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A REPORT ON FOREST FIRE FIELDWORK (NEW FOREST, MARCH 1965)

by

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SUMMARY

Measurements have been made during some controlled fires in gorse. These have included the rate of fire spread and the heat transfer to a radiometer and to cans of water in the path of the advancing fire.

The heat transfer rates agree closely with values obtained in the laboratory for wood cribs and the rates of spread are only slightly less than those calculated from the bulk density of the fuel using relations derived from laboratory experiments. Flame lengths are in good agreement with an extrapolation of laboratory data but flame deflections are not. Nevertheless it is thought that the basic mechanism controlling fire spread in deep cribs, i.e. the heating of unburned fuel by radiation through the fuel bed, is the same for these fires in gorse, though there may be some contribution from the flames above the fuel bed.

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

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1. Introduction

For some years laboratory data have been obtained by the Joint Fire Research Organization and by groups of research workers in the U.S.A. on fire spread in idealised forest fuel beds made of wood cribs. These cribs are made of layers of uniformly spaced, square section sticks, the sticks of each layer being at right angles to those of the layer below. The mechanism of fire spread in this type of fuel bed is becoming fairly well understood, at least in still air, but the laboratory experiments can only give methods of predicting rates of spread in idealised conditions. Controlled fires in the field provide an opportunity to obtain comparative measurements under practical conditions and field data from controlled burns have been collected in two ways, firstly by Foresters, who have filled in standardised data cards giving rate of fire spread and related factors, and secondly by the J.F.R.O. who have made measurements at a controlled fire at Godshill in the New Forest to obtain some quantitative information on heat transfer, wind speed and rate of spread.

This report gives the results of the measurements at Godshill and analyses their relationship with the theoretical equations. The data obtained from the cards will be discussed elsewhere.

2. The fires

The area burned was situated north east of Forest Brook Farm at Godshill, National Grid Reference SU182148, 25 in Ordnance Survey plan SU1814 and 6 in O.S. plan SU11SE (see Fig.1). It was covered mainly with gorse. In the morning a backing fire was started to create a fire break as far as the track running E.S.E. downhill. This backing fire had a fairly constant direction and rate of spread, and useful measurements were made.

The afternoon fire tended to spread up the hill across the wind and will therefore be referred to as a flank fire. The variation in wind strength and direction and the variability of the slope caused the fire to change speed and direction frequently and suddenly and it was therefore difficult to obtain measurements. There was also a failure of the recording equipment during this fire.

Only the thinner parts of the gorse were destroyed, the thicker branches remaining unburnt.

3. Measurements and results

3.1. Field measurements

Tables 1A and 1B record the measurements taken during the fires and Fig.2. shows the position of marker poles, radiometers and cans of water.

The matrix of poles was used to estimate rate of fire spread, the time at which the fire reached each pole being noted. The fires were started many metres away from each matrix of poles and the fire was thus fully developed by the time it reached the matrix.

The intensity of radiation was measured by convection-compensating radiometers developed from the design of King (see Appendix) and the readings are given in Figs 3a, b, c.

The cans of water were placed in pairs, one black and one shiny. Although convection transfer should be the same for both cans the radiation transfer will be different because of the different absorbtivity so that the difference between the temperature rises of the two cans is a measure of the total energy received by radiation transfer. The water temperatures were measured before and after the fire had passed and were corrected for heat loss by means of cooling curves. These readings were also used to estimate a mean heat transfer rate by dividing them by the residence time of the cans in the burning zone. Flame height and length* of burning zone were obtained visually. Fuel weights were measured by cutting vegetation from a defined plot and weighing it with a spring balance. Flame deflection was determined from photographs.

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*This is often referred to as depth of burning zone but it is preferred to retain length for the measure along the direction of spread.

Table 1A

Measurements at morning fire

Relative humidity	70 per cent
" " (previous day)	74 " "
Wind speed readings (cm/s)	350 305 320
Air temperature	19°C
Height of gorse bushes	Approx. 80 cm
Ground coverage	80-90 per cent
Weight of gorse on 2.3 m^2	4.5 kg
Filament pyrometer reading	1100°C (Corrected value 1050°C)
Flame angle to vertical (visual)	0°

Time (zero taken when fire reached first pole) min	s	Position reached by fire front (letters refer to Fig.2)
0	0	F
4	05	E Markers at 6 m
4	35	A intervals on
7	00	D square matrix
9	00	B Fig.2
11	30	C

Temperature of water in cans - °C

Time		Cans at E (1)		E (2)		between C & D		D	
min	s	shiny	black	shiny	black	shiny	black	shiny	black
0	0	20	20	20	20	20	20	20	20
8	15	33							
9	30		41	38	44			31	34
10	30								
12	30	36	39	38	41			33	34
14	45								
17	06					38	47		

Table 1B

Measurements at afternoon fire

Wind speed readings (cm/s)	220 550
Height of gorse bushes	Up to 150 cm
Ground coverage	50 per cent
Length of burning zone	60-90 cm
Flame angle to vertical (visual)	0 - 50°

Time min	Time s	Position reached by fire front	
0	00	M	
1	00	L	
3	10	H	Markers at 7.5 m
6	10	K	intervals on
11	00	G	square matrix
11	40	D	Fig.2.
13	10	A	

Temperature of water in cans °C

Time min	Time s	H shiny	H black	K shiny	K black	G shiny	G black	D shiny	D black
0	0	23	23	18	20	24	22	24	22
9	40	34	47						
19	30	32	41						
19	40			35	39				
21	10					36	33		
22	25							46	42
23	40								

Samples of gorse were collected for laboratory measurements.

3.2. Laboratory measurements

The distribution by weight and diameter of the gorse stems, branches and needles is given in Table 2.

Table 2

Distribution of size and weight of gorse samples

	Stem	Branch	Needles
Diameter cm	1.5 - 0.6	0.6 - 0.13	0.13 - 0.04
Weight per cent	45	18	37

The percentage weight of needles compares closely with that determined by Muraro[2] for Douglas Fir slash. If it were assumed, in the absence of other data, that the weight of all equal ranges of needle size were the same, the specific surface of the needles would account for almost all the specific surface, i.e. about 22 cm^{-1}.

A bush of gorse was exposed to radiation at an intensity approximately the same as that measured in the field viz. 4.25 W/cm^2 and the time to ignite and the duration of flaming were found to be 20 s and 40 s respectively. Moisture content and specific heat were determined as 59 per cent and 1.43 J g^{-1} $degC^{-1}$ respectively from measurements with similar gorse obtained at Boreham Wood. This moisture content and specific heat give the enthalpy required for ignition as 1710 J/g assuming that the water leaves the fuel at 100°C and the dry fuel ignites at 300°C.

Table 3 gives the values of some quantities derived from the measured data.

Table 3

Values from measurements and photographs

R	Rate of spread - Backing fire	1.7 - 2.6 cm s^{-1}
	- Flank fire	1.5 - 5.1 cm s^{-1}
ρ_b	Bulk density total including stems, branches and needles	2.5 x 10^{-3} g cm^{-1}
	Bulk density branches and needles only	1.38 x 10^{-3} g cm^{-3}
ρ_f	Fuel density	0.8 g cm^{-3}
I_o	Radiation intensity - From radiometers	AM 3.8 W cm^{-2} PM 4.1
	- From cans	AM 3.8 W cm^{-2} PM 6.5
ϕ	Flame angle to vertical from photographs - Backing fire (AM)	0 - 30°
	- Flank fire (PM)	0 - 50°
	Flame length - Backing fire (AM)	150 cm
	- Flank fire (PM)	250 - 400 cm

4. Analysis of results

The procedure followed in this section is to substitute measured values of all except one parameter in the theoretical relationships to be tested and thus to calculate a theoretical value of the remaining parameter. This theoretical value is then compared with the measured value to test the relationship. Comparisons are given in Table 4 and explained in the following sections.

Table 4

Comparison of observed and calculated values of various parameters

		Observed or derived	Calculated
Rate of spread	- Backing fire	1.7 - 2.6 cm s^{-1}	1.1 cm s^{-1} Section 4.1
	- Flank fire	1.5 - 5.1 cm s^{-1}	2.4 - 3.7 cm s^{-1} (3)
Flame length	- Backing fire	150 cm	132 - 175 cm) eqn.(6)
	- Flank fire	250 - 400 cm	124 - 280 cm)
Attenuation coefficient	- Needles	0.016 cm	0.045 cm eqn (5)
Flame angle to vertical	- Backing fire	0-30°	72 - 74° eqn (9)
	- Flank fire	0-50°	69 - 75°
Radiation intensity	- Backing fire	3.8 W cm^{-2}	
	- Flank fire	5.3 W cm^{-2}	

4.1 Rate of spread and radiation intensity

Laboratory experiments with fuel in the form of cribs of wood and beds of wood shavings have shown[4] that the rate of spread R in still air can be predicted by a heat balance, assuming heat transfer is by radiation through the fuel bed, expressed by the following equation:-

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

ρ_b is the bulk density of the fuel bed

Δh is the heat required to ignite unit mass of fuel

i_o is the radiation intensity through the fuel bed

α is the cooling coefficient

θ_o is the ignition temperature (pilot ignition is assumed as flame is present)

With wind it has been suggested[3] that equation (1) should be modified 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, assumed to be the same as the angle of the burning zone.

Let us first consider the backing fire. Since the flames were nearly vertical most of the time it is reasonable to apply equation (1). If we substitute observed values of ρ_b, Δh, i_o and $\alpha\theta_o$ in equation (1) we obtain a theoretical value of the rate of spread. Values of ρ_b = 2.5 mg cm^{-3} and i_o = 3.8 W cm^{-2} are given in table 3. Δh = 1710 Jg^{-1} is given in section 3. The value of $\alpha\theta_o$ for cooling was not observed but can be taken as[4] 1.37 W cm^{-2}. These values give a theoretical rate of spread of 0.035 cm s^{-1}. This is very much lower than the observed rates of 1.7 - 2.6 cm s^{-1}, suggesting that there must be a substantial transfer of heat from another source, for instance the flames above the fuel bed.

Since the fire was a backing fire there would be little contribution by the flames above the fuel bed if the flames were deflected. Here we disregard the slight deflection (see table 3) so that the ratio of radiation heating by the flame to radiation from the fuel bed is

$$\frac{i_f \quad E_f \quad L\,F}{i_B \quad h \quad E_B}$$

where i_f is the black body intensity of radiation at the flame temperature
E_f is the flame emissivity
L is the flame height
F is the configuration factor between the flame and the fuel ahead of the fire
i_B is the black body intensity of radiation at the temperature of the fuel bed
h is the height of the fuel bed
E_B is the emissivity of the fuel bed

Taking i_f as 17.5 W cm^{-2} (section 4.4)
E_f as 0.2 (section 4.4)
L = 150 cm (Table 3)
F = $\frac{1}{2}$ for a wide flame front
i_B = 3.8 W cm^{-2} (Table 3)
h = 80 cm (Table 1A)
E_B = 1 (section 4.4)

the above ratio is equal to 0.875. This suggests that in this fire the flame contributed nearly as much heat to the unburned fuel as did radiation through the fuel bed.

Consider equation (1) modified to include the extra radiation from the flames. The total heating rate per unit cross section of the fuel bed is then approximately 7.1 W cm^{-1}. The heat loss $2.67\alpha\theta_o$ is 3.65 W cm^{-2} ^{4} as before. Using the figures for ρ_b and Δ h quoted before we obtain a theoretical rate of spread of 0.6 cm s^{-1}. However, this is a lower extreme value since we have assumed that all the fuel is burned although it was observed that the gorse stems did not burn. The other extreme value is then obtained by considering only the finer fuel and neglecting even the heating of the gorse stems. From Table 2 the weight of the stems is 45% of the total, hence the upper extreme theoretical rate of spread is 0.6/.55 = 1.1 cm s^{-1}. The actual observed value 2 cm s^{-1} was nearer the larger value.

In discussing the afternoon fire allowance should be made for the contribution of the flames but to do this is rather more complicated than for undeflected flames and the variability of the fire is too great and the data too few to justify detailed analysis. We can however readily estimate a rate of spread on the assumption that the flames contribute little.

Taking the maximum value of ϕ measured from photographs of the afternoon fire, i.e. 50°, ρ_b and, Δh as before and a mean i_{oB} of 5.38 W/cm^2 from radiometers and can measurements we get $R = 3.5$ cm/s. Taking the minimum observed value of ϕ from photographs as zero we get $R = 2.24$ cm/s. These are of the same order as the observed speed but in view of the neglect of the flames represent only minimum estimates.

4.2. Attenuation coefficient

A knowledge of the attenuation of radiation through the fuel bed is strictly not necessary for evaluating the rate of spread in fine fuels. It is however relevant where thick fuels are involved and a discussion is included here because estimates of it are possible from two independent sets of data.

Two models of attenuation through the fuel bed have been described, single ray and multiple ray[4]. The former considers radiation to pass as a single ray in the direction of spread. The latter regards it as being radiated in all directions. The attenuation coefficient has units of length^{-1} and thus gives a measure of the relative reduction in intensity per unit distance from the flame front. The attenuation coefficient a is defined as the number of pieces of fuel per unit volume multiplied by their cross sectional area effective in attenuating radiation. On the single ray model this definition leads to the formula

$$i = i_o \quad e^{-ax} \qquad (3)$$

where x is the distance from the burning zone.
In multiple ray attenuation

$$i = i_o \quad f\ (ax)$$

where f (ax) is given in reference (4)

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

and σ is the specific surface per unit volume of fuel. The curves in Fig.4 have been derived from the readings in Fig.3 and the observed rate of spread of fire at the radiometer. a was determined from Figs 4 a, b, c, using the relation given in reference (4):-

$$^2/_3a = \int_{\infty}^{0} \left\{ \frac{i}{i_o} \right\} dx$$

and was found to lie between 0.04 and 0.05 cm^{-1}, with a mean of 0.045 cm^{-1}.

The value of a calculated from the estimate of σ, viz 22 cm^{-1} given in section 3.2 and the measured values of ρ_b and ρ_F (0.8 gm/cm^3) is 0.016 cm^{-1}, about 2½ times less than the measured value. This is almost certainly partly a consequence of the distribution of the needles not being uniform through the size range as was assumed in estimating σ and partly that in siting the radiometers they were put behind bushes where the local bulk density was higher than the mean value given in Table 3.

4.3. Flame length

From laboratory experiments[5] the following relationship between flame length L, and burning rate $\dot{m}'$ has been determined:

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

where L is in cm and $\dot{m}' = R\,\rho_b h$ is the rate of burning per unit fire front (mg $cm^{-1}s^{-1}$). By definition we have $\dot{m}' = R\rho_b\, h \times \frac{\text{burnt weight}}{\text{total weight}}$.
Taking the ratio of the burnt weight to the total weight as 0.55 (section 4.1), $\rho_b = 2.5 \times 10^{-3}$, h = 80 cm and R = 2.0 cm/s (morning), and 1.5 - 5.1 cm/s (afternoon), we obtain L = 150 cm (5 ft) for the morning fire and 120 - 280 cm (4-9.3 ft) for the afternoon fire. These compare with the values obtained from photographs of 150 cm in the morning fire and 250-400 cm in the afternoon fire.

4.4. Emissivity and radiation from length of burning zone

We assume here that

$$E = 1 - e^{-aD} \qquad (6)$$

D is length of burning zone = 75 cm and a = 0.045 cm^{-1}

$$E = 0.97$$

For flames from wood fuel the attenuation coefficient is taken from some unpublished data obtained by Heselden as 0.003 cm^{-1}.

Hence $$E = 1 - e^{-0.003D}$$

$$= 0.20 \qquad (7)$$

This is the value used in Section 4.1.

Black body emission at the flame temperature of 1050°C is 17.5 W/cm^2 so that the intensity of radiation close to the flames is expected to be about 3.5 W/cm^2. This is close to measured values of the radiation level within the fuel bed, where the hot sticks also contribute. These will be at a lower temperature but the appropriate value of E is effectively unity.

4.5. Flame angle from wind speed

Thomas, Pickard and Wraight[6] obtained equations for L and H ($H = L \cos \emptyset$) in terms of a dimensionless wind speed U* giving

$$\sec \emptyset = \frac{L}{H} = \frac{55}{38} (U^*)^{0.49} \qquad (8)$$

where $$U^* = \frac{U}{(g\dot{m}'/\rho\,\text{air})^{\frac{1}{3}}}$$

U is actual wind speed and $(g\dot{m}'/\rho\,\text{air})^{\frac{1}{3}}$ is a term having the dimensions of velocity characteristic of the buoyancy.

Values of $\emptyset$ calculated from equation 9 are given in Table 4, but neither of the values obtained is in good agreement with that observed.

If the maximum wind speed in the backing fire is compared with the maximum rate of spread and the minimum wind speed with the minimum rate of spread $^L/H$ is calculated to vary from 3.4-3.6 corresponding to a variation in $\emptyset$ from 72°-74°.

Again, taking the maximum observed wind speed in the afternoon fire with the maximum rate of spread and the minimum wind speed with minimum rate of spread $^L/H$ is between 2.86 and 3.77 and thus $\emptyset$ is 69°-75°.

5. Conclusions

The basic theoretical model of fire spread gave predicted rates of spread of the order of magnitude expected. The flame length results show good agreement between observed and calculated values particularly for the backing fire but the calculated flame angles are not at all in agreement with those observed; equation (8) gives an unrealistically small variation of flame angles because the wind speed and mass burning rate terms are raised to low fractional powers. However this report shows what may be attempted with this kind of data and in future it is hoped that circumstances will allow a rather more detailed study to be undertaken. Despite such limitations the order of magnitude of the mass rates of spread and the heating rates are the same as those found in the laboratory. This degree of agreement suggests that the spread of fire in this vegetation is essentially of the same kind as fire spread in cribs, even if there are some differences which are as yet unexplained.

With fires in real vegetation the division of fuel into the simplest categories of thick and thin presents difficulties in interpretation, because so long as some of the fuel (i.e. the thinnest) can be heated to ignition the fire may be able to spread. Thicker fuel ignites when the front of the flame zone has passed, while the thickest fuel may not even be ignited at all. It is the fire itself and the condition of the fuel that define what is thick and what is thin fuel and further theoretical studies are necessary before some attempt is made to remove the uncertainty due to this.

Acknowledgement

The extract from the ordnance survey map in Fig.1 is reproduced by permission of the Director General Ordnance Survey.

References

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APPENDIX

Note on the King Bush Fire Radiometer

This consists essentially of two Hatfield Heat-flow Disks, one blackened and the other covered with shiny aluminium foil mounted on a container full of water to keep them cool in the fire. The disks are connected in opposition so that the resultant output is a measure of radiation, the aluminium foil covered disk compensating for convection. The Hatfield Heat-flow Disk[7] is a disk of a silver-tellurium alloy between two pieces of copper gauze to which leads are attached. A flow of heat through the disk produces a temperature difference across it and generates an output from the copper, silver-tellurium thermocouple.

The King design has however been modified somewhat, Fig.5. Firstly, both disks are mounted on the front of the body. King mounted the blackened disk on the front and the shiny disk on the back, and this can lead to errors as even with the spherical shape used by King flow separation will occur round the bluff body and the convection coefficients at the two disks will be very different[8]. This may account for the considerable errors quoted by King at high wind speeds. Secondly the body is a cylinder (see Fig.5) not a sphere as in King's design. The sphere has no apparent advantages and is more difficult to manufacture. Also the large mass of metal incorporated in King's design was replaced by thinner material when it was found on testing the prototype (Fig.1) that it gave a large time constant. Further, since the heat flow disks were originally only designed for intensities of the order of 0.25 cal $cm^{-2}s^{-1}$ (3500 Btu.ft^{-2} hr^{-1}) non-linearity was shown at the higher intensities. It was therefore necessary to cut down the intensity passing through the blackened disk by screening; the most satisfactory screen was found to be a perforated aluminium foil disk, attached by high melting point grease. The output with a screen is nearly linear but falls off slightly at higher intensities.

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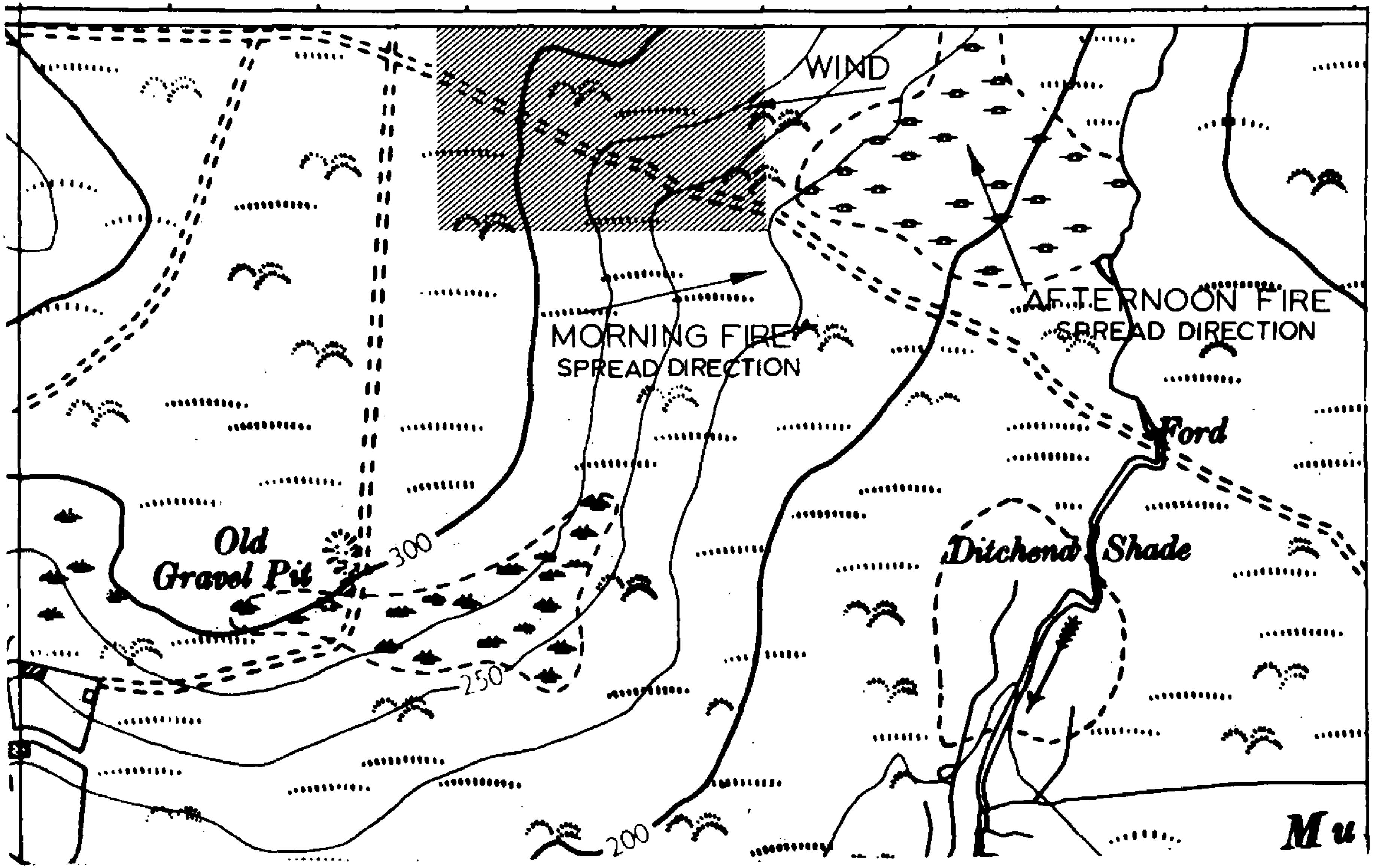


FROM 6inch ORDNANCE SURVEY PLAN SU.II.SE. SCALE ENLARGED TO 15 TO 1 MILE APPROX

FIG.1. THE LOCALITY OF THE BURN

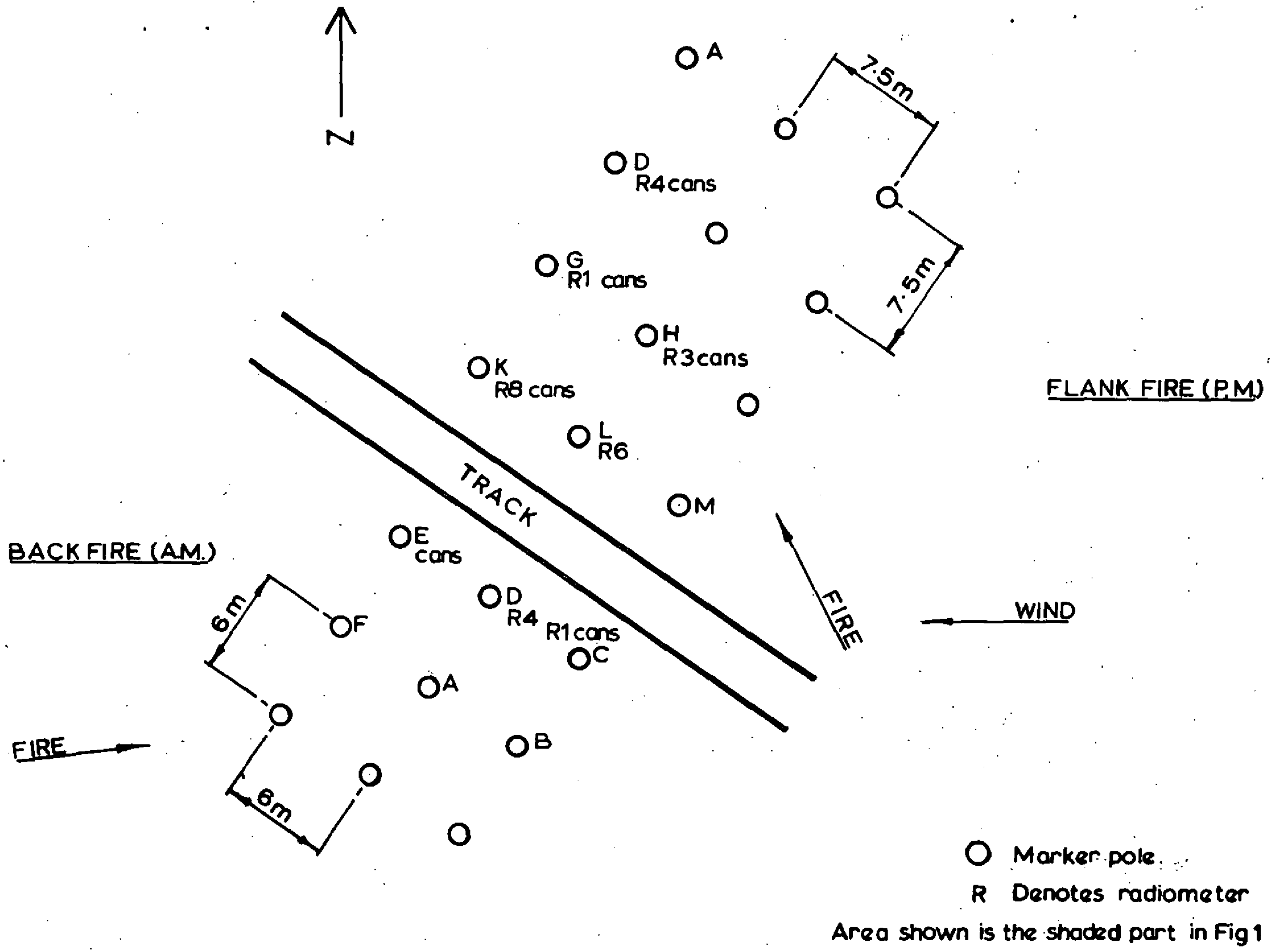


FIG.2. ARRANGEMENT OF MARKERS, CANS AND RADIOMETERS

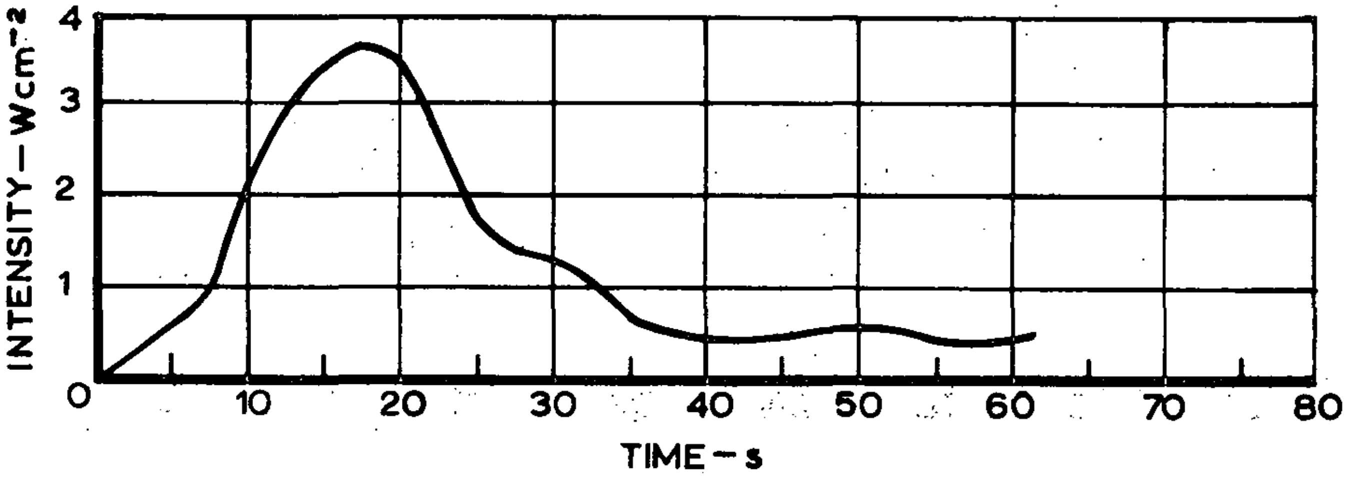


FIG 3a MORNING

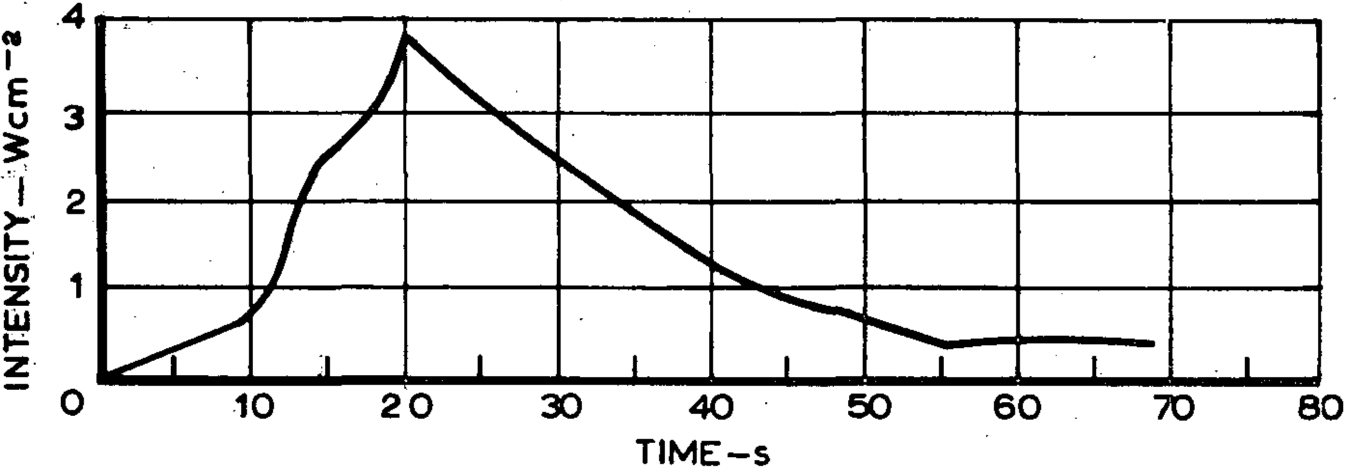


FIG 3b MORNING

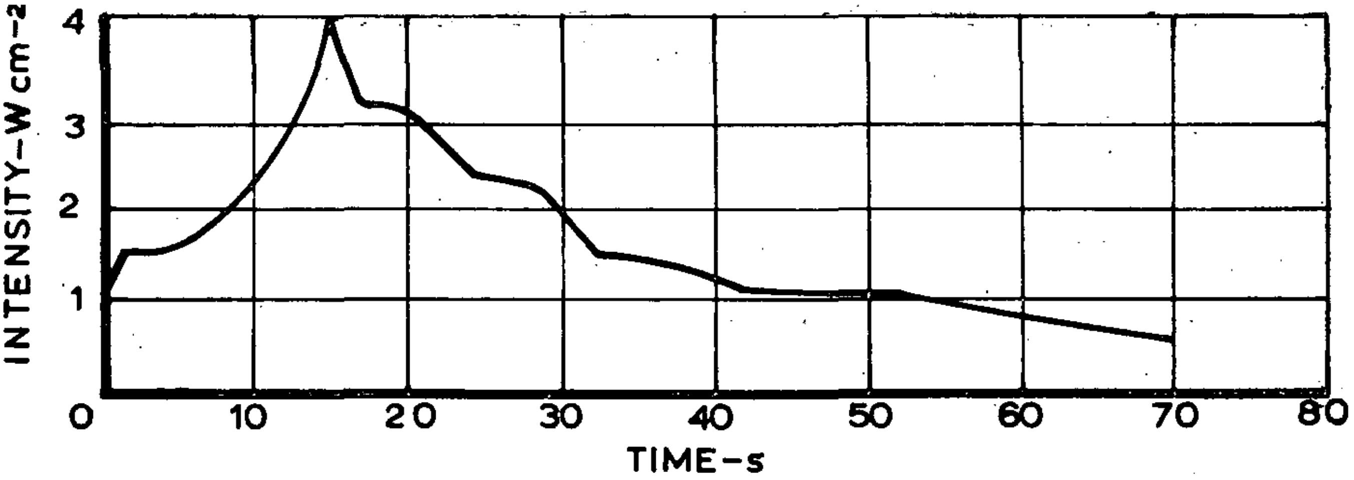


FIG 3c AFTERNOON

FIG.3. MEASUREMENTS OF RADIATION INTENSITY
(RADIOMETER RECORDS)

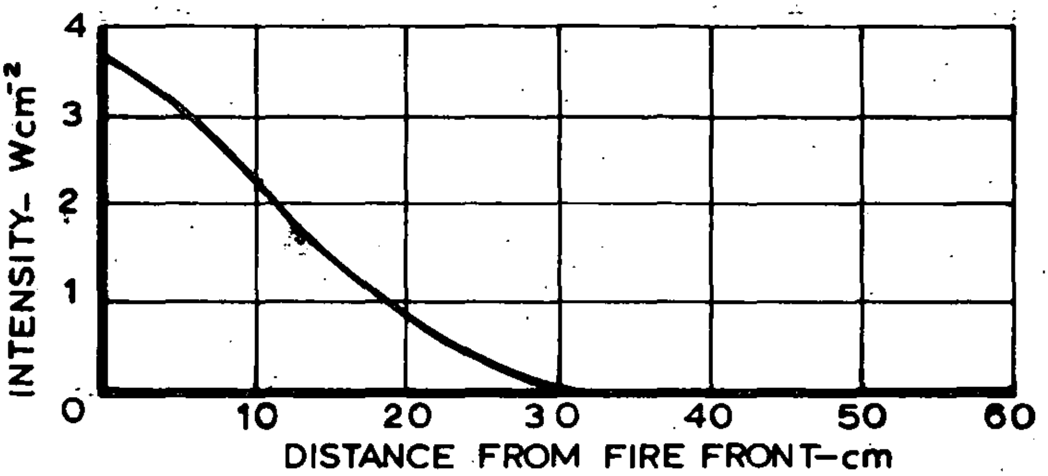


FIG4a MORNING

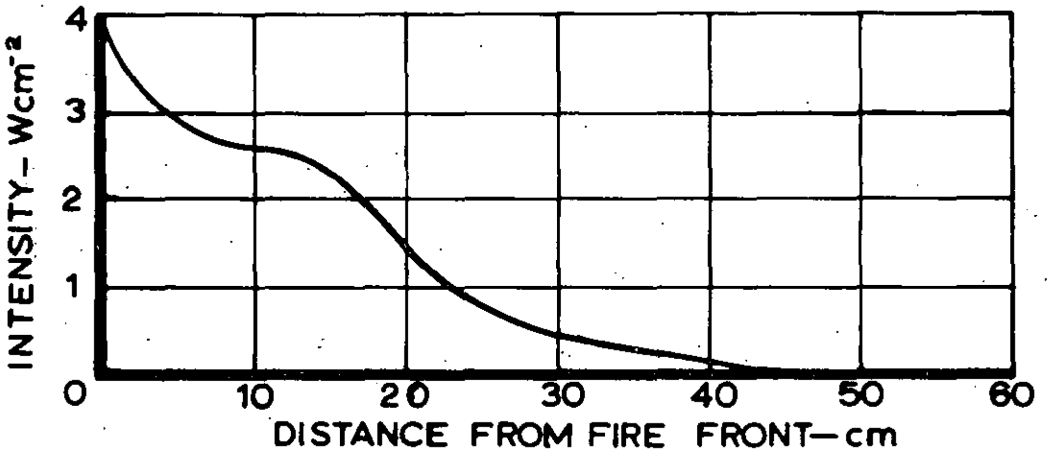


FIG4b MORNING

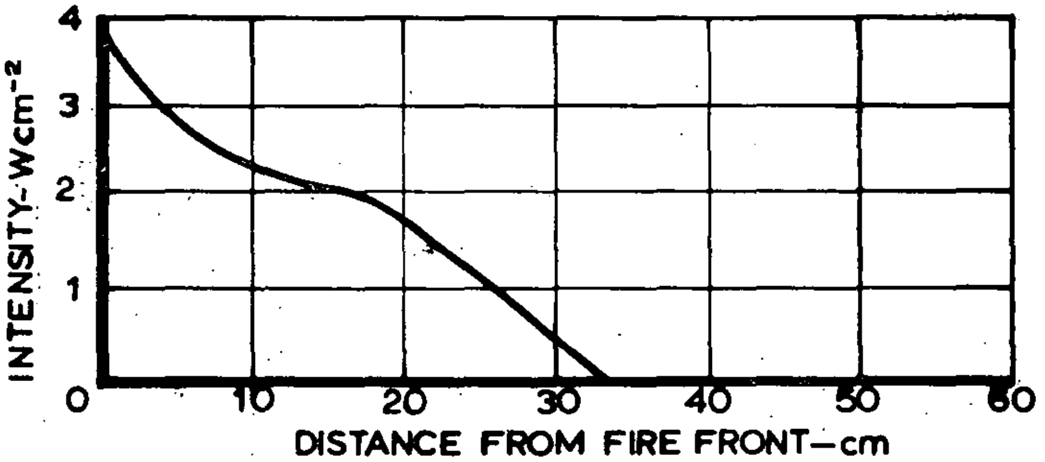
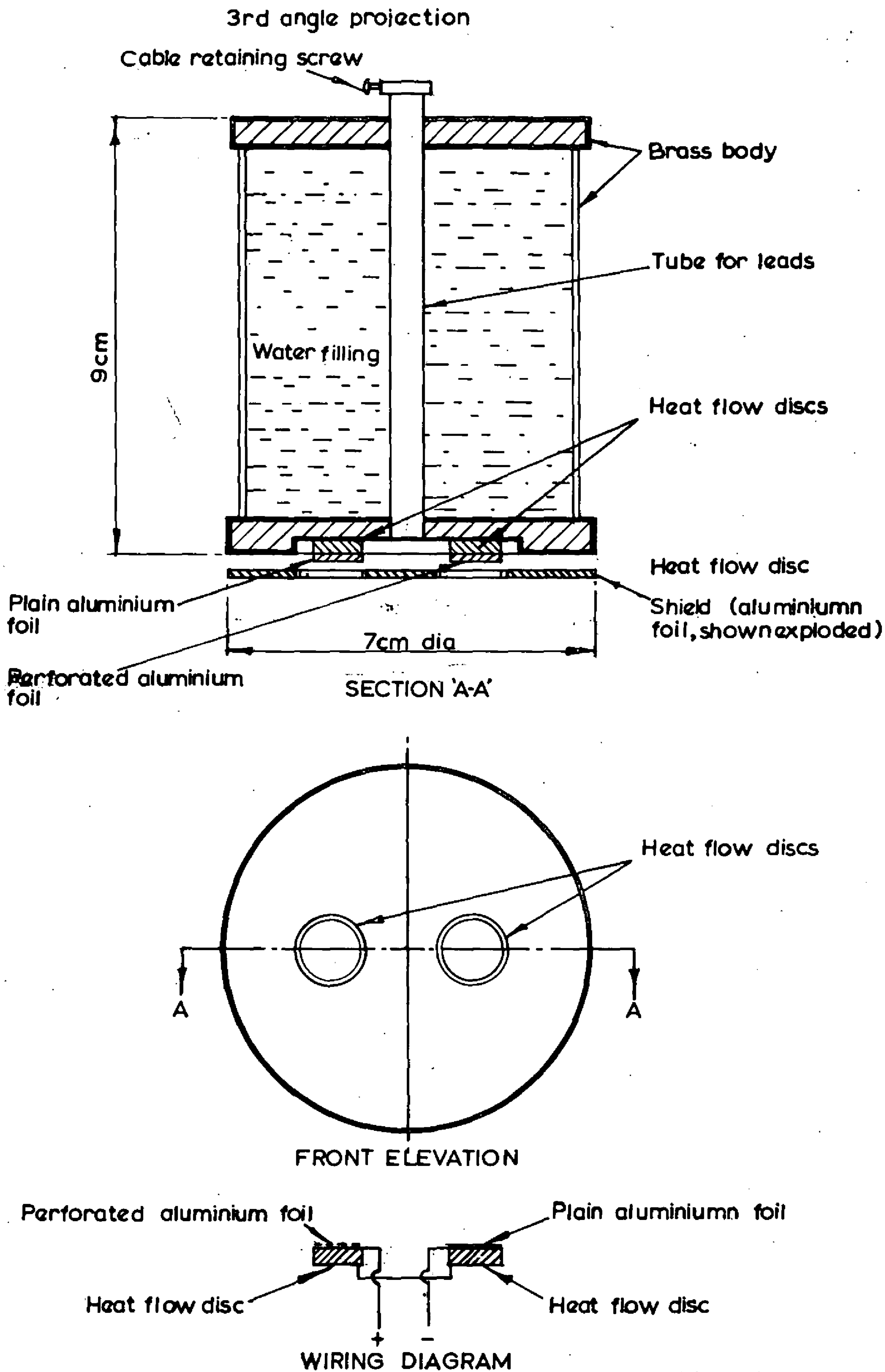


FIG4c AFTERNOON

FIG4. VARIATION OF RADIATION INTENSITY WITH DISTANCE FROM FIRE FRONT



not to scale

FIG.5. BUSH FIRE RADIOMETER (AFTER KING)