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NOTES ON FOREST FIRE FIELDWORK (NEW FOREST, 1967)

by

M. J. WOOLLISCROFT

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SUMMARY

This report describes fieldwork carried out in March 1967, to study forest and heathland fires. The main emphasis was on head fires as these are the most serious and difficult to understand.

Results suggest that radiation from the flames contributes appreciably to the spread of head fires.

Key Words: Woodland, fire, wildland, fire spread, flame

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MINISTRY OF TECHNOLOGY AND FIRE OFFICES' COMMITTEE
JOINT FIRE RESEARCH ORGANIZATION

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1. Introduction

As in previous years[1] a party from the Fire Research Station visited the New Forest to make measurements during controlled burnings carried out by the Forestry Commission. Data on seven fires were collected and are presented in this report.

2. Description of the Fires

A summary of the fires is given in Table 1.

Table 1.

Summary of Fire conditions

Number of fire	Date	Type of fire	Wind conditions	Fuel and notes
1	17/3 a.m.	Head	Light	Fairly uniform heather and dwarf gorse. Good coverage. Height 45 cm.
2	17/3 p.m.	Head	Light and variable	Sparse coverage of shallow fuel. The fire did not burn evenly, was often in danger of going out and had to be relit in many places.
3	20/3 p.m.	Head	Moderate	Heather and gorse. Fire spread up a slight slope.
4	21/3 a.m.	Backing	Very light	Bracken. Fire spread up a 20° slope.
5	21/3 p.m.	Head	Light	Heather. Good coverage.
6	21/3 p.m.	Head	Light	Tall gorse. Plot not fully instrumented.
7	22/3 p.m.	Still air	None	Gorse, heather, grass and leaves, very damp ground in a clearing.

3. Measurements and results

As a result of the experience of previous years the number of measurements was reduced and the procedure standardised. A plot was laid out as shown in Fig (1) with a 3 x 3 square matrix of poles 10 m (33 ft) apart, so that the rate and direction of spread could be determined from the time the fire front reached each pole. Standard instrumentation was then laid out as shown in Fig (2).

The radiometer used to measure flame radiation was a standard Fire Research Station type[2] pointing vertically upwards and generally fixed at the height of the fuel. The radiometer used to measure radiation within the fuel bed was the King type modified as described previously[1] facing horizontally and pointing, as far as possible, towards the advancing fire. The thermocouple was cemented into a stem of fuel. Cans of water and wood blocks[3] giving a cruder measure of heat transfer rate were placed randomly in the plot. The can measurements have a wide variation and are of little value. The wood block measurements however, are more closely related to the radiometer measurements. Both of these measurements were only intended as standby measurements in the event of failure of the radiometer. The output from the thermoelectric instruments was measured using a portable ~~chart~~ recorder sited some distance from the fire with disposable leads. Flame temperature was measured using a disappearing-filament pyrometer and measurements of flame dimensions were obtained from colour photographs, making a correction for the angle of view. Several such photographs were taken at each fire.

A sample of the unburnt fuel was cut from an area one metre square and weighed to give, together with the height, a measure of the bulk density of the fuel. These samples were taken back to the Fire Research Station, broken down into type of fuel, e.g. gorse, heather, grass and needles, stems, branches, and the weight and moisture content of each component measured.

Detailed results are given in Table 2.

4. Theoretical background

4.1. Equation of fire spread

The equation for the spread of fire in deep fuel beds in still air that has been developed from laboratory experiments is[4]:-

$$R \rho_b \Delta H = I_o - 2.67 \alpha \theta_o \qquad (1)$$

where R	is rate of spread
ρ_b	is the bulk density of the fuel
ΔH	is the heat required to raise unit weight of fuel to ignition
I_o	is the intensity of radiation from the flame zone in the fuel bed
$2.67 \alpha \theta_o$	is a cooling correction, α is the heat transfer coefficient and θ_o the temperature rise at ignition (see 5.1.1.)

For wind conditions it has been suggested that equation (1) should be modified[5] to:-

$$R \rho_b \Delta H \cos \phi = I_o - 2.67 \alpha \theta_o \qquad (2)$$

where ϕ is the angle of the flame front to the vertical.

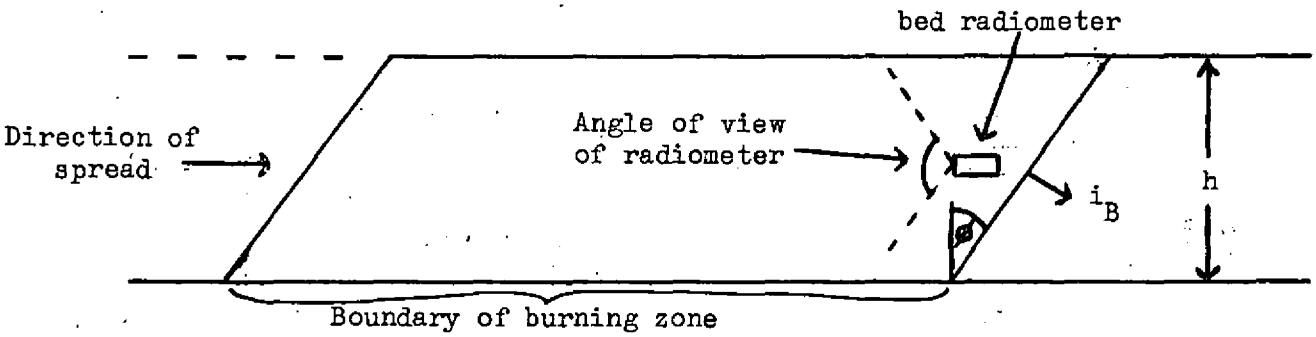
These equations are simply heat balances through the fuel bed and assume that the flames above the fuel bed are thin so that they do not contribute significantly to heating of the fuel bed

4.2. Ratio of flame and fuel bed radiation

Let us assume that both the flame and the flame front in the burning zone can be represented by radiating planes. It is reasonable to assume however that the peak intensity measured by the bed radiometer is i_B, the intensity radiated perpendicular to the flame front, even though the receiver of the bed radiometer is not perpendicular to the flame front. The burning zone is generally deep (1-2 m) and the emissivity is virtually unity and would be so even if the burning zone were substantially thinner on account of the high attenuation coefficient for radiation.

Now the peak intensity recorded, which is used for calculations of the kind discussed in Section 5, is probably reached when the radiometer is inside the burning zone (see Figure 3) and is seeing only burning fuel, when the intensity it records will be $i_B \, E_B$. Hence the heat radiated per unit time into the fuel bed ahead of the fire front will be $i_B \, E_B h/\cos \phi$ per unit width. When the flame reaches the radiometer pointing upwards (the flame radiometer) the radiometer measures

Fig. 3. Radiometer and burning zone



$$i_f \, E_f \times F$$

where i_f is the intensity radiated by a black body at the flame temperature

E_f is the flame emissivity

F the configuration factor is $\frac{1 + \sin \phi}{2}$

where ϕ is the angle between the flame and the vertical.

Thus the flame radiometer measures $i_f \, E_f \, \left(\frac{1 + \sin \phi}{2}\right)$

The bed radiometer measures $i_B \, E_B$

where i_B is the intensity of a black body radiator at the temperature of the fuel bed.

E_B is the emissivity of the fuel bed.

The total heating of the fuel by the flame is[6,7] $i_f \, E_f \, L \, \left(\frac{1 + \sin \phi}{2}\right)$

where L is the flame length.

Hence the ratio of heating by flame radiation to heating by bed radiation is

$$\frac{i_f \, E_f \, L \, (1 + \sin \phi) \cos \phi}{2 \, i_B \, E_B \, h}$$

This ratio is not quite the same as was obtained previously[6] since account has now been taken of the inclination of the fire front which causes its area to be larger than that of a vertical fire front in the same fuel.

The ratio

$$\frac{i_f\ E_f\ L\ (1 + \mathrm{Sin}\ \phi)\ \cos\ \phi}{2\ i_B\ E_B\ h} = \frac{\text{flame radiometer measurement x L}}{\text{bed radiometer measurement x h}}\ \cos\ \phi$$

Thus the flame heating to be added to I_0 in the heat balance (Equation 2 in Section 4) is given by the flame radiometer measurement multiplied by $\frac{L}{h} \cdot \cos\ \phi$

5. Discussion of results

This year's data comprise:-

1 still air fire (No. 7)
1 backing fire (No. 4)
5 head fires, in one of which (No.2) the fuel was very patchy and burning was erratic

5.1. Rate of spread

5.1.1. Still air and backing fires

The rate of spread is calculated from equation (1) by substituting measured values of bed radiation and fuel bulk density, taking ΔH as 1290 J/g (Fire 4) and 1500 J/g (Fire 7), θ_o as 300°C and $\alpha\ \theta_o$ as 1.37 W/cm^2.

The value of $\alpha\ \theta_o$ of 1.37 W/cm^2 is probably an overestimate as it was calculated assuming heat loss in free space - in fact, of course, a fuel bed is not free space.

Nearly all the heating from the bed radiation term is taken up by the cooling term. However, adding the flame heating calculated as described in Section 4 does increase the heating required by a value high enough to give the measured rate of spread as is shown in Table 3.

Table 3

Measured and required heating rates
(Still air and backing fires)

Fire No.	Bed radiation $W\ cm^{-2}$ Table 2 Column 16	Heating due to flame radiation $W\ cm^{-2}$ Table 2 Column 29	Total heat available $W\ cm^{-2}$	Total heat required to give observed rate of spread (Equation 1) $W\ cm^{-2}$ Table 4 Column 30
4	4.2	18.5	22.7	25.3
7	3.95	11.6	15.5	15.2

5.1.2. Head fires

The data are given in Table 4. Although the theoretical values of rate of spread from equation (2) are not negligible they are still much lower than those observed. We do not have sufficient data nor data of a sufficient accuracy to be able to tell whether the observed flame radiation would give sufficient extra heating to account for the rate of spread. In one fire (No. 3) it would seem in Table 4 to be more than enough but in other cases not anywhere near enough. Fire No. 6 may, however, be explained by the fact that spot fires can develop in gorse fuel ahead of the fire front, so that the 31.5 W/cm^2 is an overestimate. No measurements of flame radiation were made for Tests 1 and 2.

Table 4

Discrepancies between measured and required heating rates (Head fires)

Fire No.	Bed radiation $W\ cm^{-2}$ Table 2 Column 16	Heating due to flame radiation $W\ cm^{-2}$ Table 2 Column 30	Total heat available $W\ cm^{-2}$	Total heat required to give observed rate of spread (Equation 1) $W\ cm^{-2}$ Table 2 Column 31
3	8.0	14.6 measured	22.6	13.7
5	7.9	3.2 measured	11.1	29.5
		9.9 from flame temperature and flame thickness D cm, assuming emissivity = $1 - e^{-0.003D}$	17.8	
6	5.7	5.8 from flame temperature and length of burning zone.	11.5	31.5

5.2. Attenuation of radiation and flame length

A knowledge of the attenuation coefficient for radiation passing through the fuel bed is only necessary for predicting fire spread in thick fuel. It is of interest here, however, to compare measured and calculated values for the one fire for which the data are available. The attenuation coefficient a is a measure of the reduction of radiation intensity with distance through the fuel bed. For bracken, a value of 0.076 cm^{-1} was obtained from the data for the distribution of radiation through the fuel bed, which compares closely with the value of 0.088 cm^{-1} calculated from the theoretical relation

$$a = \frac{\sigma \rho_b}{4 \rho_f} \qquad (3)$$

where ρ_f is fuel density and the surface per unit volume σ was taken as $1/0.03 = 33\ cm^{-1}$. 0.03 cm is the average leaf thickness and as the leaves of bracken are relatively wide compared with their thickness $1/$thickness gives surface/unit volume.

In contrast with last year's results[6], Table 2 (column 12) shows that the measured flame angles are not at all in agreement with those derived from the relationship determined by Thomas, Pickard and Wraight[8].

The theoretical relationship for flame length is[9]

$$L = 400\ M^{\circ 1 \frac{2}{3}}$$

where L is in cm

and $\overset{\circ}{M}^{1}$ is mass burning rate per unit width of fire front.

This tends to overestimate flame length but to some extent this may be due to an overestimate of the percentage of fuel burnt. This is probably particularly so for the bracken fire (No. 4) where the calculated value of $R.\rho_b \Delta H \text{ Cos } \phi$ is high for a backing fire and also for the tall gorse fire (No. 6) where it is unlikely that anything but a small fraction of the fuel would have burnt in such a fast spreading fire.

6. Conclusions

As with the previous year's results it now seems that flames do in fact contribute appreciably to the rate of spread but we cannot be certain that this is the only factor other than bed radiation. In the case of head fires there may well be a contribution from forced convection.

The relation between flame angle, wind speed and mass burning rate given by Thomas, Pickard and Wraight[8] does not correlate these field data but the reasons for this discrepancy are not yet known.

7. Acknowledgements

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8. References

1) WOOLLISCROFT, M. J. and LAW, Margaret. A report of forest fire fieldwork (New Forest, March 1965). Ministry of Technology and Fire Offices' Committee Joint Fire Research Organization F.R. Note No. 647, January 1967.

2) McGUIRE, J. H. and WRAIGHT, H. Radiometer for field use. J. Sc. I. Vol. 37 pp 128 - 130 April 1960.

3) GRIFFITHS, Lynda G. and HESELDEN, A.J.M. The use of wooden blocks as simple radiometers. Ministry of Technology and Fire Offices' Committee Joint Fire Research Organization F.R. Note No. 648.

4) THOMAS, P. H., SIMMS, D. L. and WRAIGHT, H.G.H. Fire spread in wooden cribs. Department of Scientific and Industrial Research and Fire Offices' Committee Joint Fire Research Organization F.R. Note No. 537

5) THOMAS, P. H. Fire spread in wooden cribs - Part I. The effect of wind. Ministry of Technology and Fire Offices' Committee Joint Fire Research Organization F.R. Note No. 600, June 1965.

6) WOOLLISCROFT, M. J. A report on forest fire fieldwork (New Forest 1966). Ministry of Technology and Fire Offices' Committee Joint Fire Research Organization F.R. Note No. 693

7) VAN WAGNER, C. E. Fire behaviour mechanisms in a red pine plantation. Field and laboratory evidence. Congress of the International Union of Forest Research Organisations, Munich, Germany, Sept. 1967. Department of Forestry and Rural Development, Petawawa Forest Experiment Station, Ontario, Canada.

8) THOMAS, P. H., PICKARD, R. and WRAIGHT, H.G.H. On the size and orientation of buoyant diffusion flames and the effect of wind. Department of Scientific and Industrial Research and Fire Offices' Committee Joint Fire Research Organization F.R. Note No. 516, January, 1960.

9) THOMAS, P. H. Some aspects of the growth and spread of fire in the open. Forestry 1967 40 (2) 139 - 64.

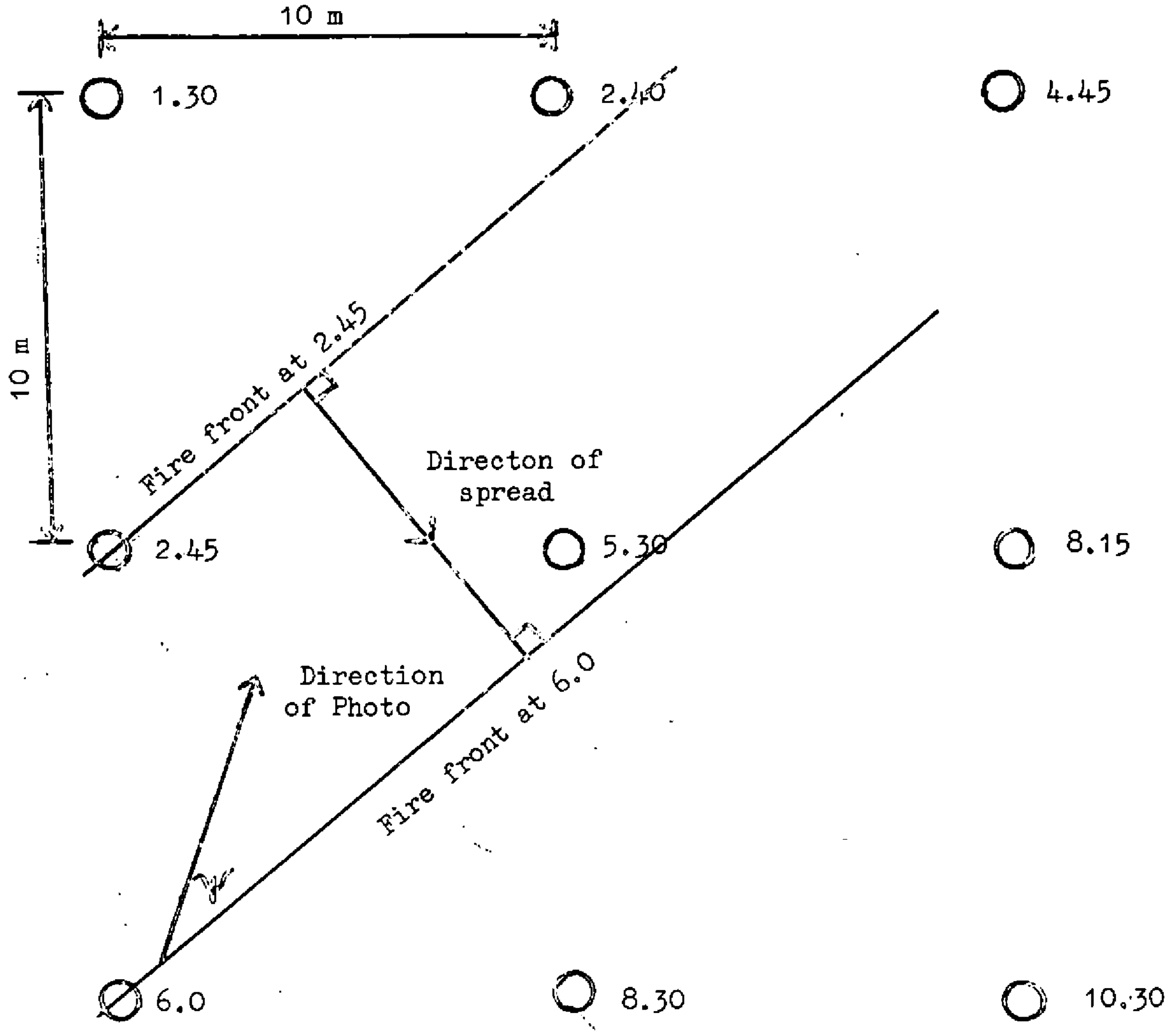

FIG. 1 TYPICAL SPREAD DIAGRAM

○ Poles (figures alongside are times in min and s at which fire reached pole)

——— Fire front (deduced from times at which fire reached pole).

Rate of spread found by measuring shortest distance between fire fronts.

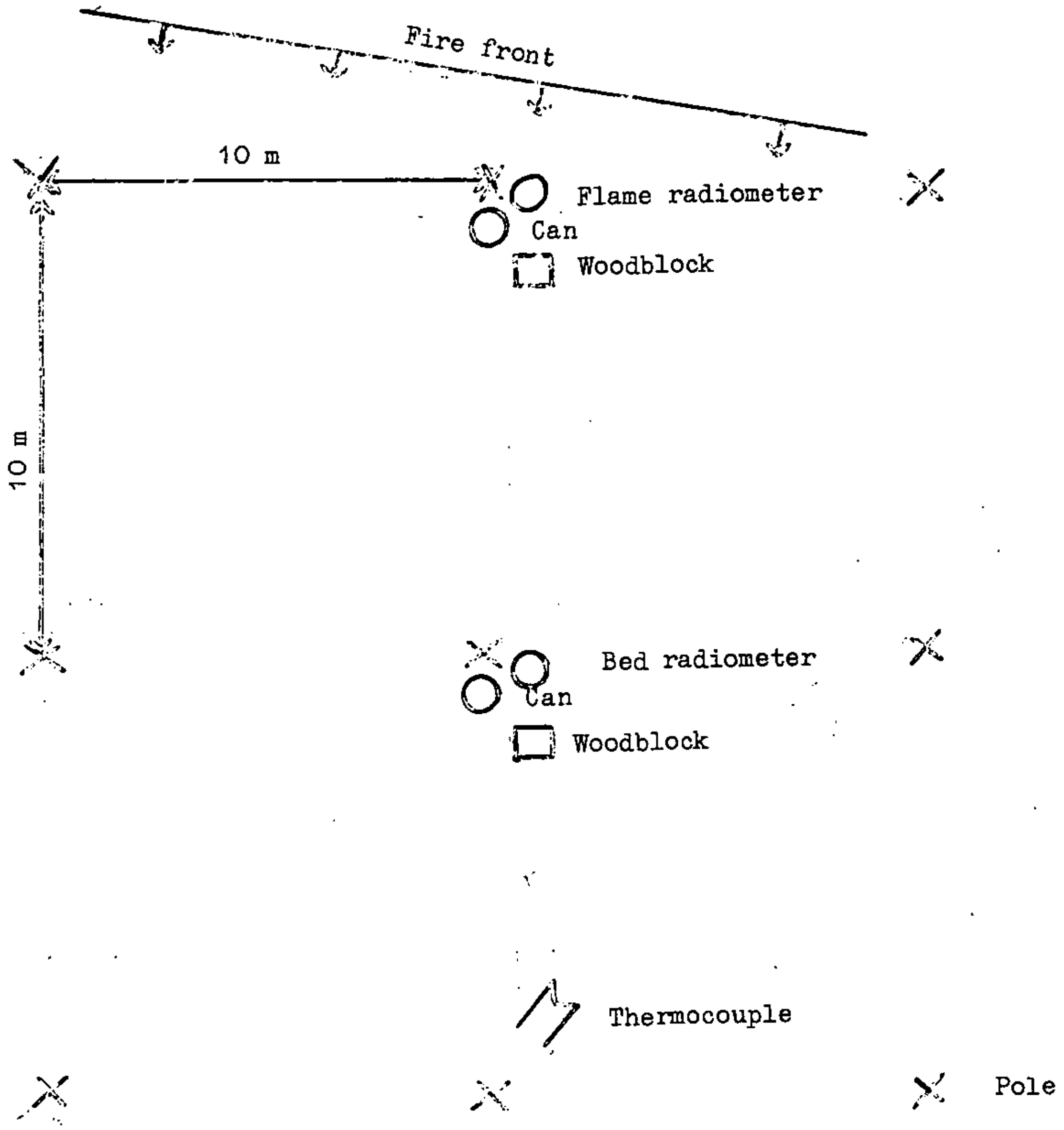

FIG 2. STANDARD ARRANGEMENT OF INSTRUMENTS

Table 2 - Notes

(1) Theoretical values obtained from equation (2), neglecting flame radiation.

(2) These values are based on previous measured values for this type of fuel, no accurate values were obtained in this series.

(3) The theoretical values of flame angle are determined from the relationship determined by Thomas, Pickard and Wraight[8].

(4) Theoretical values of bed radiation obtained from the temperature of the burning fuel bed (emissivity assumed unity).

(5) The figures in brackets for flame radiation are corrected for configuration factor and are thus a measure of the radiation from the flame $I_f \; E_f$ whereas the measured values are a measure of radiation falling on the bed, i.e. $I_f \, E_f \left(\frac{1 + \operatorname{Sin} \phi}{2}\right)$

(6) Theoretical value of flame length obtained from $L = 400 \, \dot{M}'^{\frac{2}{3}}$

(7) Obtained from equation (3).

(8) These are values from Column 31, divided by Bed Radiation as measured by the radiometer (Column 16) except where the latter is not available. In Fire 1 the temperature of the burning fuel was used to give a measure of bed radiation and in Fire 6 the wood block measurement was used.

(9) This ratio $= \dfrac{I_f \, E_f \, L \, (1 + \operatorname{Sin} \phi) \operatorname{Cos} \phi}{2 \, I_b \, E_b \, h}$

Theoretical values are derived from theoretical values of bed and flame radiation (Columns 16 and 20).

(10) Theoretical values from flame temperature and assuming flame emissivity E_f is given by

$$E_f = 1 - e^{-0.003 D}$$

where D is the flame thickness in cm.

(11) Equation (2) gives total heating rate

$$= R \, \rho_b \, \Delta H \operatorname{Cos} \phi + 2.67 \, \alpha \, \theta_o$$

Table 2

Data Sheet for Forest Fire Fieldwork 1967

1	2	3	4	5	6	7	8	9	10	11	12	13	14
Number and Type of fire	Date		Fuel type	Rate of spread (1) R(cm s^{-1})	Total bulk density ρ_b total (mg cm^{-3})	Fraction burnt (per cent)	Bulk density of burnt material ρ_b burnt (mg cm^{-3})	Mass burning rate per unit area of fire front $R\rho_b$ $\dot{M}''$(mg $cm^{-2}s^{-1}$)	Wind speed (at fuel ht.) U (cm s^{-1})	Dimensionless Wind speed U^*	Flame$^{(3)}$ angle to vertical ϕ (degrees)	Moisture content of fuel (per cent)	Ignition Enthalpy ΔH (J g^{-1})
1. Head	17/3/67 a.m.	Observed	45% Heather 49% Dwarf Gorse 6% Grass	4.5	5.4	50	2.7	12.2	125	1.7	28	35	1190
		Theoretical		0.97							58		
2. Head	17/3/67 p.m.	Observed	Heather	1.8	3.9	$40^{(2)}$	1.6	2.9	100	2.7	38	$33^{(1)}$	1140
		Theoretical		0.33							65		
3. Head	20/3/67 p.m.	Observed	80% Heather 15% Gorse 5% Bracken	6.3	4.2	$40^{(2)}$	1.7	10.7	375	5.8	66	$40^{(1)}$	1290
		Theoretical		2.7							73		
4. Backing	21/3/67 a.m.	Observed	Bracken	1.33	10.6	100	10.6	14.1	125	1.85	+24 slope 20°	40	1290
		Theoretical		0.03							+59		
5. Head	21/3/67 p.m. Main plot	Observed	Heather	8.65	7.3	36	2.6	22.4	225	2.4	41	41	1310
		Theoretical		1.4							63		
6. Head	21/3/67 p.m. Gorse	Observed	Gorse	30	2.9	25	0.7	21.0	225	1.75	50	60	1725
		Theoretical									60		
7. Fire in still air	22/3/67	Observed	12.5% Grass 4% leaves 75% Heather 8% Gorse	1.5	7.25	50	3.6	5.4	-		5	50	1500
		Theoretical		0.033									

Table 2 (continued)

Data Sheet for Forest Fire Fieldwork 1967

1	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
Number and Type of fire	Temperature of burning fuel T (°C)	Bed radiation(4) intensity I (W cm^{-2})			Mean flame temperature T_f (°C)	Flame(5) radiation (W cm^{-2})	Fuel height h cm	Mass burning rate per unit width of fire front $\dot{M}'$ (g cm^{-1}s^{-1})	Flame(6) Length L (m)	Length of burning zone D (m)	Residence time t_b (s)	Attenuation coefficient a (cm^{-1})	Theoretical heat (8) required ÷ Measured bed radiation	Black body radiation at T_f (W cm^{-2})	Ratio of heating by flame radiation to heating by bed radiation(9)	Heating by flame radiation(10) (W cm^{-2})	Total heating rate(11) (W/cm^2)
		Radiometers	Cans	Blocks													
1. Head	804	-	2.84	2.94			45	0.55	1.9	0.9	15.5						
			7.4						2.7				2.8				20.9
2. Head		5	1.48	1.49			22.5	0.065	1.1	0.6	28						
									0.6				2.1				10.7
3. Head	816	7.95	6.7	2.84		4.7(4.9)	35	0.37	2.7	1.0	13				1.8	14.6	
			8.0						2.0				1.7				13.7
4. Backing	816	4.2	2.2	2.16	1055	4.0(6.2)	30	0.42	0.9	0.6	45	0.076			4.4	18.5	
			8.0			2.05			2.25			0.088(7)	6.0	17.7	0.38		25.3
5. Head		7.9	5.6	5.66	1050	1.3 (1.6)	50	1.1	1.6	1.1	13				0.31	3.2	
						4.1			4.3				3.7	17.5	1.25	9.9	29.5
6. Head				5.65	1080		140	2.9	2.2	1.4	4.7						
						5.7			8.2					19.2	1.05	5.8	31.5
7. Fire in still air	725	3.95	0.52	2.22	940	2.9(5.8)	50	0.27	1.0	0.8	53				2.95	11.6	
			5.7			1.3			1.7				3.8	12.3	0.23		15.2