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A REPORT ON FOREST FIRE FIELDWORK (NEW FOREST, MARCH 1968)

by

M. J. WOOLLISCROFT

FIRE
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SUMMARY

This report describes some field measurements on fires in heathland fuels. Flame radiation appears to be the factor controlling head fires in the field. Fires in mixed fuels containing dry grass spread as fast as they would if only grass were present.

KEY WORDS : Fire spread, Wildland, Radiation, Flame.

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

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1. Introduction

Rates of fire spread and thermal measurements were made at controlled burnings carried out by the Forestry Commission in the New Forest in the Spring of 1968.

Similar work has been carried out in three previous years [1,2,3] and the purpose of this year's visit was to add to and consolidate that work.

The aim was to concentrate on head fires in fuel with good uniform coverage since the head fire is the most hazardous kind of fire and one whose mechanism of spread is the most difficult to understand quantitatively. As can be seen from Table 1 below this was largely achieved. Unless the fuel coverage is uniform the rate of spread of the fire cannot be constant and the understanding of fires spreading at constant speed is a first requisite.

2. The Fires

A summary of the fires is given in Table 1.

Table 1. Summary of fire conditions

Fire number	Date	Type of fire	Wind condition	Fuel and notes
1	12. 3. 68	Head	Light	Fairly uniform coverage of heather and a little dead grass.
2	13. 3. 68	Head	Moderate	Fairly uniform coverage of heath and fine grass. Boggy.
3	13. 3. 68 Afternoon	Flank	Light and variable	Rather patchy coverage of mixed fuel - dwarf gorse, heath and grass. Boggy, in a clearing.
4	14. 3. 68	Head	Light	Tall gorse, good coverage for type of fuel.

3. Measurements and results

As a result of the experience of previous years and because only two scientific staff were able to attend the fires the scope of the measurements was simplified. A plot was laid out with a standard arrangement of marker poles and instrumentation as shown in Fig. 1. Experience in previous years had shown that the rate of spread did not vary much across a plot so this year the matrix was reduced to a square of side 10 m. The rate and direction of spread was determined from the time at which the fire reached each pole.

Two radiometers measuring radiation through the fuel bed were used; one, the modified King type radiometer used in previous years[1], the second a standard J.F.R.O. field radiometer. Last year this type of radiometer, the joints of which are silver soldered with a melting point of 500°C, was used to measure flame radiation when placed in a clearing in the fuel bed and came to no harm. A calculation showed that even when exposed to 8 W/cm^2 for a period of 1 minute, (the maximum probable radiation for the maximum residence time) the radiometer would reach only approximately 200°C. An average exposure, say 4 W/cm^2 for 30 s, would give a temperature of only some 60°C. This type of radiometer had in the past been accidentally exposed to flames in compartment fires for short periods with no ill effects.

The "flame radiometer" was the standard J.F.R.O. field radiometer pointing vertically upwards and placed in a clearing in the fuel bed. Cans of water giving a less exact measure of heat transfer were placed beside each instrument. These served as a reserve measurement in the event of failure of the radiometers, but the radiometers worked satisfactorily and the measurements from the cans were not used on account of their wide variation. The output from the thermo-electric instruments was measured using a portable chart recorder sited some distance from the fire with disposable leads from the instruments. Measurements of flame dimensions were obtained from colour photographs, several being taken at each fire.

Fuel height was measured by plunging a steel measuring tape vertically into the fuel bed until it reached the ground. A sample of the fuel was cut on a measured area and weighed to give, together with the height, a measure of bulk density of 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. Flame temperature was measured by means of a disappearing-filament pyrometer.

Detailed results are given in Table 2.

4. Theoretical background

4.1. Equation of fire spread

The equation for the rate of 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 the rate of spread

ρ_b is the bulk density of the fuel

ΔH is the heat required to ignite unit mass of fuel

i_o is the intensity of heat radiation through the fuel bed

$2.67\alpha\theta_o$ is a cooling correction

α is a heat transfer coefficient and θ_o is the rise in temperature of the fuel at ignition.

For spread in a light wind 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 so thin that they do not contribute significantly to heating the fuel bed.

4.2. It can be shown[3] that the ratio of heating by flame radiation to heating by bed radiation is given by

$$\frac{i_f\, E_f\, L\,(1 + \sin\phi)\cos\phi}{2\, i_B\, h\, E_B} \qquad (3)$$

where i_f is the intensity of a black body radiator at the flame temperature.

E_f is the flame emissivity

L is the flame length

ϕ is the angle between the flame and the vertical

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

h is the fuel height

E_b is the emissivity of the fuel bed.

The above ratio is greater than the simple ratio of measured flame radiation/measured fuel bed radiation due to the greater configuration factor of the flame.

In the analysis of these results a more precise estimate of the cooling correction than the constant value of 3.7 W/cm^2 assumed previously has been introduced. For thin cylinders in free space^{6*}

$$Nu_d = \frac{2}{\ln\left\{1 + \frac{5}{(Gr_d)^{\frac{1}{4}}}\right\}} \qquad (4)$$

where Nu_d is the Nusselt number

Gr_d is the Grashof number for cylinders of diameter d

The Nusselt number is a dimensionless number containing the heat transfer coefficient. The Grashof number is another dimensionless number expressing the thermal and fluid conditions of the cylinder and the flow round it.

For the large values of Gr_d that obtain, equation (4) becomes

$$Nu_d \simeq 0.4(Gr_d)^{\frac{1}{4}}$$

so that the heat transfer coefficient is approximately proportional to $1/d^{\frac{1}{4}}$, thus α does not vary very much with d and so the assumption of constancy for the cooling correction gave a fair approximation.

For laminae^7 of thickness x, e.g. grass

$$Nu_x = 0.360\ (Gr_x)^{\frac{1}{4}}$$

and

$$\bar{\alpha} = 4/3\ (\alpha_x)$$

where $\bar{\alpha}$ is the mean heat transfer coefficient

and α_x is the heat transfer coefficient at x .

Strictly this is only valid for vertical plates but the loss from hot horizontal surfaces facing upwards^7 exceeds the loss from vertical surfaces by a fraction similar to that by which the heat loss from a vertical surface exceeds the heat loss from a downward pointing surface. The resultant effect is the same as if all surfaces were vertical. Dead grass is of course usually not vertical.

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* In fact, of course, the sticks are not in free space but are within a fuel bed so this is still only an approximation.

5. Discussion of results

This year's data comprise:-

3 head fires, two unfortunately in light winds, and 1 flank fire in a light wind and in a clearing. This latter might almost be regarded as a still air fire.

5.1. Head fires

As in previous fires[1,2,3] it can be seen from Table 2 that the observed rate of spread could not possibly have been accounted for by radiation through the fuel bed alone since if fuel bed radiation were the only source of heat there would be no spread at all or a much lower rate of spread than that observed. From Table 2 we can construct the summary Table 3.

Table 3. Summary of heat balances

Fire number	Bed radiation W/cm^2	Heating due to flame radiation W/cm^2	Total heating available W/cm^2	Total heating required (calculated) $R\rho_b \Delta H + 2.67\alpha\theta_o$ W/cm^2
1	3.4	2.7	6.1	12.5
2.	3.1	5.3	8.4	27.5
4	4.2	15.4	19.6	27.0

Since the equation of fire spread is a heat balance it is simpler to talk in terms of heating rather than spread and it is easy to convert back into rate of spread. However, due to the cooling correction the rate of spread is not directly proportional to the total heating. In each case the head fire spread faster than estimated from heating measurements.

In the case of fire No. 2 it may be that the value of total heating required had been over-estimated. The fuel bed for this fire contained 14 per cent by weight of fine grass and as in the mixed fuel head fire in 1966[2] it may well be that this fire spread as if only the grass were present. Then the calculated heat required to maintain spread is reduced from 27.5 W/cm^2 to 5.5 W/cm^2 and this is about equal to the total heating available.

Assuming the grass to be the only fuel which burned in the burning zone also brings down the theoretical flame length to nearer the measured value (Table 2) and the relationship for flame length has in general in the past been found reliable. The measured average residence time, the time of flaming of a particular piece of fuel, of 9 secs is more likely to correspond to fine grass than heath. In the case of fire No. 2 the presence of fine grass may also have speeded up the rate of spread. In the case of fire No. 1 the discrepancy in the heat balance may also be due to the presence of dry grass.

This still leaves the gorse fire (fire No. 4) for consideration. Whilst the discrepancy in the heat balance is not very large, the Home Office Manual of Firemanship[8] states that "gorse is liable to cast showers of sparks which may be carried long distances and may continue to burn for some time," and this may account for this discrepancy. The high values of intensity given by the cans of water is probably due to heating by ash and glowing embers after the fire had passed.

5.2. Flank fire

The rate of spread in fire No. 3 observed here gave a total heating requirement commensurate with what might be expected, including a reasonable estimate of flame radiation:-

Table 4. Heat balance of flank fire

Fire number	Bed radiation (measured) W/cm^2	Heating due to flame radiation (estimated) W/cm^2	Total heating available W/cm^2	Total heating required W/cm^2
3	2.9	7.4 to 8.3	10.4 to 11.3	10.4

Here we have no measured value of flame radiation but in the light of knowledge already obtained[3] it is reasonable to expect heating due to flame radiation to be some $2\frac{1}{2}$ times that due to bed radiation.

The theoretical value of the ratio

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

inserting the measured values of flame temperature, flame length, bed radiation, flame angle, and estimating E_f from flame thickness, is 2.8.

The smaller components of the other fuels were included in the burnt fraction and constituted 44 per cent of this fraction. Hence it would seem that this fire was not controlled by the grass alone. Thus flank or still air fires in mixed fuels are probably not grass controlled unlike head fires in mixed fuel.

5.2.1. Attenuation coefficient, flame length and flame angle

It was only possible to obtain attenuation coefficients in two cases. In the case of fire No. 2, the heath and grass fire, the measured value (Table 2) shows good agreement with that calculated from[4] :-

$$a = \frac{\sigma \rho_b}{4 \rho_f} \qquad (5)$$

where a is the attenuation coefficient

ρ_f is the density of the solid fuel

and σ is the surface per unit volume taken as 4/diameter for needles and 1/thickness for grass.

For fire 2 the agreement is not good when the fire is regarded as grass only, indicating that the heath had a part in attenuating the radiation even if it did not contribute much to the spread.

In the case of the gorse fire the agreement is not good probably because the radiometer was placed too near the ground where the vegetation was less thick, the needles being denser towards the top of the bush.

In general the formula[9]

$$L = 400\, \dot{m}'^{\frac{2}{3}} \qquad (6)$$

where L is the flame length (cm)

and $\dot{m}'$ is the burning rate per unit width of fire front (C.G.S. units)

gives values of flame length in good agreement with those observed. There are two fires where the agreement is not good. Fire 2 is probably really a grass fire thus $\dot{m}'$ is overestimated and in fire 4 $\dot{m}'$ may be overestimated due to spotting.

The flame angle formula[10]

$$\cos \phi = 0.69/U^{*\,0.49} \qquad (7)$$

gave rather poor agreement with the angles observed, tending to overestimate deflection. This is in agreement with last year's findings and is in spite of the wind speed being measured at the fuel height.

6. Conclusions

(1) Flame radiation is probably the controlling factor in fire spread in head fires in the field, but head fires spread faster than present theory calculates.

(2) Head fires in mixed fuels (for which no theory exists) containing an appreciable quantity of dry grass probably spread as fast as they would if only the grass were present, i.e. are grass controlled.

(3) Conclusion (2) is probably only valid for head fires.

(4) The rate of spread of a head fire in gorse may be influenced by spotting.

(5) The laboratory relationship for flame angle and windspeed is not valid in the field.

7. Acknowledgements

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TABLE 2

Observed and derived data

1 Number and type of fire	2 Date	3	4 Fuel type	5 Rate of spread R cm/s	6 Total bulk density ρ_b total mg/cm^3	7 Fraction burnt per cent	8 Bulk density of burnt material ρ_b burnt mg/cm^3	9 Mass burning rate per unit area of fire front R ρ_b $\dot{m}''$ mg cm^{-2}s^{-1}	10 Wind speed (at fuel ht) U cm/s	11 Dimensionless wind speed U*	12 Flame angle to vertical ϕ degrees	13 Moisture content of fuel per cent	14 Ignition enthalpy ΔH J/g	15 Bed radiation intensity I W/cm^2		16 Mean flame temp. T_f °C
1 Head	12.3.68	Observed Theoretical	Heather 97% Grass 3%	8.8 No spread[1]	2.43	43	1.05	9.3	75	1.07	45 48^2	30	1065	radio-meters 3.35	cans 8.4	1050
2 Head	13.3.68 a.m.	Observed Theoretical	Heath 86% Grass 14%	21 No spread[1]	2.71	63	1.7	36	417	4.05	50 70^2	Heather 30 Grass 18 Weighted mean 27.5	1010	3.12	11.6	1070
3 Flank	13.3.68 p.m.	Observed Theoretical	Gorse 46% Heath 25% Grass 29%	2.8 No spread[1]	7.2	52	3.75	10.5	112	1.72	40 58^2	Gorse 26 Heath 30 Grass 9 Weighted mean 17	785	2.96	0.96	1010
4 Head	14.3.68	Observed Theoretical	Gorse	15 0.13^1	3.09	48	1.5	22.5	127	0.935	30 46^2	35	1180	4.2	9.2	1080
2 A.Head[8]	13.3.68 a.m.	Observed Theoretical	Grass	21	0.38	100	0.38	8.0	417	6.85	50 74^2	18	810	3.12	11.6	1070

Notes

1. From equation (2) neglecting flame radiation
2. From equation (7)
3. From equation (6)
4. From equation (5)
5. From equation (3) Theoretical values derived from theoretical values of flame radiation calculated from flame temperature assuming $E_f = 1 - e^{-0.003D}$ where D is the thickness of the flame in cm
6. Calculated assuming zero flame angle since this was a flank fire
7. From equation 4
8. Values calculated for fire No.2 assuming that only the fine grass burnt
9. From equation (2)

TABLE 2 (cont'd)

1	17	18	19	20	21	22	23	24	25	26	27	28	29
Number and type of fire	Flame radiation I_f E_f W/cm^2	Fuel height h cm	Mass burning rate per unit width of fire front $\dot{m}'$ $g\ cm^{-1}s^{-1}$	Flame length L m	Length of burning zone D m	Residence time t_b s	Attenuation coefficient a cm^{-1}	Black body radiation at T_f W/cm^2	Ratio of heating by flame radiation to heating by bed radiation[5]	Mean dia. of burnt material cm	Heat transfer coefficient from fuel bed $\propto$ $W\ cm^{-2}\ {}^{o}C^{-1} x 10^{-3}$	Heat loss from fuel $2.67 \propto \theta_o$ W/cm^2	$R\ \rho_b\ \Delta H \cos \phi + 2.67 \propto \theta_o$[9] W/cm^2
1 Head	0.95 4.55	50	0.464	2 2.35^3	1.0	11	-	17.5	0.8 2.4^5	0.05	7.4^7	5.5	12.5
2 Head	2.5	40	1.45	1.3 5.1^3	1.8	9	0.032 0.035^4	18.3	1.7 3.1^5	Heath 0.06 Grass 0.016 (thickness not dia) x 0.25 width	Heath 6.5^7 Grass 1.72	4.0	27.5
3 Flank	-	35	0.368	1.7 2.05^3	1.1	39	-	15.4	2.8^6	Heath 0.035-08 Gorse 0.1 Mean 0.08	5.5^7	4.15	10.45
4 Head	5.4	150	3.37	5.0 9.0^3	3	20	0.035 0.016^4	19.0	3.75 5.3^5	0.12	5.3^7	4.0	27.0
2A Head[8]	2.5	40	0.32	1.3 1.8^3	1.8	9	0.032 0.0075^4	18.3	1.7 3.1^5	0.016 thick x 0.25 wide	1.72^7	1.3	5.5

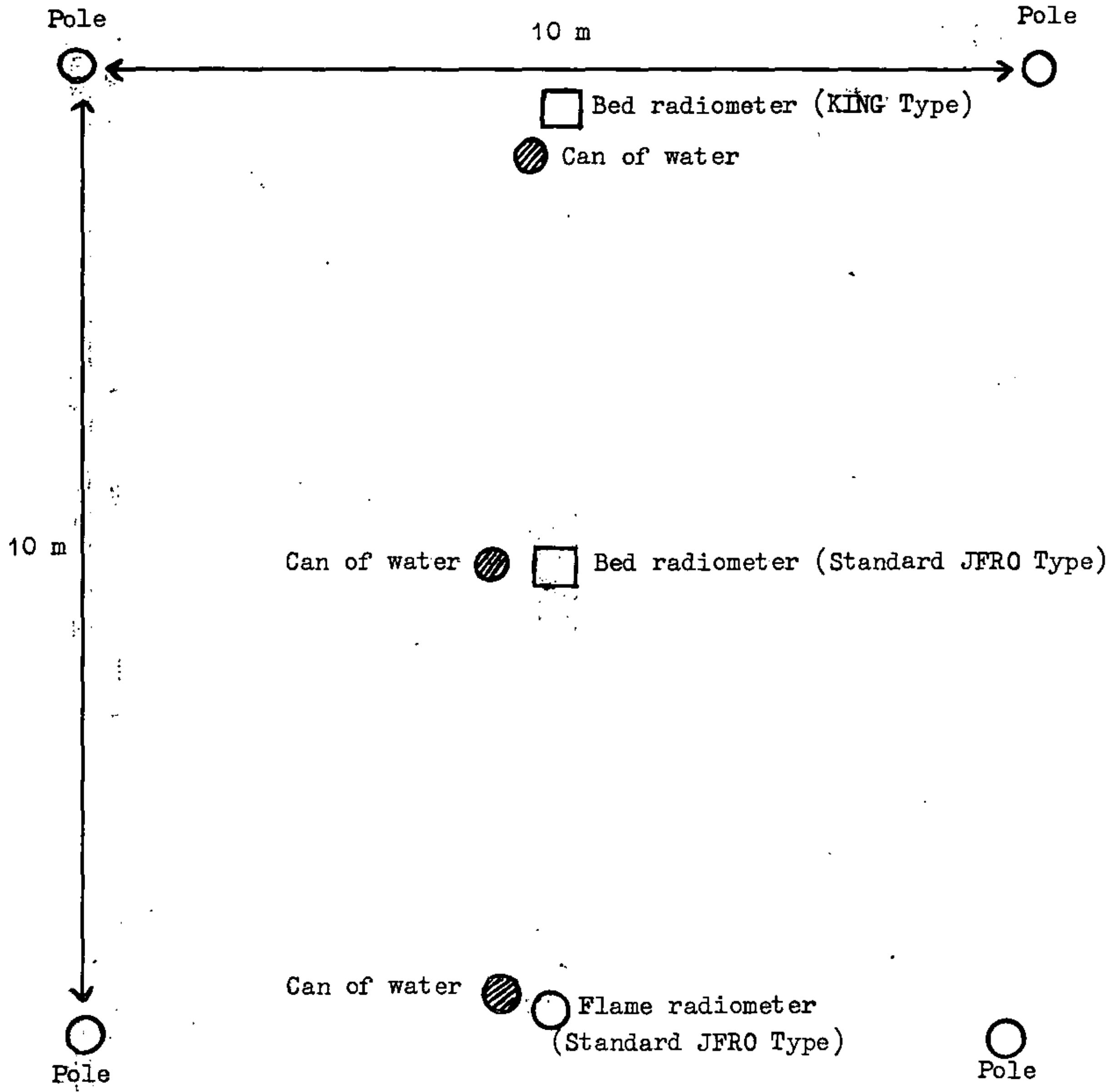

FIG. 1. LAYOUT OF STANDARD PLOT