ministry of Natural Resources' forest fire initial attack aircraft requirements. Ontario Ministry of Natural Resources, A&FMC Publication No. 140. Aviation and Fire Management Centre, Sault Ste. Marie, Ontario. 68 pages.

Martell, D.L., R.J. Drysdale, G.E. Doan and D. Boychuk. 1984b. An evaluation of forest fire initial attack resources. Interfaces 14(5): 20-32.

Mees, R.M. 1986. Locating suppression resources by travel times to wildfires. U.S. Department of Agriculture, Forest Service, Research Note PSW-387. Pacific Southwest Forest and Range Experiment Station, Berkeley, California. 5 pages.

Merrill, D.F. and M.E. Alexander (Editors). 1987. Glossary of forest fire management terms. Fourth edition. National Research Council of Canada, Publication NRCC No. 26516. Canadian Committee on Forest Fire Management, Ottawa, Ontario. 91 pages.

Moberly, H.E., J.E. Moore, R.C. Ashley, K.L. Burton and H.C. Peebles. 1979. Planning for initial attack. Revised edition. U.S. Department of Agriculture, Forest Service, Forestry Report SA-FR 2. Southeastern Area State and Private Forestry, Atlanta, Georgia. 41 pages.

Moore, J.E., R.W. Johansen and H.E. Moberly, Jr. 1976. Southern guide for using fire retarding chemicals in ground tankers. U.S. Department of Agriculture, Forest Service, Southeastern Area State and Private Forestry, Atlanta, Georgia. 28 pages.

Morris, G.A. 1987. A simple method for computing spotting distances from wind-driven surface fires. U.S. Department of Agriculture, Forest Service, Research Note INT-374. Intermountain Research Station, Ogden, Utah. 6 pages.

Muraro, S.J. 1976. Improved ignition systems. Pages 22-26 *in* Global Forestry and the Western Role. Permanent Association Committee. Proceedings, Western Forest Fire Committee Annual Meeting. December 2, 1975, Vancouver, British Columbia. Western Forestry and Conservation Association, Portland, Oregon.

Murphy, P.J., D. Quintilio and P.M. Woodard. 1989. Validation of an index system for estimating fireline production with hand tools. Forestry Chronicle 65(3): 190-193.

Murphy, P.J., P.M. Woodard, D. Quintilio and S.J. Titus. 1991. Exploratory analysis of the variables affecting initial attack hot-spotting containment rate. Canadian Journal of Forest Research 21(4): 540-544.

Murray, W.G. 1986. Air tanker and helitanker use in Canada 1978-1984. Canadian Forestry Service, Information Report PI-X-68. Petawawa National Forestry Institute, Chalk River, Ontario. 18 pages.

Murray, W.G. 1988. The role of bird dog officers in aerial fire suppression. Canadian Forestry Service, Information Report PI-X-82. Petawawa National Forestry Institute, Chalk River, Ontario. 29 pages.

National Fire Weather Advisory Group. 1990. National Weather Service fire weather program user information. National Wildfire Coordinating Group, NFES 2141. National Fire Equipment System, Boise Interagency Fire Center, Boise, Idaho. 28 pages.

Newman, M. 1974. Toward a common language for aerial delivery mechanics. Fire Management Notes 35(1): 18-19.

Newstead, R.G. and M.E. Alexander. 1983. Short-term fire retardant effectiveness in a lowland black spruce fuel complex. Pages 3-4 *in* Forestry Report No. 28. Canadian Forestry Service, Northern Forest Research Centre, Edmonton, Alberta.

Newstead, R.G. and R.J. Lieskovsky. 1985. Air tanker and fire retardant drop patterns. Canadian Forestry Service, Information Report NOR-X-273. Northern Forestry Centre, Edmonton, Alberta. 31 pages.

Ogilvie, C. 1981. Guidelines for use of the AGA thermovision in forest fire mop-up operations. Canadian Forestry Service, Forest Management Note No. 8. Northern Forest Research Centre, Edmonton, Alberta. 3 pages.

Ogilvie, C.J. 1982. The Scan Extender – a device to enhance the capabilities of the AGA 750 thermovision. Fire Management Notes 43(3): 22-24.

Ogilvie, C.J., M.E. Alexander, R.J. Lieskovsky and J. Bird. 1989. Interim guidelines for aerial application of foam on forest fires. Forestry Canada, Technology Transfer Note A-010. Northern Forestry Centre, Edmonton, Alberta. 2 pages.

Ovchinnikov, F.M. and V.M. Grumans. 1988. The speed of localizing a forest fire in tactical calculations. Lesnoye Khozyaistvo 1988(8): 52-53. [original article in Russian; see Forestry Abstract 52(10): 1000. 1991.]

Owen, D.H. 1984. On record. Canadian Forest Industries 104(1): 4.

Parks, G.M. 1964. Development and application of a model for suppression of forest fires. Management Science 10(1): 760-766.

Parrott, R.T. and C.M. Donald. 1970. Growth and ignitability of annual pastures in a Mediterranean environment. 2. Ignitability of swards of various annual species. Australian Journal of Experimental Agriculture and Animal Husbandry 10(42): 76-83.

Perry, D.G. 1989. Managing a Wildland Fire: A Practical Perspective. Fire Publications, Inc., Bellflower, California. 141 p.

Perry, D.G. 1990. Wildland Firefighting: Fire Behaviour, Tactics and Command. Second edition. Fire Publications, Inc., Bellflower, California. 412 p.

Phillips, C.B., C.W. George and D.K. Nelson. 1988. Bulldozer fireline production rates – 1988 update. U.S. Department of Agriculture, Forest Service, Research Paper INT-392. Intermountain Research Station, Ogden, Utah. 13 pages.

Pirsko, A.R. 1961. Why tie fire control planning to burning index? Fire Control Notes 22(1): 16-19.

Ponto, R.L. 1989. Bulldozer production rates and guidelines for constructing fireguard in boreal forest covertypes. Canada–Alberta Forest Resource Development Agreement Project #1457-69 Report. Forestry Canada and Alberta Department of Forestry, Lands and Wildlife, Edmonton, Alberta. 59 pages.

Potter, M.W., R.G. Newstead, D. Quintilio and C.Y. Lee. 1981. Forest fire initial-attack planning with a programmable hand-held calculator. Canadian Forestry Service, Forest Management Note No. 10. Northern Forest Research Centre, Edmonton, Alberta. 7 pages.

Pouliot, L. 1991. Forecasting fire weather indices. Environment Canada, Atmospheric Environment Service, Quebec Weather Centre, Montreal, Quebec. 85 pages.

Preece, N., P. Latz, D. O'Byrne, H. Portlock and J. Waithman. 1989. Fire management manual for central Australian parks and reserves. Conservation Commission of the Northern Territory, Alice Springs. 125 pages.

Pyne, S.J. 1984. Introduction to Wildland Fire: Fire Management in the United States. John Wiley and Sons, New York, New York. 455 p.

Quintilio, D. and A.W. Anderson. 1976. Simulation study of initial attack fire operations in the Whitecourt Forest, Alberta. Canadian Forestry Service, Information Report NOR-X-166. Northern Forest Research Centre, Edmonton, Alberta. 35 pages.

Quintilio, D., G. Bisgrove and T. Van Nest. 1985. Aerial igniters provide a new dimension to indirect attack. Pages 71-73 *in* Dubé, D.E. (Compiler). Proceedings of the Intermountain Fire Council 1983 Fire Management Workshop. October 25-27, 1983, Banff, Alberta. Canadian Forestry Service, Information Report NOR-X-271. Northern Forest Research Centre, Edmonton, Alberta.

Quintilio, D., T.A. Van Nest, P.J. Murphy and P.M. Woodward. 1990. Determining production rates of initial attack crews. Pages 105-113 *in* Alexander, M.E. and G.F. Bisgrove (Technical Coordinators). The Art and Science of Fire Management. Proceedings of the First Interior West Fire Council Annual Meeting and Workshop. October 24-27, 1988, Kananaskis Village, Alberta. Forestry Canada, Northwest Region, Information Report NOR-X-309. Northern Forestry Centre, Edmonton, Alberta.

Rawson, R. 1977. A study of the distribution of aerially applied fire retardant in softwood plantations. Forests Commission, Fire Research Branch Report No. 1. Division of Forest Protection, Melbourne, Victoria. 8 pages.

Rees, B. 1983. Retardant distributions from six agricultural aircraft. Forests Commission, Victoria, Fire Research Branch Report No. 16. Division of Forest Protection, Melbourne, Victoria. 9 pages.

Riebold, R.J. 1959. Tractor-plow tactics. Fire Control Notes 20(3): 69-76.

Robertson, P.E. 1989. Efficiency of fire protection programmes in New Zealand. New Zealand Forestry 34(1): 13-16.

Schmidt, R.G. and G.C. Reinhart. 1982. Line production estimating guides for fire behavior fuel models. Fire Management Notes 43(3): 6-9.

Shields, H.J. 1969. Helicopter rotor downwash effects. U.S. Department of Agriculture, Forest Service, Special Report ED&T 1818. Equipment Development Center, San Dimas, California. 13 pages.

Show, S.B. and E.I. Kotok. 1937. Principles of forest-fire detection on the national forests of northern California. Technical Bulletin No. 574. U.S. Department of Agriculture, Forest Service, Washington, D.C. 32 pages.

Smith, E.L. 1984. Simulation modelling for wildfire suppression. Pages 219-228 *in* Mesnard, G. (Editor). Modelling and Simulation. Proceedings of the International AMSE Conference, Volume 4. August 13-17, 1984, Minneapolis, Minnesota. Association for the Advancement of Modelling and Simulation Techniques in Enterprises, Tassin, France.

Sneeuwjagt, R.J. and G.B. Peet. 1985. Forest fire behaviour tables for Western Australia. Third edition. Department of Conservation and Land Management, Perth, Western Australia. 59 pages.

Stechishen, E. 1970. Measurement of the effectiveness of water as a fire suppressant. Canadian Forestry Service, Information Report FF-X-23. Forest Fire Research Institute, Ottawa, Ontario. 12 pages + appendix.

Stechishen, E. 1976. Cascading Fire-Trol 931 fire retardant into a jack pine stand. Canadian Forestry Service, Information Report FF-X-58. Forest Fire Research Institute, Ottawa, Ontario. 18 pages.

Stechishen, E. and G.L. Halicki. 1984. The Dromader M-18 aircraft: its role as an air tanker. Canadian Forestry Service, Information Report PI-X-40. Petawawa National Forestry Institute, Chalk River, Ontario. 22 pages.

Stechishen, E. and E.C. Little. 1971. Water application depths required for extinguishment of low intensity fire in forest fuels. Canadian Forestry Service, Information Report FF-X-29. Forest Fire Research Institute, Ottawa, Ontario. 64 pages.

Stockstad, D.S. 1979. Spontaneous and piloted ignition of rotten wood. U.S. Department of Agriculture, Forest Service, Research Note INT-267. Intermountain Forest and Range Experiment Station, Ogden, Utah. 12 pages.

Storey, T.G., G.W. Wendel and A.T. Altobellis. 1959. Testing the TBM aerial tanker in the Southeast. U.S. Department of Agriculture, Forest Service, Station Paper No. 101. Southeastern Forest Experiment Station, Asheville, North Carolina. 25 pages.

Taylor, D.F. and G.W. Wendel. 1964. Stamper Tract prescribed burn. U.S. Department of Agriculture, Forest Service, Research Paper SE-14. Southeastern Forest Experiment Station, Asheville, North Carolina. 12 pages.

Taylor, J. 1989. Federated Farmers and rural fires. Pages 218-220 *in* Proceedings of the Prevent Rural Fires Convention. May 23-24, 1989, Wellington, New Zealand. Ministry of Forestry, Palmerston North, New Zealand.

Underwood, R.J. and P.E.S. Christensen. 1981. Forest fire management in Western Australia. Special Focus No. 1. Forests Department, Perth, Western Australia. 34 pages.

Van Wagner, C.E. 1965. Aids to forest fire control planning at Petawawa. Canada Department of Forestry, Publication No. 1127. Forest Research Branch, Ottawa, Ontario. 20 pages + maps.

Van Wagner, C.E. 1987. Development and structure of the Canadian Forest Fire Weather Index System. Forestry Technical Report 35. Canadian Forestry Service, Ottawa, Ontario. 37 pages.

Vines, R.G. 1981. Physics and chemistry of rural fires. Pages 129-149 *in* Gill, A.M., R.H. Groves and I.R. Noble (Editors). Fire and the Australian Biota. Australian Academy of Science, Canberra, Australian Capital Territory.

Wade, D.D. and J.D. Lunsford. 1989. A guide for prescribed fire in southern forests. U.S. Department of Agriculture, Forest Service, Technical Publication R8-TP 11. Southern Region, Atlanta, Georgia. 56 pages.

Welsh, J.F. 1965. Backpack mist blower as a fireline builder. Fire Control Notes 26(4): 8-9.

Wiitala, M.R. 1992. IASELECT: Initial attack resource selector user's manual. U.S. Department of Agriculture, Forest Service, Pacific Northwest Region, Aviation and Fire Management, Portland, Oregon. 31 pages + appendix.

Wilson, A.A.G. 1988. Width of firebreak that is necessary to stop grass fires: some field experiments. Canadian Journal of Forest Research 18(6): 682-687.

Wilson, A.A.G. 1992. Assessing fire hazard on public lands in Victoria: fire management needs, and practical research objectives. Department of Conservation and Environment, Research Report No. 31. Fire Management Branch, Melbourne, Victoria.

Wilson, C.C. 1975. Detection and control of forest fires for the protection of the human environment – proposals for a global programme. Food and Agriculture Organization of the United Nations, Rome, Italy. 63 pages.

Wilson, C.C. and J.D. Dell 1971. The fuels buildup in American forests: a plan of action and research. Journal of Forestry 68(8): 471-475.

Wilson, R.A. Jr. 1985. Observations of extinction and marginal burning states in free burning porous fuel beds. Combustion Science and Technology 44(3&4): 179-193.

Wilson, R.A. Jr. 1987. A theoretical basis for modeling probability distributions of fire behavior. U.S. Department of Agriculture, Forest Service, Research Paper INT-382. Intermountain Research Station, Ogden, Utah. 11 pages.