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A REPORT ON FOREST FIRE FIELDWORK
(NEW FOREST, MARCH 1966)

by

M. J. WOOLLISCROFT

January, 1968

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SUMMARY

Measurements were made during controlled fires in heathland fuels in order to test relationships found to be valid in the laboratory.

In general fire spread theory based on a heat balance seems to be valid but in the field radiation from the flames appears to be a significant or even the controlling factor.

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

A REPORT ON FOREST FIRE FIELDWORK (NEW FOREST, MARCH 1966)

by

M. J. Woolliscroft

1. Introduction

As in the previous year[1] a team from the Fire Research Station visited the New Forest in March 1966 in order to take measurements at controlled burnings carried out by the Forestry Commission. The purpose of this visit was:

a) to confirm data obtained from last year's backing fire;

b) to obtain detailed data on head fires, e.g. rate of spread, radiation intensity and in particular, flame radiation;

c) probably most important of all, to obtain information and experience which would assist in interpreting the data on the fire record cards which are being filled in by foresters.

2. The Fires

A summary of the fires is given in Table 1 below:

Table 1

Summary of Fire Conditions

Date	Type of fire	Wind	Fuel and Notes
16.3.66.	Backing	Light	Gorse. Dense and uniform, 1 metre high. Difficult to keep fire alight.
17.3.66.	Head	Gentle breeze	Heather. Uniform fuel. Fast and constant rate of spread. Open heathland.
17.3.66.	Backing	Gentle breeze	Heather. Fire spread up a 20° slope. Only measurement was rate of spread with a line of poles. No radiometers.
18.3.66.	Head	Light and variable in direction	Mixed fuel. Dwarf Gorse, Cross-leaved Heath and Fine Grass. This fire was carried out in a clearing. The coverage was patchy and the height non-uniform. Later it will be considered as:- (1) a mixed fuel fire. (2) a fine grass fire.

3. Measurements and Results

The rate of spread was obtained regardless of direction of spread from the times at which the fire front reached each pole of a rectangular matrix of poles. Fuel height was measured directly and, with a measurement of weight of fuel per unit area, gave a measure of bulk density. This was corrected later to allow for the unburnt fuel. A sample of the unburnt fuel was broken down into size ranges and the size/weight distribution of the fuel was obtained approximately. The minimum diameter of unburnt fuel was measured from a sample of the residue remaining after the fire. Thus from the above size weight distribution an estimate was made of the percentage of fuel burnt. Radiation intensity was measured by means of radiometers based on the design of King(2) as described in the 1965 report[1]. There was, however, some difficulty due to the wires breaking internally and the mineral-insulated copper-covered connecting leads proved unwieldy. The instrument has since been redesigned.

Cans of water were used to measure heating intensity. The lengths of the burning zone, flame lengths, flame angles, etc. were obtained from photographs. The wind speed was measured near the ground since the fuel bed is in the boundary layer of the atmosphere and the velocity effective in bending the flames is much lower than the free stream wind speed. Flame temperature was obtained by means of a disappearing-filament pyrometer and temperature of the burning wood by means of a thermocouple embedded in a gorse stem. Detailed results are given in Table 2.

The measurements of heating intensity were obtained directly from the temperature rise of the water in the cans. A laboratory test with a bed of sampled heather gave a similar temperature rise to that recorded in the field and the temperature fell only $\frac{1}{2}$ degC in ten minutes. The wood temperature recorded in the laboratory (765°C) was of the same order as the field value of 685°C. Residence times are based on the measured length of burning zone and the rate of spread but a sample of heather exposed in front of the radiant panel to an intensity of 4 W cm^{-2} burned for about 50 s which is comparable, though somewhat larger, to the residence time of 35 s in Table 2. There was no very noticeable difference between results given by the black and the shiny cans; the latter became covered in tar in the 1965 tests and temperatures obtained by last year's extrapolations appear to be incorrect. Clinical thermometers placed in the cans this year did not register a rise in temperature, although they should have done so if last year's extrapolations had been valid.

4. Theoretical Background

4.1. Equation for fire spread

The equation for spread of fire that has been developed from laboratory experiments is:

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

where R is the rate of spread, ρ_b is the bulk density of the fuel, ΔH is the heat required to raise unit weight of the fuel to ignition, i_o is the radiation intensity and $2.67 \alpha \theta_o$ is a cooling correction. All this equation really says is that the heating intensity in the fuel bed is equal to the heat necessary to raise the fuel to ignition temperature. The above equation should apply for still air conditions, for thin flames (which do not therefore contribute significantly to the heating of the fuel), and for thick fuel beds where most of the heat comes from the glowing sticks or embers; convection is assumed to be negligible. These conditions give a vertical flame front.

It has been suggested[4] that the effect of wind is to incline the burning zone and that the rate of spread perpendicular to the front is the same as for still air, see (Fig. 1).

Equation (1) then becomes

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

4.2. Ratio of flame and fuel bed radiation

It can be shown (see Appendix) that for a wide inclined flame the ratio of heating by flame radiation to heating by radiation through the fuel bed is given by:-

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

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

ø 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.

Comparison of flame radiation to bed radiation is made in the last line of Table 2. The "observed" values are based on observed values of flame radiation and the "theoretical" values on $E_f = 1 - e^{-.003D}$ where D is flame thickness in cm.

5. Discussion of Results

5.1. Rate of spread and radiation intensity

5.1.1. Backing fire in gorse

This can be compared with a backing fire in gorse observed in 1965 (see Table 3).

Table 3

Comparison of data for two backing fires in gorse

	1965	1966
R cm/s	1.7 - 2.6	0.9
Peak intensity i_o from radiometers W cm^{-2}	3.8	3.9
Flame height cm	150	200
Length of burning zone cm	75	125
P_b total mg cm^{-3}	2.5	7.3
P_b burnt mg cm^{-3}	1.4	4.0

However, as in 1965, the spread cannot be entirely accounted for by radiation through the fuel bed. No direct data on flame radiation or flame temperature and thickness from which flame radiation could be derived are available for the 1966 gorse fire so that the ratio of flame radiation to bed radiation for this fire cannot be found, but the measured bed radiation was 3.9 W cm^{-2} and the theoretical value on the basis of equation (1) was $i_o = 9.8$ W cm^{-2}, over twice that measured, suggesting that heat transferred from the flame was about as important as bed radiation. To some extent the discrepancy

5.1.1. Backing fire in gorse (Cont'd.)

between the observed rate of spread and that expected from the bed radiation theory may be due to the inhomogeneity of the fuel in the field. The theory was verified in the laboratory for cribs of uniform stick size. In the field there is a wide range of stick sizes. An attempt has been made to correct for this by deducting an estimate of the weight of the unburnt fuel as described in section 3. It is still, however, probable that there are two or more burning zones. In the first only light fuel burns and this gives rise to the high rate of spread. Behind this burns some of the thicker fuel. Controlled experiments with non-uniform fuel beds or modifications to the theory are needed to resolve this problem fully.

Table 2 shows that the observed and theoretical values of flame length are in close agreement.

5.1.2. Backing fire in heather

The value of $R\rho_b \quad H + 2.67\alpha\theta_o$ (equation (1)) was 8.0 which is comparable with that for the 1966 backing fire in gorse (9.8). The fire spread faster than the 1966 gorse fire because although the bulk density ρ_b was nearly the same, heather has a lower moisture content and hence its ignition enthalpy, i.e. the heat required to bring the fuel to ignition is lower (1250 J/g).

5.1.3. Head fires

The comparison of observed and theoretical values of R given in Table 2 (fires 2, 4 and 4a, R calculated from equation (2) with i_o as the observed value of radiation intensity) shows that the rate of spread of both the head fires was substantially greater than could be accounted for by radiation through the fuel bed alone, indicating that flame radiation or convection transfer must be significant or even the controlling factor.

Fire 4a is a different interpretation of fire 4.

Initially it was assumed on the basis of an examination of samples of the fuel and the residue that the grass and the cross-leaved heath and some of the gorse had burnt in the burning zone, 56 per cent of the total weight in all (see note on data sheet explaining how this was obtained). However, this proportion of the fuel burning at the measured rate of spread would have required an impossibly high heating intensity (71 W cm^{-2}) and gave theoretical values of flame length much greater than that observed. Also the burning and residence time of 10 secs was much too low for heather or gorse.

For fire 4a the fuel was regarded as consisting of grass only, and a much more realistic value of required heating was obtained. Also flame length, flame angle etc. were much closer to the theoretical values on this basis. This indicates that where there are mixtures of fuels, the thinner fuel tends to control the rate of spread. This is not to say that the rest of the fuel does not burn but it does so much more slowly and not in the main burning zone, which may be very important for analysing the card fire data.

5.2. Attenuation of radiation and flame length

Some mention should probably be made of attenuation and flame length since, among other things, these are important for estimating the distance ahead of the fire from which is heated by the fire and hence for determining fire breaks. The attenuation coefficient is a measure of the reduction of the heating intensity as it passes through the bed. The theoretical values of attenuation coefficient 'a' derived from the formula[2]

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

where ρ_f is the fuel density, σ is the surface per unit volume = $4/_d$ for thin needles (where d is the stick or needle thickness), are shown in Table 2 to be comparable with those obtained from the radiometer traces, (Fig. 1).

Apart from test 4, which has been shown to be a misinterpretation, Table 2 also shows that the observed and theoretical values of flame length are in reasonable agreement. The theoretical values of flame length have been derived from the formula[5]

$$L = 400\ \dot{m}'^{\frac{2}{3}} \qquad (5)$$

where L is flame length in cm and $\dot{m}'$ is mass burning rate per unit width of fire front in c.g.s. units.

In contrast to last year there is also good agreement between the observed flame angles and the theoretical values[6] obtained from:-

$$\cos \phi = 0.69/U^{*0.49} \qquad (6)$$

The measured flame angles also fit well with other data plotted against a Froude Number $U/\sqrt{gh}$ where U is the wind speed and h the flame height.

6. Conclusions

(1) Heating from flames does contribute substantially to fire spread. In the case of the head fires investigated in the course of this work heating from flames is probably the controlling factor. The rate of spread even in a backing fire was higher than calculated and this, too, may be due to flame radiation.

(2) The laboratory relationship for flame length fits the data from these fires. This year's data show good agreement with theoretical values although last years do not.

(3) This work has succeeded in its main aims of verifying some of last year's findings and of obtaining more detailed data on head fires. Information has been obtained which will be valuable in classifying the fire card data, in particular the suggestion that in the case of mixed fuels containing fine grasses, the fine grass controls the rate of spread.

7. Acknowledgements

Thanks are due to Mr. R. Hodgson of the Forestry Commission without whose co-operation and considerable assistance this work would not have been possible, and to Mr. S. Atallah who was in charge of the team in the field while working at the Joint Fire Research Organization during sabbatical leave from Tufts University, Massachusetts, U.S.A.

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APPENDIX

The ratio of the heating of a fuel bed by an inclined flame to the heating through the fuel bed

The configuration factor of an inclined flame (Fig. 2) at any point on the plane of the fuel bed is $\frac{1}{2}(1 - \text{Cos } w)^7$.

Hence the total heating of the fuel by the flame is given by

$$\int_{-\infty}^{0} \frac{i_f E_f}{2} (1 - \cos w)\, ds$$

where $i_f E_f$ is the intensity of the flame and neglecting change in thickness along the flame.

Referring to (Fig. 2), $h = L \text{ Cos } \phi$

$$r = \frac{h}{\text{Sin } w}$$

$$\therefore \quad r = \frac{L \text{ Cos } \phi}{\text{Sin } w}$$

$$ds = \frac{r dw}{\text{Sin } w}$$

$$ds = \frac{L \text{ Cos } \phi \, dw}{\text{Sin}^2 w}$$

$$\therefore \quad \text{Total heating} = \int_{0}^{\frac{\pi}{2}+\phi} \frac{i_f E_f}{2} (1 - \text{Cos } w) \frac{L \text{ Cos } \phi \, dw}{\text{Sin}^2 w}$$

$$= \frac{i_f E_f}{2} L \text{ Cos } \phi \int_{0}^{\frac{\pi}{2}+\phi} \left(\frac{1}{\text{Sin}^2 w} - \frac{\text{Cos } w}{\text{Sin}^2 w} \right) dw$$

The integral becomes:

$$\left\{ - \text{Cot } w + \frac{1}{\text{Sin } w} \right\} = \frac{1 - \text{Cos } w}{\text{Sin } w}$$

As $w \to o$ this tends to $\frac{1 - (1 - w^2/2)}{w} = \frac{w}{2} \to o$

Thus the total heating by an inclined flame is

$$i_f \, E_f \, \frac{L \operatorname{Cos} \emptyset}{2} \left(\frac{1 + \operatorname{Sin} \emptyset}{\operatorname{Cos} \emptyset}\right) = i_f \, E_f \, \frac{L}{2} \, (1 + \operatorname{Sin} \emptyset)$$

$$= \frac{I_o L}{2} (1 + \operatorname{Sin} \emptyset)$$

where $\emptyset$ is the angle between the flame and the vertical

The heating through the fuel bed is

$$I_B \, E_B \, h$$

$$\frac{i_F \, E_f \, L \, (1 + \operatorname{Sin} \emptyset)}{2 \, I_B \, E_B \, h}$$

Since deriving this quantity the author has found that a similar result has been obtained by Van Wagner[8].

Table 2

Detailed results

Units		March 16th		March 17th				March 18th			
		1		2		3		4		4a[1]	
		Gorse (backing fire)		Heather (head fire)		Heather (backing fire, up 20° slope)		Dwarf gorse, cross leaved heath and fine grass (head fire)		Fine grass (head fire)	
		Observed	Theoretical	Observed	Theoretical	Observed	Theoretical	Observed	Theoretical	Observed	Theoretical
cm/s	Rate of spread R	0.89	0.35 eqn (1)	6.75	1.77 eqn (2)	1.17		14.6	0.85 eqn (2)	14.6	5.0 eqn (2)
mg/cm^3	Total bulk density ρ_b total	7.26		6.81		6.81		5.84		0.73	
-	Per cent burnt[2]	55		43.5		43.5		56		100	
mg/cm^3	Bulk density of burnt fuel ρ_b burnt	4.0		2.96		2.96		3.27		0.72	
$mg\ cm^{-2}s^{-1}$	Mass burning rate per unit area $\dot{m} = R\ _b$ burnt	3.6		17.8		3.46		47.7		10.7	
cm/s	Wind speed U	68		133				42.5		42.5	
Dimensionless	U*	1.05			1.66	2.05		0.39		0.65	
-	Flame angle to vertical ø	40°	48° eqn (6)	60°	62° eqn (6)	20°		35°	0° eqn (6)	35°	30° eqn (6)
-	Per cent moisture	59		38		38		59, 40, 25		25	
J/g	Ignition enthalpy H	1710		1250		1250		1800[3]		960	
°C	Temperature of burning wood T							685			
W/cm^2	Radiation intensity I	Radio-meters 3.9 Cans 0.3	9.8 eqn (1)	Radio-meters 4.25 Cans 4.5	16.2 eqn (2)		8.0 eqn (1)	Radio-meters 4.15 Cans 7.3	4.73 eqn (2)	Radio-meters 4.15 Cans 7.3	12.0 eqn (2)
°C	Flame temperature							980°C		980°C	

Table 2 (Cont'd.)

Detailed results

Units		March 16th		March 17th				March 18th			
		1		2		3		4		4a[1]	
		Gorse (backing fire)		Heather (head fire)		Heather (backing fire, up 20° slope)		Dwarf gorse, cross leaved heath and fine grass (head fire)		Fine grass (head fire)	
		Observed	Theoretical	Observed	Theoretical	Observed	Theoretical	Observed	Theoretical	Observed	Theoretical
W/cm^2	Flame radiation[4]				4.4[5]			2.85	4.22	2.85	4.22
cm	Fuel height h	100		40		40		35		35	
gm cm^{-1} s^{-1}	Mass burning rate per unit width of fire $\dot{m}'^{1}$	0.36		0.71		0.139		1.65		0.37	
m	Flame length L	2.0	2.0 eqn (5)	2.3	3.15 eqn (5)			2	5.7 eqn (5)	2	2.08 eqn (5)
m	Length of burning zone D	1.25		2.4		2.4		1.4		1.4	
s	Residence time t_b		140 $D = Rt_b$		35 $D = Rt_b$				10 $D = Rt_b$		10 $D = Rt_b$
cm^{-1}	Attenuation coefficient a	0.067	0.044	0.025	0.037						
Dimensionless	Ratio of flame heating to bed heating - eqn (3)				5.65			3.1	4.6	3.1	4.6

Notes:

1. This was in fact the same fire as fire 4, but the quantities tabulated are derived by assuming the fuel effectively to consist of fine grass only. The values of $\rho_b \Delta H$, residence time, flame length and so on are then more realistic.
2. Per cent burnt. This was obtained by breaking down samples of unburnt material into stems, leaves etc, weighing, and then comparing measured diameters of these samples with the minimum diameter of samples of the stems and branches remaining after the fire.
3. Includes an allowance for drying of the stems not actually burnt.
4. Measured value corrected for flame angle, radiometer pointing vertically upwards. Theoretical value obtained from $E = 1 - e^{-0.003\Delta}$ where $\Delta = D \cos \phi$.
5. Calculated on an assumed flame temperature of 1000°C.

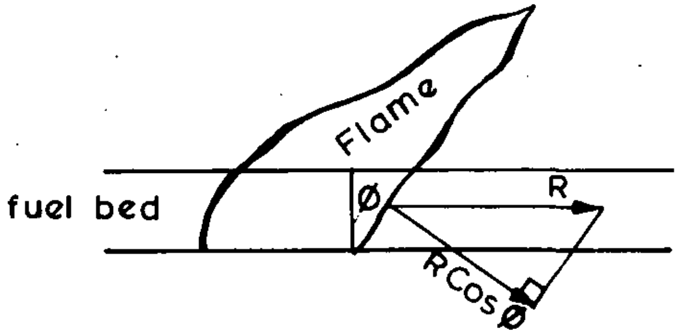
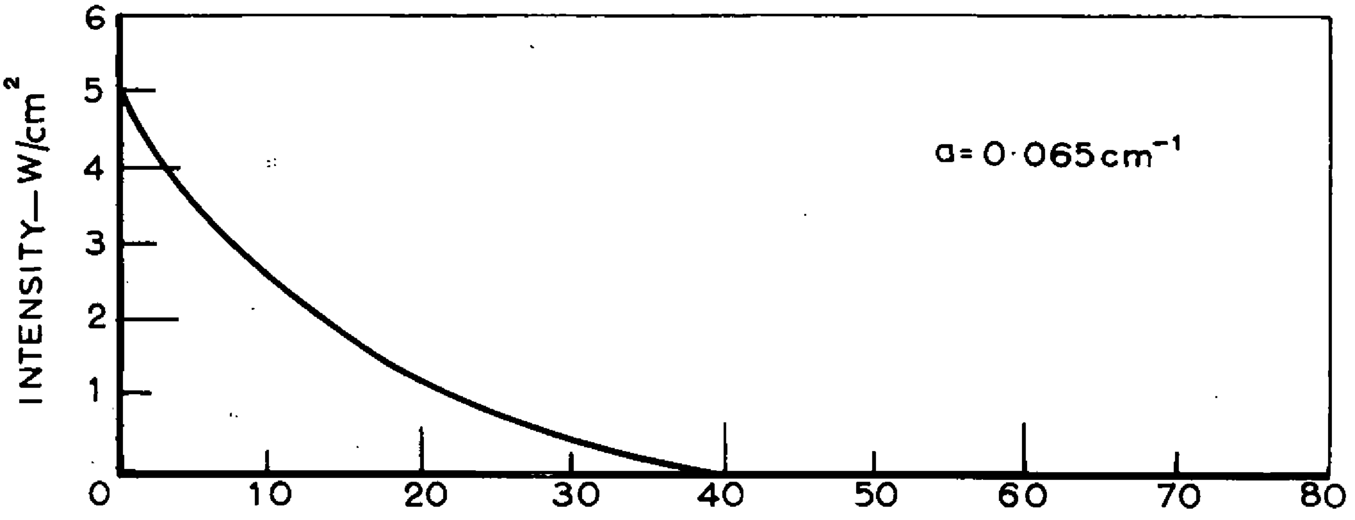
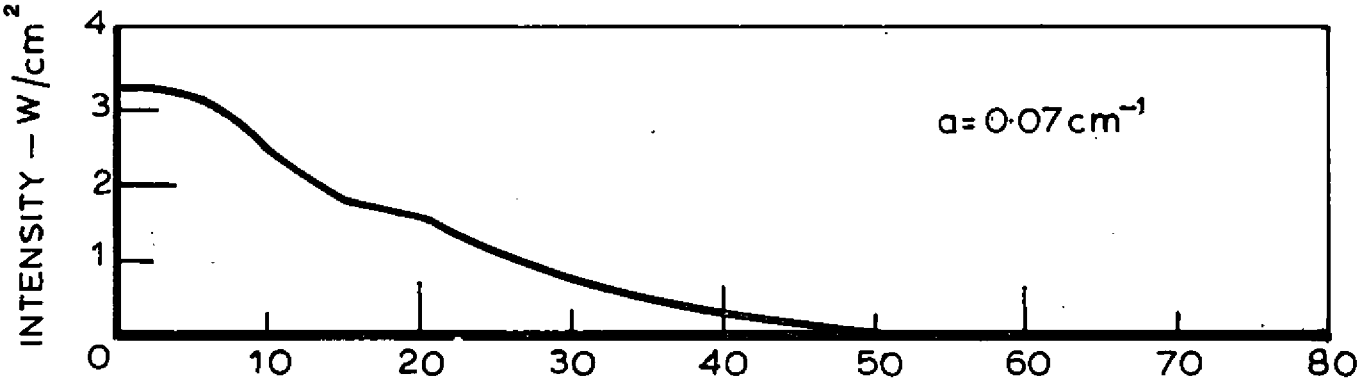


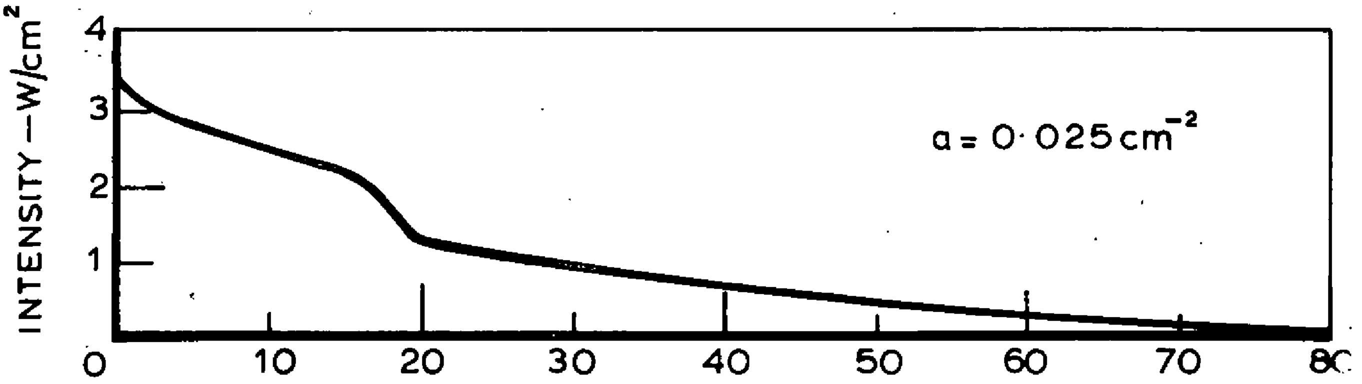
FIG.1. DIAGRAMMATIC VIEW OF INCLINED FIRE FRONT



(a) FIRE No.1. RADIOMETER 5



(b) FIRE No.1. RADIOMETER 1



(c) FIRE No.2. RADIOMETER 4

Values for the attenuation coefficient 'a' derived from the above curves are shown

FIG .2. VARIATION OF RADIATION INTENSITY WITH DISTANCE FROM FIRE FRONT

FR. 003 1/7051

FR. 6.03 1/7952.

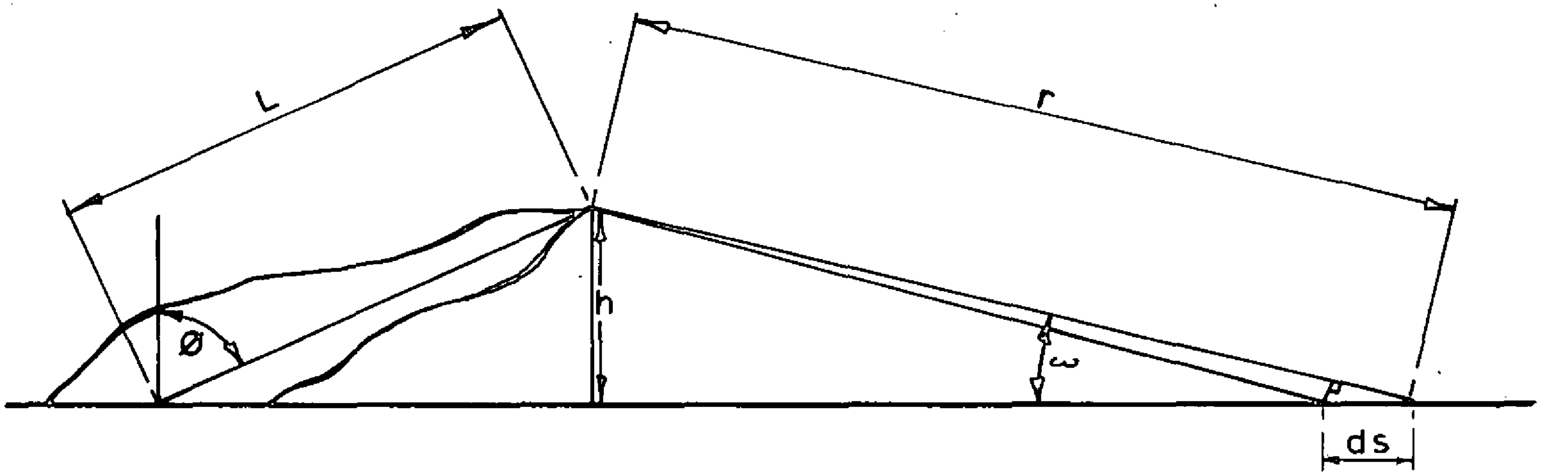


FIG.3. FLAME RADIATING TO A FUEL BED