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FIRE BEHAVIOUR MECHANISMS IN A RED PINE PLANTATION: FIELD AND LABORATORY EVIDENCE

by
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ABSTRACT

This paper, a discussion of forest-fire behaviour in a 50-foot-high red pine plantation, is based on both field and laboratory research. Nine experimental fires were observed in the plantation under various weather conditions, on plots up to half an acre in size. About 40 red pine needle fuel beds were burned in the laboratory at various moisture contents and slopes. The fires fitted naturally into three classes: 1) surface fires burning against the wind; 2) surface fires burning with the wind; and 3) crown fires. The general conclusion was that radiant heat is the primary means by which the three types of plantation fire spread, although the mechanism varies from class to class. The main process is radiation through the fuel bed in the first class, from the flames in the second class and through trunk space and crown layer in the third class. Field and laboratory evidence, as well as published material from several sources, was used to develop expressions linking rate of advance and fire intensity in the two classes of surface fire with pertinent variables such as fuel moisture content, fuel weight, flame dimensions, and radiant flux from the burning zone. For one crown fire, a heat balance was drawn between the radiant flux from the flame front and the energy required to preheat the unburned fuel to ignition temperature. It was concluded that the crowning phase in such fires is quite unable to advance by itself and requires convective help from the surface-phase burning zone.

The plantation fires advanced at from 0.4 to 46 cm./sec. (0.8 to 90 ft./min.), and ranged in intensity from 210 to 53,700 cal./sec. per cm. of fire front (25 to 6500 Btu/sec. per foot of front). It was concluded that this range nearly encompasses the fire behaviour to be expected on an area of any size as long as the fires advance in a line. Greater intensities would require intensive fire-spotting or violent turbulence around the fire edge, and could be observed only in large fires.

EXTRAIT

Cette communication - qui traite du comportement des incendies de forêt dans une plantation de Pins rouges hauts de 50 pieds - est étayée sur des recherches effectuées tant sur le terrain qu'en laboratoire. Sous diverses conditions atmosphériques, 9 feux ont été expérimentalement observés dans des places-échantillons contenant jusqu'à une demi-acre. Quarante litières d'aiguilles prélevées sous des Pins rouges (*Pinus resinosa* Ait.) ont été brûlées en laboratoire: leur teneur en humidité - qui variait de 0 à 26 p. 100 - a été enregistrée, de même que la pente de la cuvette qui les contenait. Les feux se sont rangés dans trois classes: 1) feux de surface brûlant contre le vent; 2) feux de surface brûlant avec le vent et 3) feux de cime. La conclusion générale en découlant est que la chaleur radiante constitue le moyen essentiel d'expansion des trois types d'incendie de plantation, encore que leur mécanisme varie d'une classe à l'autre. Le principal processus est la radiation à travers la couche de combustible pour la première classe, à partir des flammes pour la seconde, et d'un arbre à l'autre pour la troisième. Les données recueillies en forêt et au laboratoire, de même que celles tirées des publications de maintes provenances, ont servi à l'élaboration des rapports entre le taux de propagation et l'intensité de l'incendie dans les deux classes de feu de surface comportant des variables pertinentes telles que teneur en humidité et poids du combustible, les dimensions des flammes et la radiance du foyer de l'incendie. Dans un feu de cime, un équilibre calorifique s'est établi entre le flot rayonnant du front de l'incendie et l'énergie requise pour porter le combustible non brûlé à la température d'incandescence. D'où la conclusion que les feux de cime ne peuvent se propager sans la convection provenant du feu de surface.

Les feux de plantation se propageaient à raison de 0.4 à 46 cm/sec (0.8 à 90 pieds/min.) et leur intensité variait de 210 à 53,700 calories/sec par cm de tête de feu (25 à 6500 Btu/sec par pied de tête de feu). Il en a été conclu que cette gamme englobe le comportement de tout feu susceptible de se manifester dans une aire de quelque étendue que ce soit, en tant que les feux se propagent en ligne. De plus grandes intensités impliqueraient l'énergie supplémentaire fournie par des feux disséminés ou par une violente turbulence (remous d'air) autour du champ de l'incendie, et ne pourraient s'observer qu'en cas de feux très grands.

FIRE BEHAVIOUR MECHANISMS IN A RED PINE PLANTATION: FIELD AND LABORATORY EVIDENCE

by

C.E. Van Wagner[1]

INTRODUCTION

Research on the behaviour of forest fires varies from simple observation of natural fires and their burning conditions to model laboratory studies of combustion principles and mechanisms of fire advance. So far, however, theories developed in the laboratory have received little testing in controlled field research. It ought, therefore, to be possible to make useful advances in forest fire behaviour science by combining laboratory and field approaches in the same project. This paper is an account of one such effort made with the aim of defining fire behaviour in a red pine (*Pinus resinosa* Ait.) plantation and determining the mechanisms of advance at various levels of fire intensity. The work was done at Petawawa Forest Experiment Station, Chalk River, Ontario.

The ultimate aim of all research on forest fire behaviour is the better control of forest fires. One obvious way to achieve this is to develop satisfactory means of predicting fire behaviour.

The problem of predicting fire behaviour is solved in several stages. The first of these is the adequate objective description of forest fire in terms that are directly related to suppression effort and fire effect. The second stage is the choice and definition of the important fuel and weather variables affecting fire behaviour. The list of all factors known to have some effect on forest fires is, however, hopelessly long. The chances of choosing the ones that really matter are much improved if the physical mechanisms important in forest fires can be identified. The third stage, the actual correlation of fire behaviour with burning conditions, can then be carried out with better assurance.

Granted that fires can be observed, described, and understood, a major stumbling block to prediction remains, namely, the difficulty of

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describing the fuel in some valid way. The immense natural variation in forest type and topography poses a formidable problem. The red pine plantation chosen for this work provided simple, uniform fuel conditions. It could almost be described as an outdoor fire laboratory.

In all, nine experimental fires have been conducted in the red pine plantation, ranging from gentle surface fires to full-fledged crown fires. In addition, the experience gained with some 25 fires in natural stands of red, white, and jack pine is drawn upon indirectly. Laboratory work consisted in burning small fires in a tray 48 by 30 inches in size, some horizontal, some sloped at varying degrees. The literature on laboratory fire research was studied, and appropriate acknowledgement is made of several ideas used in the present work.

The principal sections of this paper are, first, a description of the fuel complex in the red pine plantation and the fires burned in it, second, a discussion of the three classes of fire observed and their propagation mechanisms and, third, some comments on prediction of fire behaviour in the plantation.

In most of the paper the Metric System of units is used, but some tables contain data in both the English and the Metric systems. Some compound quantities important in fire research are listed in Table 1 with their English-Metric equivalents.

TABLE 1. ENGLISH - METRIC EQUIVALENTS FOR SOME QUANTITIES IMPORTANT IN FOREST FIRE RESEARCH.

Fuel weight per unit area:	1 lb./ft.^{2} = 21.8 ton/acre = 0.488 gm./cm.^{2}
	1 gm./cm.^{2} = 2.05 lb./ft.^{2} = 44.7 ton/acre
Heat of combustion:	1 Btu/lb. = 0.556 cal./gm.
	1 cal./gm. = 1.80 Btu/lb.
Rate of advance:	1 ft./min. = 0.91 chain/hr. = 0.508 cm./sec.
	1 cm./sec. = 1.97 ft./min. = 1.79 chain/hr.
Wind speed:	1 mph = 88 ft./min. = 0.447 m./sec.
	1 m./sec. = 2.24 mph = 197 ft./min.
Energy transfer rate per unit area:	10,000 Btu/ft.^{2}-hr. = 0.754 cal./cm.^{2}-sec.
	1 cal./cm.^{2}-sec. = 13,300 Btu/ft.^{2}-hr.
Energy output rate per unit length of front or	
Forward energy transfer rate per unit length of front:	1 Btu/sec.-ft. = 8.26 cal./sec.-cm.
	1 cal./sec.-cm. = 0.121 Btu/sec.-ft.

TABLE 2. PLANTATION CHARACTERISTICS, SHOWING RANGE OF VARIATION AMONG PLOTS.

	English units	Metric units
Total height	40 to 50 ft.	12.2 to 15.2 m.
Height to live crown	20 to 30 ft.	6.1 to 9.2 m.
Depth of live crown	18 to 24 ft.	5.5 to 7.3 m.
Basal area	175 to 250 $ft.^2$/acre	40 to 58 $m.^2$/hectare
Average tree diameter	5.2 to 6.2 in.	13.2 to 15.7 cm.
Number of trees	1140 to 1420 trees/acre	2820 to 3500 trees/hectare

THE PLANTATION AND ITS FUEL

The red pine plantation chosen for the outdoor fires was 40 to 50 feet (12 to 15 metres) high and contained about 1200 trees per acre (300 per hectare). More detailed data are in Table 2. The forest floor was a layer of pine needles 2½ inches (6.3 cm.) thick, the upper ½ inch (1.3 cm.) being fresh litter and the rest partially decomposed duff. No green surface vegetation was present. The total fuel available for burning amounted to about 24 tons per acre (54 metric tons per hectare), of which half was green foliage. This fuel was arranged in several distinct layers; from the ground upward these were duff, litter, loose bark and dead branches on the lower trunks, and green foliage. Their respective weights and bulk densities are listed in Table 3.

TABLE 3. AVERAGE FUEL QUANTITIES AND ARRANGEMENT FROM CROWN DOWNWARD.

Fuel component	Weight, dry (tons/acre)	Weight, dry ($lb./ft.^2$)	Weight, dry ($gm./cm.^2$)	Vertical depth (cm.)	Bulk density ($gm./cm.^3$)
Live crown foliage	10.0	.46	.22	700	.00032
Dead branches	1.0	.046	.022	-	-
Loose bark	0.3	.013	.006	-	-
Litter	1.3	.060	.029	1.4	.021
Duff	11.2	.515	.25	5	.05
Total	23.8	1.09	.53		

The litter layer in such a plantation, being open in structure and well exposed, dries within a day or two after rain, and its moisture content adjusts fairly well to daily changes in relative humidity. The underlying duff layer, denser and less exposed, requires many days to dry after a heavy rain; meanwhile a fire will consume the litter layer only. Usually, only when the duff layer becomes dry enough to burn will the fire attain sufficient intensity to involve the crown fuel. The loose bark and dead branches contribute little weight on an area basis but serve to make each tree a flaming column in intense fires. The foliage is the only material that burns in the crowns, and it is interesting to note that its bulk density in the crown space is about one hundredth of that of the surface fuel (Table 3).

PROCEDURES

Laboratory

Red pine needles collected in late autumn were burned on an asbestos pad in a tray 48 inches long, 30 inches wide and 2 inches deep under a smoke hood equipped with an exhaust fan. Separate lots of needles were adjusted to various moisture contents from zero to 26 percent. The lower values were obtained by oven-drying at various temperatures, the higher values by conditioning with added water for several days. Moisture-content samples were taken immediately before ignition, which was made across one end of the tray. Temperatures on the surface were measured with 30-gauge chromel-alumel thermocouples, and thermal radiation from both the burning zone and the flames with a radiation pyrometer. All laboratory fires were burned in fuel beds 3 centimetres thick (about twice the depth of natural litter) containing 0.06 gm. $cm.^{-2}$ of fuel with a bulk density of 0.02 gm. $cm.^{-3}$ (the same as natural litter).

For some fires the tray was tilted at various angles up to 35° from horizontal. In this way increased rates of advance could be obtained without a wind tunnel.

Field

Plots of two sizes were laid out, 75 feet square (0.13 acre = 0.05 hectare) and about 100 by 200 feet (0.46 acre = 0.19 hectare). Fire guards were constructed around them and the interiors staked with a grid system. Plots were burned on different days at various degrees of fire danger. Standard weather readings required for determination of the Forest Fire Danger Index (Anon., 1956) were taken daily and during the fires. Instruments were set up on the day chosen for each fire, and samples for moisture-content determination were taken just before lighting. The fires were first set in a line along one side of the plot and sometimes on another side as well. Rate of spread was measured by timing the arrival of the fire at the various grid points. Fuel weight was sampled by categories before the fire and again shortly after. Temperature was measured with 20-gauge thermocouples and recorded automatically on strip charts. Six thermocouples were suspended in a vertical set from ground level to 33 feet (10 metres) above. Radiation emitted by the fire was measured with a hand-held radiation pyrometer. Wind speed was recorded continuously around each fire with four Casella sensitive anemometers mounted 4 feet (1.2 metres) above ground. Finally, each fire was photographed in several stages. Figures 1 to 9 illustrate the different classes and intensities of fire encountered. In all of them except Figure 9 the fire is shown as advancing from right to left.

FIRE DESCRIPTION AND CHARACTERISTICS

The principal terms used here to describe fire behaviour are (a) linear rate of advance and (b) fire intensity, or energy output rate per unit length of fire front. The fire front is assumed to be at right angles to the direction of advance. Rate of advance is given simply as feet per minute or centimetres per second, fire intensity as Btu's per second per foot of fire front or as calories per second per centimetre of fire front. Energy output is computed according to Byram (1959) with the formula:

$$I = H\,w\,R \qquad (1)$$

where I is energy output rate per unit length of front, cal. $sec.^{-1}$ $cm.^{-1}$

H is heat of combustion, cal. $gm.^{-1}$

w is fuel consumed, gm. $cm.^{-2}$

R is rate of advance, cm. $sec.^{-1}$.

Byram (1959) estimates the natural range of fire intensity at from 40 to 250,000 cal. $sec.^{-1}$ $cm.^{-1}$. Most of this immense range is contributed by the rate of advance, which can vary about 100-fold. The weight of fuel consumed varies about one tenth as much, while the heat of combustion is relatively constant among forest fuels.

In this paper, the low heat of combustion was used, i.e., energy required to vaporize water of reaction was presumed lost. The basic value of H was taken as 4430 cal. $gm.^{-1}$, reduced slightly for the actual moisture content in each fire. No reduction was made for the energy radiated; I thus represents the total heat output.

Additional data presented, when available, are (a) flame length, depth and angle, (b) radiation emitted by flame or burning zone, and (c) temperature profiles. At some of the earlier fires these properties were not measured. All fires were intended to burn with straight fronts at right angles to the direction of advance; in most cases the intention was realized well enough for practical purposes.

The 22 horizontal laboratory fires are described in Table 4 in order of increasing rate of advance. They all burned either in still air or against a very light air current, with flames tilted 10 to 45 degrees away

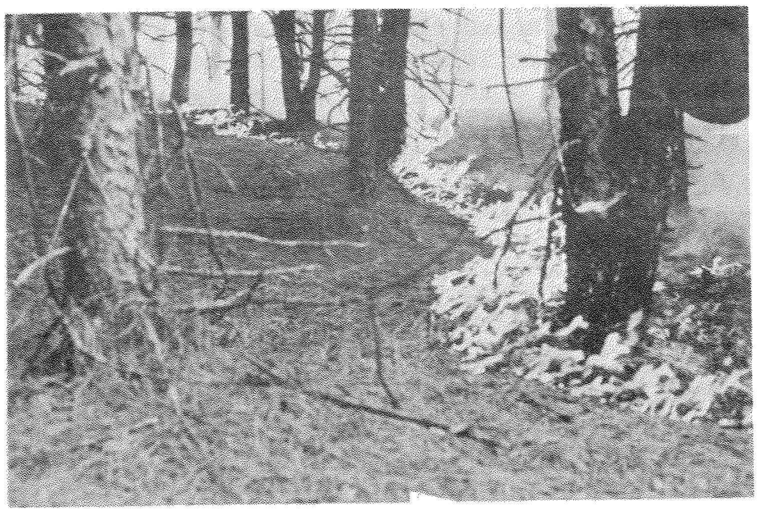

Figure 1. Typical backfire burning against gentle wind.

Figure 2. Fire burning in still air.

Figure 3. Surface headfire of moderate intensity.

Figure 4. Surface headfire shortly before crowning.

Figure 5. Fire in process of crowning

Figure 6. Side view of crown fire C4 burning steadily with no turbulence visible.

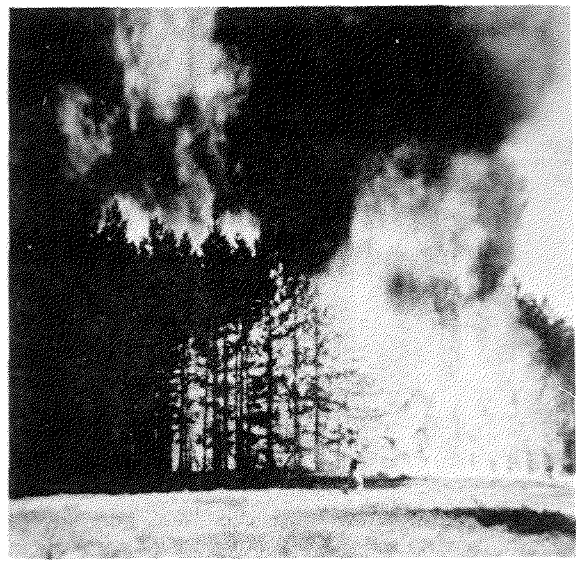

Figure 7. Side view of crown fire C6 at maximum development just before it dropped to ground because of wind shift. Note figure in middle foreground.

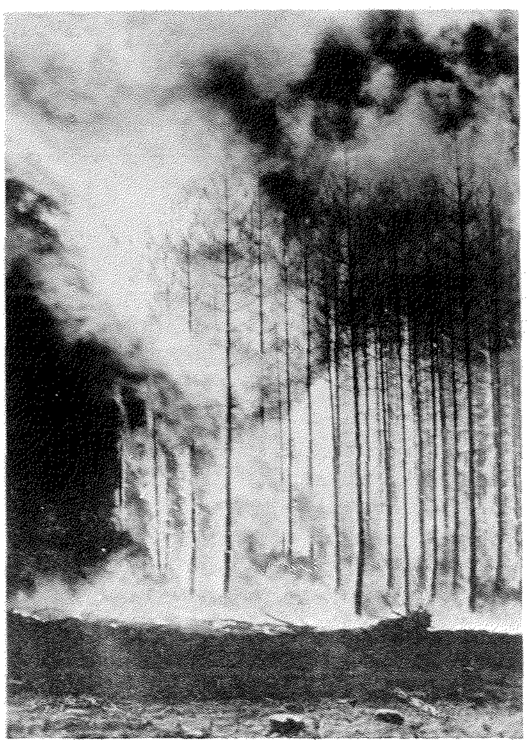

Figure 8. Crown fire burning out at end of plot.

Figure 9. Rear view of crown fire lit along near edge of plantation. Note seated figure at lower right.

TABLE 4. BEHAVIOUR OF LEVEL LABORATORY FIRES IN BEDS OF RED PINE NEEDLES 3 CM. DEEP, WEIGHING 0.06 GM./CM.^{2} AND WITH BULK DENSITY 0.02 GM./CM.^{3}.

Fire No.	Moisture content (%)	Rate of advance (cm./sec.)	Energy-output rate (cal./sec.-cm.)	Max. surface temperature (°C)[1]	Flame length[2] (cm.)	Width[2] of burning zone (cm.)
1	23.3	0.137	36	730	13	6
2	22.7	0.153	40	870	13	-
3	26.2	0.178	46	650	13	-
4	20.0	0.183	48	870	18	8
5	25.0	0.193	50	870	15	10
6	18.6	0.193	51	820	18	-
7	17.4	0.224	58	870	20	9
8	18.3	0.228	59	870	18	-
9	13.3	0.234	62	820	18	10
10	15.8	0.249	66	900	20	-
11	15.2	0.259	68	820	20	-
12	14.4	0.274	72	620	23	10
13	13.5	0.274	72	870	25	10
14	11.9	0.295	78	840	28	11
15	9.8	0.320	85	900	-	-
16	7.6	0.346	92	840	30	14
17	8.2	0.361	96	-	25	10
18	7.5	0.381	101	700	25	15
19	4.2	0.437	116	820	25	-
20	1.7	0.490	132	870	35	-
21	0	0.554	147	820	30	20
22	0	0.590	157	800	35	-

[1]Thermocouple (30-gauge) not corrected for radiation loss.

[2]Measured roughly with a scale.

from the direction of advance; there was no evidence that variation in flame angle affected the rate of advance. These fires achieved reasonable equilibrium for about 3 feet of their travel distance.

Behaviour data of the sloped laboratory fires are listed in Table 5. These fires leaned toward the fuel bed, with the result that the flame angle - i.e. the angle between flame and unburned fuel - was lower than that suggested by the slopes.

The outdoor plantation fires are described in two tables. Table 6 gives information about burning conditions, rate of advance and energy output, while Table 7 contains the available data on flame dimensions, radiation, and temperature. The R series of fires was on plots 75 feet square, the C series on plots 100 by 200 feet. In some cases both headfire and backfire data were obtained from the same fire. The most striking result was the 250-fold range in fire intensity (Figures 1 and 7), expressed by the energy output rates listed in Table 6. The question arises whether all these fires reached equilibrium behaviour on the small areas provided. Since the surface fires burned with straight fronts and reasonable stability for periods of 5 to 20 minutes, it is safe to assume that they did attain equilibrium. The crown fires, however, showed an obvious tendency toward higher intensity down the centre. Although crown fire C4 burned fairly steadily for about 2 minutes, R1 and C6 were possibly still increasing in intensity when they were stopped. Evidently crown fires in the plantation may require plots larger than 100 by 200 feet for equilibrium behaviour.

The thermocouple temperatures reported in Tables 4 and 7 require some interpretation. Thermocouples in hot gas are subject to error by radiation loss to cooler surroundings. Rough calculation of this error places the laboratory values about 100°C too low. Errors in the less intense outdoor fires should then be about three times as great, since thermocouples three times as thick were used in the field. In the most intense field fires, with their thick flames, the quoted values should be nearly correct. It is thus probable that the maximum temperatures in all fires were of the same order, namely, about 1000°C. The chief value in the temperature-profile records lies in their ability to describe the shape and extent of the burning zone.

The plantation fires fall readily into three classes: surface backfires (burning against the wind), surface headfires (burning with the wind), and crown fires. Obviously not observed here was the fourth and most extreme class of fire behaviour, which is dominated by intensive fire-spotting or massive turbulence. Apart from the tremendous differences in fire intensity, there were obvious differences from class to class in structure and in sensitivity to external burning conditions. The level laboratory fires clearly belong to the surface backfire class, and the sloped laboratory fires to the surface headfire class.

TABLE 5. BEHAVIOUR OF LABORATORY FIRES IN SLOPED PINE NEEDLE BEDS OF MOISTURE CONTENT 10 PERCENT. AVERAGES OF TWO FIRES AT EACH SLOPE.

Slope of bed[1] (deg.)	Flame angle[2] (deg.)	Flame length (cm.)	Rate of advance (cm./sec.)	Energy-output rate (cal./sec.-cm.)	Radiation from[3] flame (cal./cm.-sec.)	Calculated efficiency factor e[4]
0	90	20	0.326	86	0.6	0.43
5	85	25	0.393	104	0.7	0.32
10	80	25	0.425	112	0.7	0.29
15	70	30	0.598	158	0.8	0.36
20	55	35	0.884	234	0.8	0.38
25	45	45	1.16	300	1.0	0.43
30	35	75	2.20	580	1.0	0.43
35	25	90	4.06	1070	1.1	0.37

[1]Angle between bed and horizontal.

[2]Angle between flame front and unburned fuel.

[3]Measured with radiation pyrometer parallel to fuel bed.

[4]Efficiency of fuel preheating process based on radiation from flame and through fuel bed.

TABLE 6. BURNING CONDITIONS, RATES OF ADVANCE, AND ENERGY OUTPUT RATES ON THE RED PINE PLANTATION FIRES.

Fire No. and type	Burning conditions						Fire behaviour					
	Fire Danger Index	Fuel Moisture content (%)			Wind at 4-ft. level		Fuel consumed		Rate of advance		Energy-output rate	
		Litter	Duff	Crown foliage	mph	m./sec.	lb./ft.^{2}	g./cm.^{2}	ft./min.	cm./sec.	Btu/ sec.-ft.	cal./ sec.-cm.
Backfires												
R1	14	10	54	-	-[1]	-	0.22	0.11	0.8	0.4	25	210
C2	11	14	54	-	-	-	0.23	0.11	1.0	0.5	31	260
R2	11	12	25	-	-	-	0.27	0.13	1.1	0.6	40	330
R5	9	4	40	-	-	-	0.30	0.15	1.4	0.7	52	430
Headfires												
C1	10	17	48	-	1.3	0.58	0.21	0.10	3.4	1.7	92	760
R2	11	12	25	-	1.5	0.67	0.28	0.14	3.1	1.6	116	960
C2	11	14	54	-	1.3	0.58	0.23	0.11	4.1	2.1	122	1010
R4	8	13	62	-	2.0	0.89	0.20	0.10	5.0	2.5	132	1090
R5[2]	9	4	40	-	1.7	0.76	0.30	0.15	6.6	3.4	260	2150
R3	13	9	60	-	3.7	1.65	0.27	0.13	20	10	710	5860
Crown fires												
R1	14	10	54	100	3.1	1.38	0.45	0.22	35	18	2100	17300
C4	16	12	24	135	3.4	1.52	0.91	0.44	55	28	6100	50500
C6	16	12	66	95	3.8	1.70	0.58	0.28	90	46	6500	53700

[1]Winds against fire or very light.

[2]Trees removed during previous winter to allow sun to reach litter surface.

TABLE 7. FLAME DIMENSIONS, RADIATION AND TEMPERATURE OF SOME FIRES FROM TABLE 6.

Fire No. and type	Energy-output rate (cal./sec.-cm.)	Fire dimensions[1] (m.)		Emitted flame radiation (cal./cm.$^{-2}$ sec.)	Max. Temperature,[2] °C at several heights (metres) above ground			
		Length of flame	Width of burning zone		Surface	0.3	5	10
<u>Backfire</u>								
C2	260	0.3	0.15	0.5	600	240	50	25
<u>Headfires</u>								
C1	760	0.6	0.5	1.4	760	650	60	40
C2	1010	0.6	0.6	1.3	-	-	-	-
R5	2150	1	1.5	1.5	-	-	-	-
R3	5860	2.5	3	1.8	-	-	-	-
<u>Crown fires</u>								
R1	17300	15	8					
C4	50500	21	14	2.8	860	955	560	780

[1]Estimated during fires and from photographs.

[2]Measured with 20-gauge thermocouples. Values in low intensity fires probably below true temperatures owing to radiative loss from thermocouple to cool surroundings.

MECHANISMS OF ADVANCE

General

The basic premise in considering mechanisms of fire propagation is that a fire must transfer ahead of it enough thermal energy to preheat the unburned fuel to a state in which it can be ignited by the approaching flames. Energy is first required to heat the moist fuel, then to evaporate the free water, and finally to heat the dry fuel to ignition temperature. Simms (1964) gives 300°C as the surface temperature at which the escaping flammable gases can be ignited. Allowing reasonable values for several constant factors, and assuming that the free water is driven off at boiling point, the following equation can be deduced to express the effect of fuel moisture on the energy required for ignition:

$$h = 110 + 620\,m. \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

where h is the energy required in cal. $gm.^{-1}$ and

m is moisture-content fraction in gm. moisture per gm. of dry fuel.

There are four basic possible modes of heat transfer in a forest fire: spotting ahead by the transport of flaming brands, conduction, convection, and radiation. The fires in question were not affected appreciably by spotting, and conduction is commonly discounted as too slow to be of importance in transferring heat through a porous fuel bed. The remaining discussion of the experimental fires will deal with the possible roles of convection and radiation in the forward transfer of heat. Each of the three classes of fire observed will be discussed in turn.

Surface Backfires

Fires burning in windless conditions or against the wind are, for many natural fuel beds, of sufficiently low intensity to be modelled directly in the laboratory without any problems of scale reduction (Figures 1 and 2). Consequently there are several good published studies on this class of fire, with general agreement on its mechanism of propagation.

Thomas *et al.* (1964) first proposed radiative heat transfer through the fuel bed as the dominant mechanism in wood cribs and fine fuels burning in the absence of wind. This concept was further analyzed and developed from data on wood crib fires (Thomas, 1964, and Thomas *et al.*, 1965), the result being this simplified relation linking the rate of advance with the pertinent variables:

$$Rdh = i - C \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (3)$$

where R is rate of advance, cm. $sec.^{-1}$

d is bulk density of fuel bed, gm. $cm.^{-3}$

h is required energy for ignition, cal. $gm.^{-1}$

i is horizontal radiation through fuel bed, cal. cm.$^{-2}$ sec.$^{-1}$

C is rate of energy loss by cooling during preheating, dependent on nature of fuel particles and bulk density.

Fang (1966) also performed a theoretical analysis, treating radiative heat transfer through the fuel bed and bulk density (or void fraction) as the main factors and, with the evidence of a series of fires in beds of wood excelsior, reached a similar conclusion. McCarter and Broido (1965) and Byram *et al.* (1966) present the same picture. Anderson (1964) showed that the rate of advance in pine needle litter does not increase at depths over 1.5 inches. Beaufait (1965) burned laboratory fires against the wind in beds of pine needles and reported that varying wind velocity has little effect on the rate of advance; general observation of field backfires confirms this principle. All references agree that radiation from overhead flame plays a minor role in propagating backfires.

The main purpose of the level laboratory fires was to investigate the effect of moisture content throughout its practical range. Figure 10 shows the rate of advance in the level laboratory fires plotted against moisture content. A straight line would apparently do justice to most of these data, and, indeed, several of the aforementioned workers have assumed straight-line relationships over narrow moisture ranges. However, Thomas' formula (Expression 3) predicts that the rate of advance R shall have a curvilinear relationship to the energy h required for ignition, which in turn depends directly upon moisture content m. The rate of advance was accordingly replotted against h (calculated from Expression 2) also in Figure 10. Included in the graph for comparison is a hypothetical curve of rate of advance that assumes a net forward heat transfer rate of 1 cal. cm.$^{-2}$ sec.$^{-1}$ through the vertical plane of the burning fuel bed. The data, as can be readily seen, match this curve better than they match any straight line. It is also obvious that the data, although they cover the full range of moisture content that will support fire in such a fuel bed, occupy a part of the curve with relatively little curvature. The extreme inner part of the curve is, of course, never observed in nature, being outside the limit imposed by the energy required to ignite dry fuel.

The curve drawn in Figure 10 assumes a rate of heat transfer i through the fuel bed independent of moisture content; actually, i ought to be slightly lower at high moisture content owing to expected lower temperatures and narrower burning fronts. However, the temperatures reported in Table 4 seem to be independent of moisture content. Also, repeated readings of the radiation emitted by the burning zone, with the radiation pyrometer held obliquely in front of the fire, produced values of from 1.0 to 1.3 cal. cm.$^{-2}$ sec.$^{-1}$ without any observable variation with moisture content. Nevertheless, a curve calculated by allowing (i-C) to increase gradually from 0.9 to 1.1 cal. cm.$^{-2}$ sec.$^{-1}$ with decreasing moisture content would fit the data in Figure 11 almost exactly. With temperatures of at least 800°C in the burning zone (Table 4), the emitted radiant intensity of 1.0 cal. cm.$^{-2}$ sec.$^{-1}$ implies an emissivity of about 0.5, which seems reasonable.

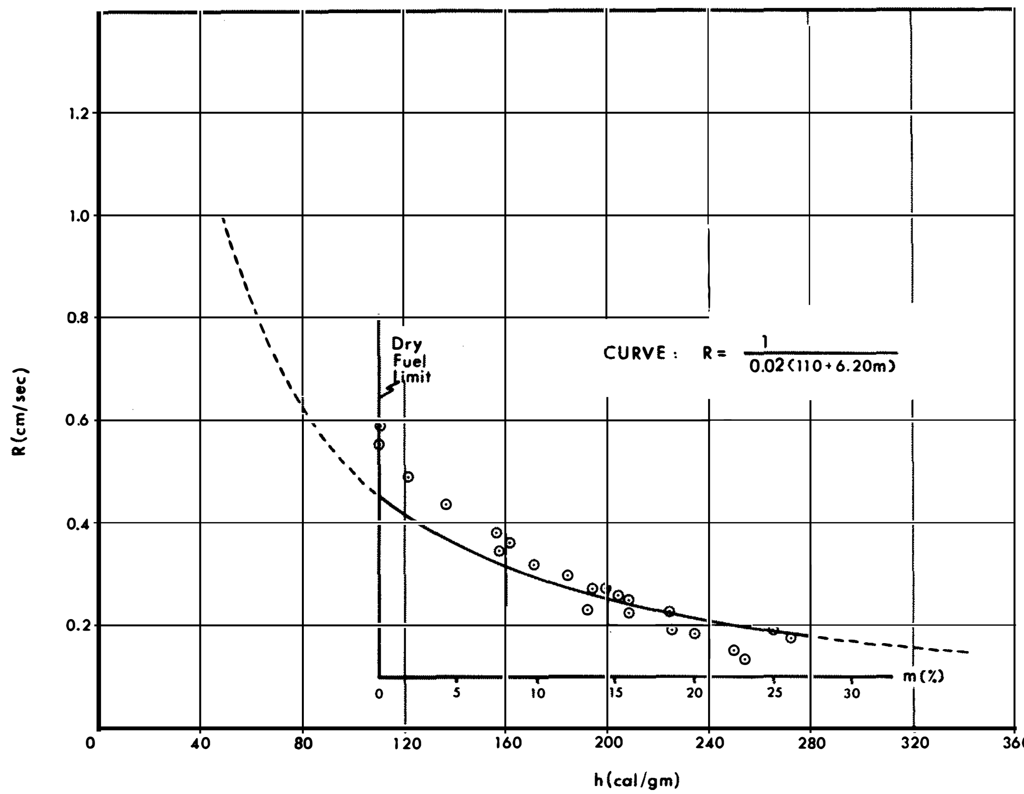

Figure 10. Level laboratory fires. Rate of advance R plotted against moisture content m, and against energy h required to heat fuel to ignition temperature. Hypothetical curve assumes heat transfer rate of 1.0 cal. cm.$^{-2}$ sec.$^{-1}$ through fuel bed.

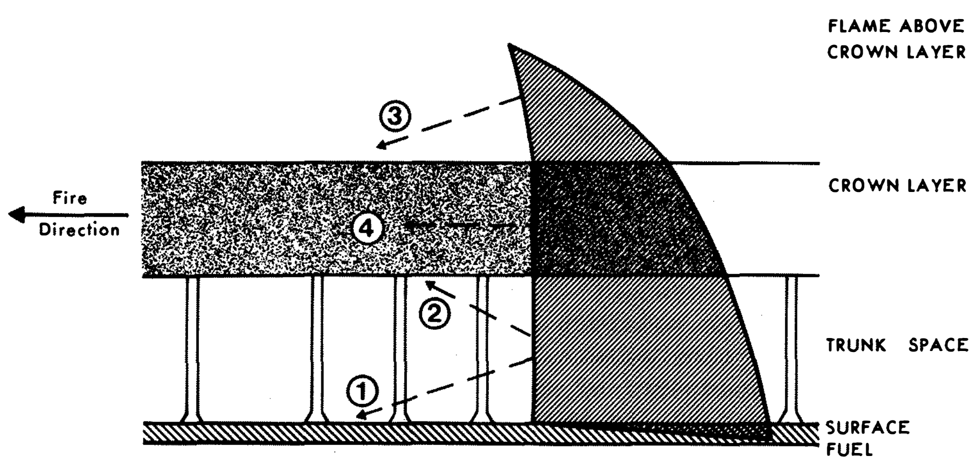

Figure 11. Diagram of crown fire C4 showing four components of radiation forward. Trunk space flame radiates (1) to surface fuel and (2) to crown fuel. Flame above crown radiates (3) to crown layer and flame within crown layer radiates (4) through crown layer.

The rates of advance in the field backfires were slightly faster than in the laboratory fires of apparent equal moisture content. It is difficult, however, to estimate true moisture content or bulk density of fuel burning in the field, since continuous gradients exist from the litter down through the duff. The greater intensities of the field backfires were mainly due to greater fuel consumption.

Although the effect of moisture content on the rate of advance of backfires has been well established, the question of just how the necessary energy is transferred through the fuel bed is still partly open. Thomas *et al.* (1965) estimate the cooling loss in crib fires at 0.24 cal. cm.$^{-2}$ sec.$^{-1}$, just enough to account for the difference between the observed emitted radiation from the burning zone in the present fires and the calculated necessary heat transfer rate. Fang (1966) measured the incident radiation 1 inch ahead of the burning zone in a fuel bed of wood excelsior and found only 0.23 cal. cm.$^{-2}$ sec.$^{-1}$, not enough to account for the required total in his fires. He concluded that local convection at the burning front supplied most of the rest.

In the present experiment, a simple radiometer inserted upright in a pine needle bed 6 centimetres deep gave recordings of about 0.46 cal. cm.$^{-2}$ sec.$^{-1}$ just in front of the burning front. Direct measurement of this quantity is difficult, since the radiometer must react with great speed to follow the rapidly increasing incident radiation intensity as the fire approaches. These measurements are undoubtedly on the low side, and it is safe to conclude that the greater proportion of the heat transfer through the fuel bed is by radiation. Thomas' concept possibly breaks down at very high and very low bulk densities but is quite adequate for the range of interest here.

Some general remarks about surface backfires in pine needle beds can be made:

(1) They are affected by wind only slightly as long as they burn against it.

(2) They are directly affected by the structure and bulk density of the fuel bed, and compaction of the litter layer as the season progresses should reduce the rate of advance.

(3) They are directly affected by fuel moisture, the inverse of the rate of advance being proportional to moisture content.

(4) Theoretically, their rate of advance is not affected by the weight of fuel consumed or fire intensity, as long as the flames do not become long and thick enough to radiate appreciably ahead of the fire. That is, at a given moisture content, the thickness and weight of the fuel bed, within reasonable limits, should have little effect, and rate of advance should depend on bulk density alone.

(5) Surface backfires in such fuels exhibit a very modest range of behaviour and, of all the kinds of forest fires, are the simplest and most predictable.

Surface Headfires

Since surface headfires may advance at rates far beyond the upper limit possible by heat transfer through the fuel bed, the necessary forward heat transfer must be accomplished by the overhead flame. Basically, there are two possibilities: random contact by horizontal tongues of flame ahead of the fire, and radiation from the flame front. Some visual evidence on these is presented first.

On several occasions, the effect of a sudden increase in wind velocity on a low-intensity fire was observed. The small flames were immediately flattened and spread out so as to deepen the burning zone many times. During this phase the flames licked directly at the surface of the unburned fuel. As the intensity increased, however, they stood more upright; once fully developed, they rose at a steep angle. This phenomenon might be expected, since the angle of flame tilt in a given wind depends mainly upon the upward momentum of the rising gases within the flame; as this quantity increases, the wind should have less and less effect on the flame angle. As the flames deepened, their radiant intensity increased several times over (Table 7), and their increased length provided a greater radiating surface. At the same time, there was neither visual nor photographic evidence of random tongues of flame at surface level. Rather, the fully developed flames made a clean, sharp angle with the unburned fuel (Figures 3,4 and 5). It is thus difficult to escape the conclusion that the mechanism of heat transfer in such fires is essentially one of flame radiation.

The rates of advance and the energy outputs of the surface headfires were very sensitive to wind speed (Table 6). The effect of wind on the spread of fire in wood cribs has been studied in the laboratory (Thomas, 1965a, and Byram *et al.*, 1966), but the mechanism is apparently quite different from that in surface headfires in pine litter. Thomas (1965a) demonstrated that crib fires in wind spread by radiation from the inclined burning front within the crib, overhead flame radiation being unimportant; such a mechanism predicts only a 20 percent increase in rate of advance from the level to a 35° slope. Wood cribs are obviously an inadequate laboratory model for wind-driven or sloped fires in thin beds of fine fuel.

Rothermel and Anderson (1966) and Beaufait (1965) report the behaviour of headfires in pine needle beds in a wind tunnel. Although the narrow width of their fuel beds (18 inches) precludes the full effect of flame radiation, these authors suggest this mechanism as being one of the reasons for the increased rate of advance with wind. Energy-output rates of up to 800 cal. sec.$^{-1}$ cm.$^{-1}$ were attained by Beaufait, and 2000 cal. sec.$^{-1}$ cm.$^{-1}$ by Rothermel and Anderson (estimated from their data in each case). The latter authors obtained solid evidence of a temperature rise in the fuel before the arrival of the flames.

If the qualitative evidence points to flame radiation, it should be possible to develop some quantitative theory to test against the laboratory and field data. In a recent paper (Van Wagner, 1967), a simple expression was derived for the total radiation received by a horizontal element of fuel surface as a flame approaches and engulfs it:

$$Q = \frac{iL}{2R} (1 + \cos A) \quad \text{.............................} \quad (4)$$

where Q is total radiation received, cal. $cm.^{-2}$

i is radiation intensity emitted by flame surface, cal. $cm.^{-2}$ $sec.^{-1}$

L is flame length, cm.

R is rate of advance, cm. $sec.^{-1}$

A is angle between flame front and unburned fuel.

By equating Q with h, the energy required for ignition (Expression 2), a formula linking rate of advance R with flame length and angle, flame radiation intensity, and fuel moisture content can be readily derived:

$$R = \frac{eiL\ (1 + \cos A)}{2w\ (110 + 620\ m)} \quad \text{...........................} \quad (5)$$

where e is the efficiency of the fuel-preheating process. This expression depends on several assumptions that simplify what is probably a very complex phenomenon. These are: (a) flame radiation is the sole means of forward heat transfer; (b) the flame extends in a straight line with a frontal surface of uniform height; (c) radiation is emitted uniformly from the flame's whole surface; (d) the fuel is a smooth, thin layer heated uniformly throughout its depth; and (e) cooling losses from the fuel surface are incorporated, with the radiation absorptivity of the fuel, into an efficiency factor assumed constant for the fuel bed.

Several researchers have shown that flame length L is proportional to a fractional power of the energy-output rate, or fire intensity. Expression 5 can thus be carried a step farther by substituting for L a term of the form kI^n, in which n is a fractional exponent and k a constant. Thomas (1963) and Anderson *et al.* (1966) both assign n a value of 2/3, which fits the data in Tables 3 and 6 fairly well. If the heat of combustion H is assumed constant and it is recalled from Expression 1 that I = HwR, then the following expression results:

$$(wR)^{1/3} = \frac{kie\ (1 + \cos A)}{2\ (110 + 620\ m)} \quad \text{......................} \quad (6)$$

in which k = 1.1 in the metric units used here.

Plainly R is in very delicate balance, since changes in any of the factors on the right side of Expression 6 are magnified to the power 3 in the resulting value of R. Since these factors are interdependent, there may be a compounding effect as well. Furthermore, the faster the fire advances, the thicker the burning zone becomes, and the less is the fuel per unit area that need be preheated by flame radiation before the fire front arrives.

The remaining fuel can be heated and ignited within the burning zone, as described by Byram *et al.* (1966).

Thomas (1965b) undertook a more rigorous analysis of the flame radiation mechanism and described mathematically the transition from a regime of radiation within the fuel bed to one of flame radiation above the fuel bed. He predicted three stages of fire spread by flame radiation: (1) a "thin-flame" stable equilibrium with rate of advance about twice that due to fuel-bed radiation alone; (2) a zone of instability in which the rate of advance may fluctuate widely; and (3) a "thick-flame" stable equilibrium with rate of advance many times the "thin-flame" level. Observation of many experimental fires, including the plantation fires of Table 5, suggests that Thomas' three-stage pattern is indeed found in nature. Surface headfires advancing at about 2 cm. sec.$^{-1}$ are common with light winds in pine stands and appear quite stable. A stronger wind results in headfires that advance at 5 to 10 cm. sec.$^{-1}$, like R5 and R3 in Table 6. These headfires appear very sensitive to slight changes in wind or fuel. The fast-spreading stable equilibrium cannot be observed on the surface in the pine plantation, since the fire crowns first. Local experience, however, suggests that surface fires in leafless hardwood stands in the spring reach an upper limit of about 20 cm. sec.$^{-1}$, with fire intensities of about 8000 cal. sec.$^{-1}$ cm.$^{-1}$.

This three-stage pattern may be due mainly to the way in which the emissivity of the flame varies. Since maximum flame temperatures are fairly uniform regardless of fire intensity, flame thickness is the main factor governing the emissivity of the flame and its emitted radiation intensity. A thick 900°C flame radiates 2.6 cal. cm.$^{-2}$ sec.$^{-1}$ as a black body, but a thin one may emit only 0.5 cal. cm.$^{-2}$ sec.$^{-1}$ at emissivity 0.2. In a given fuel bed, the rate of advance during the zone of instability is affected (Expression 6) by both radiation intensity and flame angle; however, once black-body thickness is achieved, further effect can be obtained only by greater flame tilt. Since the wind's ability to tilt flames decreases as they become longer and thicker, the fire should react less and less to further increments of wind speed and a fair degree of stability should result. A sharp contrast between the effects of wind and those of slope is now apparent. The sloped fires of Table 5 leaned toward the fuel bed, suggesting that flames actually bathe the fuel ahead even on a moderate slope. Very high intensity and unstable behaviour are therefore to be expected on steep slopes.

The theoretical efficiency factors e of the sloped laboratory fires were calculated from Expression 5 and allowance was also made for heat transfer through the fuel bed. A constant 3 cal. sec.$^{-1}$ cm.$^{-1}$ was added to the flame radiation, i.e. 1 cal. cm.$^{-2}$ sec.$^{-1}$ in a 3-cm.-deep fuel bed. The resulting quotients (Table 5) ranged from 0.29 to 0.43 (average 0.38), indicating that the calculated rates of forward heat transfer were adequate to preheat the fuel to the ignition state with ample allowance for various losses, and also that the theory is fairly consistent over the observed range of fire behaviour. Unfortunately, there is insufficient information about the plantation headfires to permit a similar numerical analysis.

To sum up, some general remarks about surface headfires in contrast to backfires in the plantation follow:

(1) The range of intensity is much wider in surface headfires than in backfires, about 10-fold as compared with 3-fold.

(2) The major propagation mechanism in surface headfires is probably flame radiation, as compared with fuel-bed radiation in backfires.

(3) Over much of their range, surface headfires exhibit great instability, magnifying and compounding any variations in fuel moisture content, flame dimensions or flame angle. Backfire-spread rates, on the other hand, are little affected by fire intensity, and react in simple proportion to changes in fuel moisture or bed density.

(4) Surface headfires should theoretically be much less sensitive to the structure and bulk density of the fuel bed than are backfires.

(5) Surface headfires are more difficult to reproduce in the laboratory because of the greater length of run needed to ensure equilibrium and the greater width required to test the effect of flame radiation.

Crown Fires

Of the three plantation crown fires, only C4 maintained a steady state for as long as 2 minutes. Fire R1 existed as a crown fire for less than a minute before it had to be put out. Fire C6 steadily increased in intensity, and had probably reached equilibrium (Figure 7) when it was halted by a wind shift; the description in Table 6 applies to a period of about half a minute. Lower moisture content in the crown foliage is probably the main reason for the faster rate of advance. The following description of fire C4 is generally true for C6 as well as for two crown fires observed in a stand of mixed jack and red pine.

The trees on plot C4 averaged 15 metres in height, and the live crowns were about 7 metres deep. After C4 was lit in a line on the upwind end, a lull in the wind permitted the fire to burn with moderate intensity for several minutes. The wind then regained its average strength, first spreading and flattening the flames. As the intensity increased the flame front became more erect; at a rate of advance of about 8 cm. sec.$^{-1}$ and an intensity of about 6000 cal. sec.$^{-1}$ cm.$^{-1}$, the crowns began to burn. This estimate of behaviour at the moment of crowning is necessarily rough, since the transition took place within less than a minute. The flame front from then on was nearly vertical, with flames rising about 8 metres above the crowns. The temperature profile record obtained after crowning began shows that temperature rose sharply within a few seconds at all levels up to 10 metres, and photographs confirm this (Figure 6). The depth of the burning zone was about 15 metres and was fairly constant from the ground to crown level. Only above the treetops did the flames converge. The crowns appeared to be a solid mass of fire. The trunk space, however, was not always completely filled with flame; it presented a furnace-like effect, bright red but often permitting a view of the individual flaming trunks within the fire front. Readings of emitted radiation were similar in both crown and trunk space, about 2.8 cal. $cm.^{-2}$ $sec.^{-1}$. In spite of a wind at treetop level of about 5 m. $sec.^{-1}$, the flames above the crowns were tilted only 5 or 10 degrees.

The vertical shape of the fire front once again suggests radiation as the main mechanism of forward heat transfer. Four components of radiation were considered (Figure 11) in the analysis:

(1) From trunk space to ground.

(2) From trunk space to lower surface of crowns.

(3) From overhead flame to upper surface of crowns.

(4) From burning crowns through crown layer.

It was assumed that radiation from the burning crowns was absorbed in the crown space only, none escaping up or down. The first three radiation components were calculated from Expression 4, QR being the desired quantity (= iL/2). Angle A was taken as 90° and L as the height of the radiating front in each case. For the fourth component, QR was simply the product of i and L. A value of 2.8 cal. $cm.^{-2}$ $sec.^{-1}$ was used for trunk space and crown, and 2.0 for the overhead flame.

The rates of forward heat transfer required to maintain the 28 cm. $sec.^{-1}$ rate of advance in the surface and crown phases were calculated separately from the expression

$$q = Rwh \quad (7)$$

where q is rate of energy required per unit of

fire front to heat fuel to ignition temperature,

cal. $sec.^{-1}$ $cm.^{-1}$.

These results all appear in Table 8. Apparent at once is the much greater forward rate of heat transfer required in the crown phase, owing to its much higher moisture content. It is also apparent that radiation from the trunk space was hardly sufficient to propagate the surface phase if the entire weight of surface fuel consumed (0.19 gm./cm.) is used in the calculation. Probably, however, the fire could advance by preheating only a small fraction of this amount, leaving the rest to be ignited and burned during passage of the burning zone. The surface phase can thus be accounted for with an efficiency e of perhaps only 0.3, which makes adequate allowance for cooling losses and interception by tree trunks.

The crown phase, on the other hand, required much more than the other three radiation components together could supply; without effective radiation from above and below the crowns, the deficit would be even greater. Convective heat rising from the ground must have completed the drying and preheating of the crown fuel before it could burn.

TABLE 8. ENERGY TRANSFER RATES AVAILABLE AND REQUIRED TO PREHEAT FUEL TO IGNITION TEMPERATURE IN CROWN FIRE C4. ALL QUANTITIES IN TERMS OF ENERGY TRANSFER RATE PER UNIT LENGTH OF FRONT, CAL.SEC.$^{-1}$ CM.$^{-1}$.

Surface Phase		
Radiative energy available, QR		
(1) Trunk space to ground		1120
Energy required, Rwh		1070
Crown Phase		
Radiative energy available, QR		
(2) Trunk space to lower crowns	1120	
(3) Overhead flame to upper crowns	800	
(4) Crown space to crowns	1960	
Total of 2, 3, and 4		3880
Energy required, Rwh		5840

If the above analysis is approximately correct, the conclusion is inescapable that crown fire in such a stand is unable to rush ahead of the surface fire, and that the burning front in such a fire must be roughly vertical. In fact, to become independent of the surface fire, the crown phase would have to double its radiant intensity to about 5 cal. cm.$^{-2}$ sec.$^{-1}$, a value far above any observed in forest fires.

The crown phase can be pictured as a fire in a fuel layer that is propagated mainly by radiation within the layer, so that Thomas' Expression 3 applies. According to this theory, the lower the bulk density of foliage in the crown layer, the faster the fire could advance. The limit would be reached when there was insufficient crown fuel to maintain a flame of the required depth and temperature; a fast-moving fire in a sparsely crowned stand could then only burn individual trees without producing a continuous crown phase. Conversely, as the crown bulk density increased, the rate of advance would be slowed, the limit perhaps being reached when the burning zone became too thin to maintain its radiant intensity. The difficulty in such speculation lies in estimating the joint effects of the surface and crown phases on each other. The simple analysis undertaken here only hints at how fire behaviour might be affected by variations in stand structure.

Since the front in these crown fires was essentially vertical, the question arises whether the crown phase could continue without the wind that was necessary to start it. In other words, is a crown fire a self-perpetuating equilibrium once it has stabilized? Crown fire C6 sheds a little light on this point. It was advancing at an intensity of well over 50,000 cal. sec.$^{-1}$ cm.$^{-1}$ when the wind, until then behind it, suddenly shifted 90 degrees. The crown phase ceased at once, leaving only a slow-moving surface fire.

Crown fires C4 and C6 burned on fronts of 25 and 35 metres respectively, and the fuel on the edges did not receive the full radiant effect predicted by Expression 4. However, fire C6 attained a rate of well over 40 cm. sec.$^{-1}$, and several local fires in pine stands have spread at such rates with similar intensities (e.g. Van Wagner, 1965). Thus it may be that the fires on plots C4 and C6, in spite of their small size and short duration, portrayed very well the behaviour to be expected in crown fires of much larger extent.

Some general remarks about crown fires in pine plantations or similar conifer stands are possible:

(1) Crown fires have a relatively narrow range of behaviour, though much more intense than surface fires.

(2) Radiation through the trunk space and the crown layer is probably the principal mechanism of advance.

(3) The crown phase is dependent on the surface phase and is unable to advance ahead of it, the result being a nearly vertical burning front.

(4) Since the flames in crown fire are thick enough to radiate as a black body, the radiant intensity remains constant and the rate of advance is quite stable in a given fuel type as long as the wind is behind them.

PREDICTION OF FIRE BEHAVIOUR

An obvious question is: With the theories and data available, what can be done to predict fire behaviour in the red pine plantation under any set of weather conditions? The first possibility is that prediction might be made directly with expressions like (3) for backfires and (6) for headfires. All the factors required are listed below:

Moisture content of litter and duff;

Moisture content of crown foliage;

Wind speed in the stand;

Bulk density of the litter;

Fuel amount available for burning;

Flame length and angle;

Forward heat transfer rate from flame or through fuel bed.

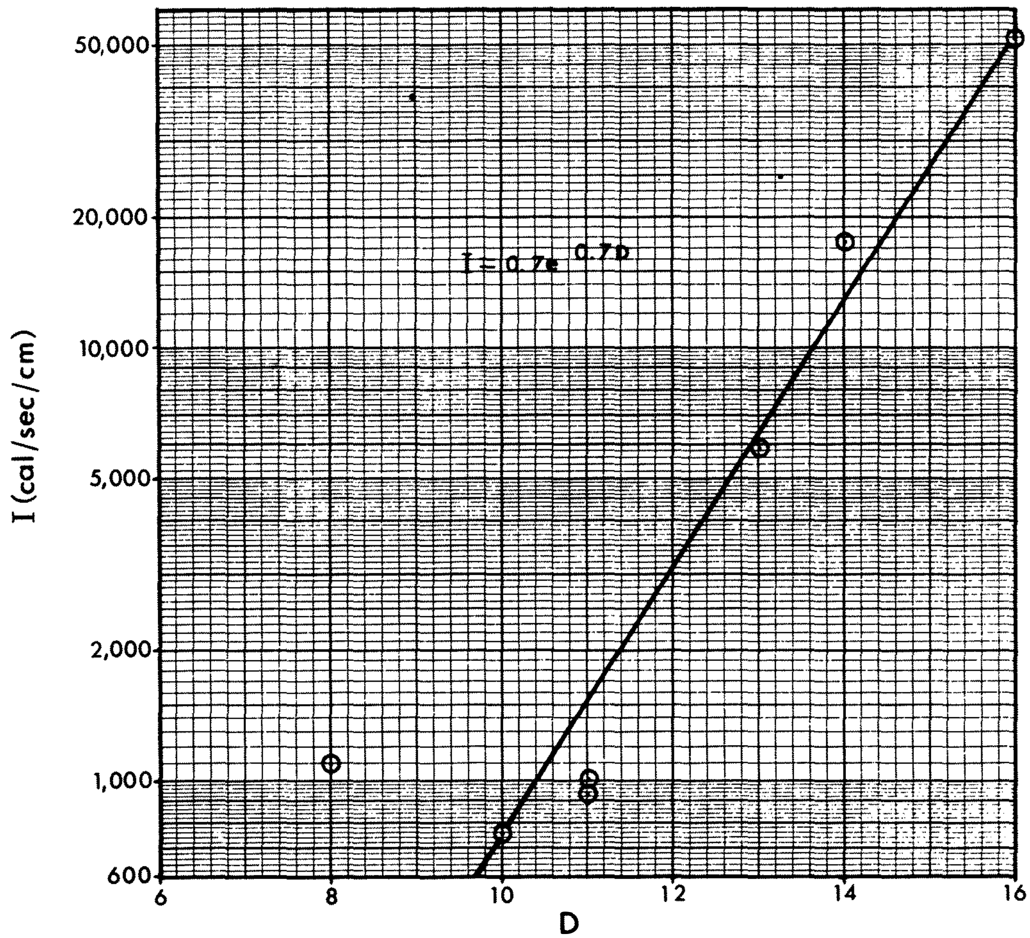

Figure 12. Graphical relation between fire intensity I and fire danger index D in the surface headfires and crown fires.

Wind speed is included in the list because of its obvious effect on fire behaviour, but no attempt has been made to incorporate it into any of the expressions developed in this paper. The current Canadian forest fire danger rating system (Williams, 1963) provides daily weather readings, a coded estimate of litter moisture content, and a measure of the degree of drought. By combining this information with data obtained from the field experiments, indexes to predict rate of advance and intensity could be developed, although the number of fires reported here is probably too few to warrant the attempt.

A second possibility is that fire intensity may bear some simple empirical relation to the fire danger index (Anon., 1956). The thread of theory is stretched thin here, since the danger index is a complex function of the current and recent weather, and fire intensity does not increase in a smooth manner. Nevertheless, the intensity I of the experimental surface headfires and crown fires, when plotted against fire danger (Figure 12), makes a reasonably smooth curve of the form

$$I = 0.7e^{0.7D} \text{ cal. sec.}^{-1} \text{ cm.}^{-1} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (8)$$

where D is fire danger index and e the base of natural logarithms.

Besides having some predictive value, this expression provides an interesting concept of the fire danger index that bears investigation in other forest types.

For practical purposes, backfires are of such low intensity that accurate prediction of their behaviour is hardly necessary. Unless deliberately set for prescribed burning or to control another fire, backfire is always accompanied by a headfire of much greater interest. In the pine plantation, backfires advance at from about 0.3 to 1.0 cm. sec.$^{-1}$ and will not burn when the surface-moisture content exceeds about 25 percent.

The headfires are more erratic. Light winds should result in rates of advance up to about 3 cm. sec.$^{-1}$, above which behaviour is unstable. When wind within the stand exceeds 1.5 m. sec.$^{-1}$ and surface-fuel moisture content dips below 12 percent after a week without rain, crowning becomes possible. As long as the crown fire advances essentially as a line, the rate of advance should be about 30 to 50 cm. sec.$^{-1}$.

It is apparent that, even with simple theories and a uniform forest type, prediction of fire behaviour with any accuracy is still a formidable problem. What accuracy can eventually be achieved is not yet clear.

FINAL DISCUSSION

The foregoing evidence assigns thermal radiation the main role in propagating line fires within the intensity range covered here. It also suggests that, on level ground, convection is the controlling process only in the transitional stage while a surface fire gathers intensity. (Convection is again important, of course, at the upper end of the intensity scale when a massive convection column causes violent turbulence at ground level.) Although radiation accounts for a small proportion of a forest fire's heat output, there is still enough to supply the required ignition energy. For the assumed ignition temperature of 300°C, the required effective heat transfer to the unburned fuel need only amount to h/H, or about 5 percent of the heat of combustion at 15 percent moisture content. The calculated radiative energy reaching the unburned fuel was ample in the sloped laboratory fuels and in crown fire C1, and probably enough in the plantation headfires. The estimated total radiation as a proportion of total energy output (assuming simple two-faced flame fronts) was about 40 percent for the sloped laboratory fires, about 20 to 28 percent for the surface headfires, and 19 percent in crown fire C4. Considering the difficulty of obtaining the required measurements, these values seem reasonable. McCarter and Broido (1965), for instance, estimated radiative energy from wood-crib fires at 43 percent and predicted lower proportions in larger fires.

The main effect of fuel moisture content on fire behaviour is, for the ignition mechanism assumed here, simply one of delay. The moister the fuel is, the longer the time required to ignite it, and the slower the fire can advance. The effect on the rate of advance is simply proportional in backfires, but in headfires, in which the rate of advance depends on fire intensity as well, the effect of fuel moisture may be greatly magnified.

A forest fire of any of the three classes described here is assumed to advance in uniform fuel as a line at constant intensity without regard for the size of the burned area behind it. This simple line-fire concept is, of course, quite inadequate for fires that are seriously affected by large-scale transport of flaming brands far ahead of the main fire, or by violent turbulence occurring around the edge when a massive convection column forms. Since these processes can be observed only in large, very intense forest fires, it is difficult to obtain measurements of their additional effect in advancing and intensifying the main burning zone. For example, when Chandler *et al.* (1963) sought information on the behaviour of large forest fires, they examined records of 1621 fires covering more than 300 acres but found acceptable spread data on only 110.

Field test fires of the size described can obviously not shed any light on large-scale fire-spotting and turbulence. However, if 1 mile per hour (45 cm. $sec.^{-1}$) is taken as a reasonable upper limit for normal line-fire advance in the forest, it is surprising how seldom a sustained rate of advance greater than this can be confirmed. When exceptionally fast rates of spread are reported, it is sometimes difficult to judge whether only a few spot fires occurred ahead of the main fire or whether the whole fire front was effectively advanced at the rate stated.

The better normal line-fire behaviour can be understood and predicted, the better additional effects of fire-spotting and turbulence can be isolated and measured. The attraction of laboratory fire research lies in the close control of variables and in the ease of instrumentation. On the other hand, field experiments are more likely to demonstrate the actual processes at work in real forest fires of different types. A balanced combination of the two approaches ought to provide the shortest route to an adequate practical and theoretical understanding of forest fire.

LIST OF SYMBOLS

A - Flame angle (angle between flame and unburned fuel)

C - Rate of energy loss by cooling

D - Fire danger index, Ontario

d - Bulk density

e - Efficiency of fuel preheating process, or base of natural logarithms

H - Heat of combustion

h - Energy required to heat fuel to ignition temperature

I - Fire intensity (energy-output rate per unit of front)

i - Emitted radiation intensity

k - Constant

L - Flame length

m - Moisture content, fraction of dry weight

n - Fractional exponent

Q - Radiative energy received by fuel during approach of fire

q - Energy-transfer rate required to preheat fuel at given R

R - Rate of advance of fire

w - Weight of fuel consumed per unit of ground area

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