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THE RATES OF SPREAD OF HEAD FIRES IN GORSE AND HEATHER

by

P. H. THOMAS

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SUMMARY

Various measurements made during ten controlled head fires in the New Forest have been reported by Woolliscroft, who calculated that flame radiation contributed significantly to the spread. Here, these data are discussed further.

There are two or three apparently anomalous rates of spread which one cannot resolve with the few data available, but the rate of spread is broadly related to the amount of fuel and the wind speed,

viz $$R\rho_b = a + bU$$

where R is the rate of spread in m/s
ρ_b is the bulk density of the fuel in kg/m^3 (including water content)
U is the wind speed m/s
a is 0.15 kg/m^2 s^1
b is 0.16 kg/m^3

KEY WORDS: Fire spread, rate, wildland, wind.

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An estimate has been made of the attenuation coefficient 'k'' in a relation between the emissivity of the flames ϵ_f in head fires and D the length of the flame zone,

$$\text{viz} \quad \epsilon_f = 1 - e^{-k'D}$$

These data give $k' = 0.10 \ m^{-1} \pm 0.036 \ m^{-1}$ which is lower than the figure employed by Woolliscroft and leads to lower estimates of flame radiation. Although it would seem possible to attribute the effect of wind solely to its effect on flame radiation, considerations of stability suggest that even these lower estimates of flame radiation are too high (perhaps because the flame is more like a series of separate flames than a continuous one), and convection must play a role at least comparable to flame radiation.

An equation for 'R' which is practically as accurate as the above and has some theoretical justification but is more complicated has been obtained by assuming heating by convection is proportional to wind speed.

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INTRODUCTION

Teams from the Fire Research Station, Boreham Wood, visited the New Forest in March of each of the years from 1965 to 1968 to make measurements of the rate of spread, the flame geometry and the heat transfer in various controlled burns in heathland, gorse, etc. which could be regarded as experimental fires. The data have appeared in reports by Woolliscroft and Law[1], and by Wolliscroft[2,3,4]. Whilst some features of the fires could be reconciled with theory it was clear, that there were certain differences in behaviour between fires in the field and fires in the laboratory.

The main conclusions of the work were:

(1) that the laboratory relationship between the flame deflection and the wind speed appeared to be inadequate for describing behaviour in the field;

(2) that head fires spread at a rate significantly faster than could be accounted for by radiation from the burning fuel heating up the unburnt fuel;

(3) that head fires, though not necessarily backing and flank fires, in mixed fuels containing an appreciable quantity of dry grass probably spread as fast as they would if only the grass were present.

It was suggested that there may well be a contribution from forced convection to the heat transfer to the unburnt fuel ahead of the fire.

Woolliscroft made a number of detailed calculations of the heat balance for the advancing fires. Some of the discrepancies revealed in these are suggested in this paper as being due to an overestimate of flame emissivity and an overestimate of cooling loss.

In this report the data are considered in further detail from which it would appear that with some reservations it is possible to correlate the rates of spread of most of the reported burns with the bulk density of the fuel and the wind speed.

We shall first present an empirical correlation of the data and follow it by giving a partial theorectical basis for them.

THE RATES OF SPREAD OF HEAD FIRES - EXPERIMENTAL DATA

Table 1 presents relevant data taken from the four reports referenced above. Some other data appear in Table 3. Two fires, one in still air and the other a flank fire, are included in Table 1 in order to get values of the rate of spread corresponding to zero wind speed.

EMPIRICAL CORRELATIONS

Figure 1 shows the bulk density of material burnt against the initial bulk density. We take $W'/W = \rho_b'/\rho_b$ where W is the fuel per wind area and the ' refers to the amount burnt.

Figure 2 shows how the fraction burnt decreases with moisture content.

$$\frac{W'}{W} = \frac{\rho_b'}{\rho_b} = 0.8 - 0.9\,m \qquad (1)$$

Other data in references (1) and (2) which are not included in Table 1 show that backing fires, like the still air fire, burn out more of the fuel than head fires for the same moisture content. The results for the two head fires where the moisture contents of the various fuels in the mixture were different and recorded separately, suggest that the moisture content of the driest fuel, grass, is most useful as a measure of the fraction of fuel finally burnt in those fires. The estimates made by Woolliscroft for fires 1967/2 1967/3 lie close to the line. For the range of these data, there does not appear to be a significant effect of wind speed on the relation between fraction burnt and moisture content. If ρ_b^* is taken as a fraction of the initial dry weight of fuel that fraction is $(1 + m)\rho_b'/\rho_b'$ which decreases less rapidly with m than does ρ_b'/ρ_b but the decrease is still marked and over the range $0.2 < m < 0.6$ is approximately $0.9 - 0.8\,m$.

In interpretating relations involving ρ_b' and ρ_b it must be remembered that ρ_b was measured by direct weighing while ρ_b' was estimated from an examination of the loss in weight and loss of volume of various types of fuel, needles, twigs etc. in the various size fractions.

Figure 3 shows the mass rate of burning per unit width perpendicular to the direction of travel of the fire front for the different wind speeds. The mass rate of burning per unit width of fire front multiplied by the calorific value of the fuel is commonly described as the fire intensity.

There are three gross departures from the curve. Fire 1967/2 was mentioned by Woolliscroft as spreading sporadically through sparse fuel, having to be relit at times. Fire 1966/4 he suggested as perhaps being better regarded as a grass fire in which the fuel, other than the grass, burnt behind the main front without influencing it and so should be regarded as a grass fire. The flame lengths were more consistent with this view. If this view is again taken the effective bulk density of burnt material ρ_b' is that of the grass alone, viz 0.72 mg/cm^3 and the result is then close to the line drawn in Fig. 3. The main difficulty with this view is that it only applies to certain fires. Such a view reduces $R\rho_b'$ for the third exceptional fire 1967/3, increasing the departure from the main trend and it could affect other fires in mixed fuels. These latter two fires are both in mixed fuels (as are some others) but there are too few data for comparable fuel mixtures to explore any anomalous behaviour. The two fires for which the height of the fuel was very different from the others lie on the general trend and could be regarded as showing the importance of fuel mass per unit volume (bulk density) as opposed to fuel mass per unit ground area (fuel loading). By including a mean value of ΔH, the heat required to raise 1 Kgm of fuel to ignition, it is possible to represent the vertical axis in Fig. 3 as a scale of nominal forward heat flux and this scale has been included in the right-hand side. The value of $R\rho_b'\Delta H$ for still air is about 50-100 KW/m^2, typical of the radiation from the solids burning in the fuel bed.

The line drawn in Fig. 3 is

$$100 R\rho_b' = 6.5 + 8U$$

Figure 3 shows that there is a real correlation between $R\rho_b'$ and U but not that R and ρ_b' are related inversely. This reciprocity between R and ρ_b', a characteristic previously demonstrated for still air fires[5], is shown in Figure 4 where R has been normalised to a still air value by plotting an equivalent rate

$$\text{viz} \quad \frac{R}{1 + \frac{0.065}{0.080} U} \qquad \text{against} \quad 1/\rho_b'$$

The reciprocity between R and ρ_b' is seen to be valid over a range of 4 to 1 in ρ_b' with the two exceptions of fire 1967/2 (see comments above) and fire 1967/3.

We shall later show that the contribution of flame radiation is correlated with wind speed and that the upward trend with U is partly due to this. The radiation from flames is dependent on wind speed through its effect on flame length and flame deflection and both may be affected by changes in radiating temperatures owing to the effect of the wind on combustion. Van Wagner[6] and Woolliscroft[3] have given the geometric expression for the change in radiation as a function of deflection.

SLOW AND FAST FIRE SPREAD

It will be important for our discussion of the relative roles of convection and flame radiation to refer to the question of stability. A fuller discussion of spread theory based on radiation heating[7] appears later, where an examination of the equations determining the rate of fire spread shows that it is possible to have either one of two different rates of spread for the same conditions, the choice of one or other probably depending on the previous history of the fire and perhaps other circumstances. A third possible intermediate equilibrium rate of spread is unstable: the two stable rates are referred to as slow (thin flame) spread and fast (thick flame) spread. The measurements made by Woolliscroft enabled him to estimate the ratio of radiation from the flame to radiation through the fuel bed and he obtained values of about 5 or 6 at the most, and over 1.5 for several fires*. Theory suggests that 1.5 is as high as can be obtained with the stable slow (thin flame) spread. If the flame radiation for any reason becomes higher theory suggests that the spread moves over to the fast rate with thick flames and for this the ratio of flame radiation to the fuel bed radiation is many times greater. This is <u>not</u> the explanation of the high value of $R\rho_L'$ for fire 1966/4 because the flame should be correspondingly longer which it was not. The data therefore correspond essentially to a slow (thin flame) spread but with the quantitive reservation mentioned above. This is to some extent supported by the fact that a large experimental fire at Trensacq (France) which has been interpreted as spreading at the fast (thick flame) equilibrium rate had a mass rate of burning about ten times faster than the experimental fires being discussed here[5].

Again by comparison with the statistical analysis made by Woolliscroft[8] the experimental fires in Table 1 are typical of slow rather than fast fires. The stability argument can readily be modified if a convection term is included in the forward heat flux.

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*It will be shown below that Woolliscroft calculations of flame radiation were too high.

CONVECTION

It is difficult to formulate a detailed or exact model allowing for convection of hot gases through the fuel bed in advance of the fire but a few simple calculations can be made to indicate whether such a mechanism is relevant here.

A rough estimate of the minimum possible contribution of the convection neglecting loss from this fuel bed may be made as follows.

In high winds one can assume that hot gases flow horizontally through the fuel bed at a velocity related to that measured just above. Clearly the fuel exerts some drag on the main air stream. If regarded as a rigid body there would be no flow in the fuel bed itself and if treated as exerting no drag, the velocity would approach the free stream value 'U' except that ground shear would keep it less than U. Based on Woolliscroft's measurements of bulk density, specific surface, etc., a rough estimate neglecting ground shear (see Appendix I) shows that downwind of the fire front where the flow is horizontal the mean velocity of the gases within the fuel bed V may be as little as 1/10 of the velocity above the fuel bed. Near to the fire front, that is before the wind has been slowed down by unburnt fuel, one must expect higher values.

Differences between the fuel beds affect the calculation but in view of the crudity of the estimates a single value of 1/10 is taken, so that the convection flux q_c'' is written as c. 1/10 $U K_p \rho_g \theta$, where ρ_g is the density of the gases, K_p their specific heat and θ their temperature rise above ambient at the fire front.

The heat balance equations in references (5) and (7) which are discussed in greater detail below, can accommodate this term by replacing the forward fuel bed radiation flux, viz $i_B \epsilon_B$ by $i_B \epsilon_B + q_c''$ where i_B is the black body radiation flux from the burning solids and ϵ_B is their emissivity. Where $\epsilon_B \sim 1$ we introduce an effective forward flux

$$f_B = i_B + q_c''$$

If we neglect flame radiation and cooling (see Appendix 2) we have

$$R\rho_b' \doteqdot i_B/\Delta H + \frac{K_p \rho_g \theta}{10\,\Delta H} \cdot U \qquad \text{———} \quad (2)$$

an equation which roughly follows the form of the data in Fig.3. For U = 4 m/s (roughly the upper limit for these data) the maximum contribution to the flux of this term is

$$\Delta(R\rho_L') = 4 \times 0.1 \times \frac{1.3 \times 290 \cdot \theta}{(T + \theta)\,10^3} \quad \text{kg m}^{-2}\text{s}^{-1}$$

where ΔH is taken as 1.0×10^6 J/kg

K_p as 1×10^3 J/kg^{-1} deg C^{-1}

ρ_g as $1.3 \frac{T}{T+\theta}$ kg m^{-3}

θ is the rise above an ambient absolute temperature T in deg C

$\Delta(R\rho_L') < 0.15$ kg m^{-2} s^{-1} which approaches a half of the increase above still air values in Fig. (3).

We cannot exclude convection at this stage especially near the fire front where the velocity will be higher and certainly we cannot easily estimate the relative contributions of convection and flame radiation. Later in this paper we shall in fact make a heat balance in some detail and estimate an empirical value of q_c''.

THE EFFECT OF MOISTURE

If ΔH is the heat required to raise fuel to ignition then the heat flux which must be supplied to thin fuel to allow the flame to propagate is $R\rho_L \Delta H$. If, in mixed fuels, only thin fuel burns, the remaining thick fuel will have taken up some heat. Then $R\rho_L \Delta H$ is a maximum value (not all the interior of thick fuel is heated). However, some fuel which is not heated to ignition may be ignited (and burnt) by the ignited thin fuel and may or may not contribute to the spread; we have to choose pragmatically whether $R\rho_L \Delta H$ or $R\rho_L' \Delta H$ is the better measure of the heat flux required to ignite the fuel.

Accordingly we have analysed the data statistically, excluding those which appear for various reasons to be anomalous. The results are summarised in Table 2.

Table 2

	y		σ/y	
1A	$R\rho_b \Delta H/10$ kw/m^2	$57 + 27.4(U-\bar{U}) + 3.06\ (m-\bar{m})$	33%	$\bar{U} = 1.6$ m/s $\bar{m} = 38.4\%$
1B	$R\rho_b' \Delta H/10$ kw/m^2	$23.2 + 9.6(U-\bar{U}) + 0.36\ (m-\bar{m})$	19%	Excluding 1964/2, 1967/2 1967/3
1C	$100\ R\rho_b$ kg/s	$43 + 17.3(U-\bar{U}) + 1.53\ (m-\bar{m})$	30%	
1D	$100\ R\rho_b'$ kg/s	$18.6 + 7.1\ (U-\bar{U})$	23%	
2A	$R\rho_b \Delta H/10$ kw/m^2	$43.6 + 9.2\ (U-\bar{U})^*$	54%	$\bar{U} = 1.57$ m/s $\bar{m} = 35\%$
2B	$R\rho_b' \Delta H/10$ kw/m^2	$21.4 + 7.7\ (U-\bar{U})$	26%	Excluding above fires and 1967/6
2C	$100\ R\rho_b$ kg/m^{2}s	$36.8 + 9.0\ (U-\bar{U})$	46%	
2D	$100\ R\rho_b'$ kg/m^{2}g	$18.2 + 7.3\ (U-\bar{U})$	24%	* $\bar{U}$ term not significant

From Fig. 1 we have

$$\rho_b'/\rho_b \quad 0.45\ (1 - 0.02\ (m-\bar{m})\ )$$

and near the mean value of moisture content the calculation of ΔH can be written as $\Delta H = 1260\ (1 + 0.017(m-\bar{m}))$ kilojoule/kg

Since ρ_b is the measured density of wet fuel

$$\rho_b = \rho_{dry}\ (1 + \frac{m}{100}) \doteq 1.38\ (1 + 0.007\ (m-\bar{m}))$$

With these relations the four regressions in the first set (1A - 1D) are roughly consistent with each other and all indicate that R increases as m increases - a result quite contrary to expectation.

However, the significance of the 'm' term is lost if fire 1967/6 is excluded and the second set of regressions (2A - 2D) in Table 2 show these modified results. Since m in this small sample is correlated with fuel height, bulk density and fuel composition (fire 1967/6 had the highest moisture content and is one of the two gorse fires), it is possible that its relevance in the analysis is compounded with other effects, though the use of these instead of 'm' worsens the correlation.

Some support, albeit indirect, for the view that the gorse fire 1967/6 is different from the others is seen in the data for the duration of flaming, viz t_B. This, derived from measurements of 'D' the length of the flaming zone and the rate of spread, is shown in Fig. 5, where fire 1967/6 is separated from the other head fires. The above equations for ρ_i'/ρ_i and ΔH show that the effects of m on ρ_i' and ΔH largely cancel out each other, so that regression 2B may be regarded as the most satisfactory of the regressions although not the best statistically.

Regression 1D

$$R\rho_i' = 7 \times 10^{-2} + 7 \times 10^{-2}\ U \qquad (3A)$$

approximates to the line drawn in Fig. 3.

Regression (2B) is

$$\frac{R\rho_i'\ \Delta H}{10} = 9 + 8\ U \qquad (3B)$$

However ρ_i' is not known a priori and the use of ρ_i for prediction introduces more uncertainty than ρ_i'. A possible reason for this would be that the value of ρ_i' is to some extent determined by R and some variations in ρ_i' compensate for some of those in R.

For these New Forest fires it is provisionally best therefore to take an equation insensitive to m (except in its small effect on ρ_i) by incorporating

$$\rho_i' = 0.45\ \rho_i$$

into regression 1D viz

$$R\rho_i = 0.15 + 0.16\ U\ \mathrm{kg/m^2 s}$$

Returning to Fig. (5) we see that t_B increases with 'm' at a much higher rate than do any of the other quantities, so that the rate of spread varies only weakly if at all with 'm' despite the more slower rate of consumption of a wet fuel element and the consequent greater value of D for wet fuel. The increase in D tends to increase ϵ_f and the contribution of flame radiation whatever other effects tend to decrease it. Inserting the estimated values of ΔH which depend on m into the empirical correlation has not improved it, on the contrary it has slightly worsened it.

HEAT BALANCE

In order to relate the above correlations more closely to theory we must first discuss the radiation attenuation coefficient for the flame.

Flame emissivity and the effective flame thickness

An approximate formula for the emissivity of a flame of thickness $\bar{D}$ is

$$\epsilon_f = 1 - e^{-k\bar{D}}$$

Strictly this applies only to one wave length of radiation, but empirically determined values of 'k' are sometimes conveniently used to correlate flame data. Here, there is the additional problem of the varying flame thickness and we shall therefore consider a characteristic thickness, viz. that of the base D and examine the equation

$$\epsilon_f = 1 - e^{-k'D} = 1 - e^{-k'Rt_B} \qquad (4)$$

where t_B is the time for an element to flame i.e. the "residence time".

k' may be regarded as k, modified by a flame shape factor

Woolliscroft gives the following field data.

Table 3

Fire reference year and number	Fire type	R m/s	t_B* s	Rt_B* m	$1 - \frac{I_m}{\sigma T_F^4} = 1 - \epsilon_f$	$k' = \frac{-\log(1-\epsilon_f)}{Rt_B}$ m^{-1}
1966 4	Head	0.146	10	1.46	0.80	0.15
1967 3	Head ('Up slight slope')	0.063	13	0.81	0.73	(0.39)
4	Backing	0.0133	45	0.60	0.65	(0.72)
5	Head	0.0865	13	1.12	0.91	0.084
7	Still air	0.015	53	0.80	0.53	(0.79)
1968 1	Head	0.088	11	0.97	0.945	0.058
2	Head	0.21	9	1.89	0.86	0.080
4	Head	0.15	20	3.00	0.72	0.11

*t_B was deduced from a measure of $D = Rt_B$

I_m is the measured flame radiation corrected for the orientation of the radiometer with respect to the flame, σ the Stefan-Boltzman constant and T_F the absolute flame temperature. Fig. (6) shows a plot of $1 - \epsilon_f$ against Rt_B and it is not easy to derive a best value for k'. One might justify treating the still air fire, and the backing fire as different from the group of horizontally spreading head fires on the grounds that they could have flames of a shape different from those in head fires.

For the horizontal head fires alone, k' would appear to be $0.096\ m^{-1} \pm 0.036\ m^{-1}$, say $0.1\ m^{-1}$ i.e. the effective thickness of the flame is about $\frac{1}{3}$ of the base dimension if the 'correct' value of k is $0.3\ m^{-1}$ (unpublished data of Heselden)[1] as used by Woolliscroft. For undeflected flames of a triangular shape one might expect the effective dimension to be $\frac{1}{2}$ of the base dimension, but for deflected flames the ratio of the mean thickness to the base dimension is necessarily less, see Fig. (7).

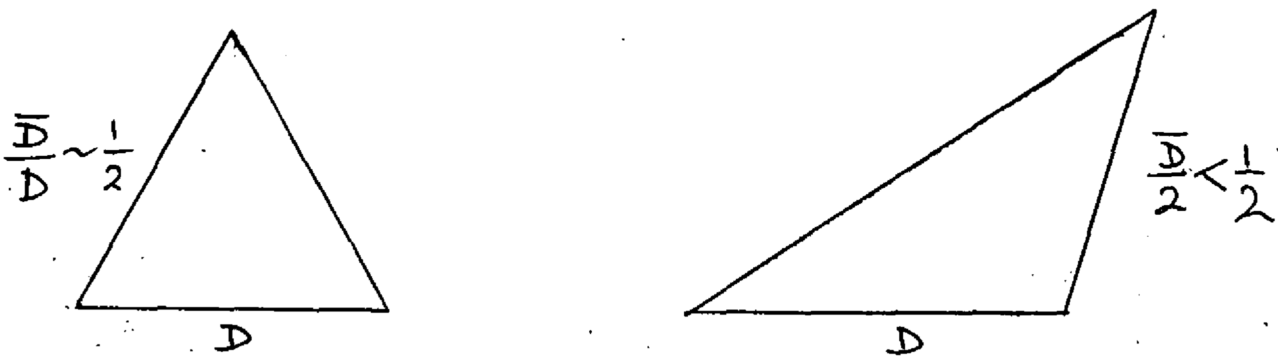

Fig. (7)

Such an argument does not explain the apparently very high (and possibly false) values of k' for the still air and backing fires, but there are too few data to explore the gross departures from the general trend.

<u>The theoretical heat balance</u>

We now consider the forward flux of sensible heat per unit width of fire front and write

$$i_B h + i_f \phi L \epsilon_f + h q''_c = R W' \Delta H + q'_L \qquad (5)$$

where h is the height of the fuel bed

L is the length of the flames

ϕ is the fraction of radiation emitted by the flames arriving on the fuel bed (i.e. the configuration factor)

q_c'' is the net convection transfer per unit cross section of fuel bed

q_L' is the heat loss by radiation per unit width of fire front which is neglected (see Appendix 2)

W' is the effective fuel loading, taken here as the burnt material $\rho_b' h$

ΔH is the heat required to raise unit mass of fuel to ignition

We take

$$L = 400 (RW')^{\frac{2}{3}} \text{ in c.g.s. units}^{(5)}$$
$$= 18.6 (RW')^{\frac{2}{3}} \text{ in kg, m.s. units}$$

disregarding the weak effects of U and of D* on this and assume

$$1 - e^{-k'Rt_B} \sim k'Rt_B$$

(an error of about 6 per cent for the largest value of Rt_B is incurred if k' is taken as 0.1 m^{-1}).

We then have

$$\left[I_B h\right] + 18.6\, k' \left[R^{5/3} W'^{2/3} i_f t_B \phi\right] = \left[R \rho_b' h \Delta H\right] + q_L' - q_c'' h \quad (6)$$

We shall assume that the convection flux is proportioned to U for a given initial temperature and a given fuel bed. We have argued that while long range convection heating may be small we have no way of easily estimating the short range effect. This may well be non-linear with U but we shall assume the simplest likely relation as a first approximation.

Table 4 lists values of the terms in brackets together with Uh to which $q_c''h$ is expected to be proportional. Fire 1966/4 is treated as grass only.

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*This correlation is less valid for very high wind speeds and large D/L than for low winds and small D/L. The use of experimental observations for L weakens the theoretical basis for what follows and incorporates additional observational error. Apart from fires 1967/5, 1967/6 and 1968/2 which have relatively short flames in relation to R the measured values of L generally follow the trend but are on average about 25% shorter than calculated.

Table 4

Terms in heat balance equation

Year and Test No.	$i_B h$* Kw/m	Uh m^2/s	$R^{5/3}$ $W'^{2/3}$ ϕ t_B i_f* (Kw kg.m.s. units)	RW'ΔH Kw/m	1.86 $R^{5/3}$ $W'^{2/3}$ ϕ $i_f t_B$ Kw/m
1966 2	18	0.53	65	100	120
4	15	0.15	24	67	44
1967 1	14	0.56	13	65	24
2	11	0.22	2.4	7.3	4
3	28	1.31	13	48	24
5	39	1.12	39	150	72
6	80	3.15	106	505	196
7	20	0	4.3	41	8
1968 1	17	0.38	18.7	48	35
2	12	1.67	82	153	152
4	63	1.91	207	360	384

*Values of ΔH, i_B, i_f, and ϕ from references 1-4; other data are reproduced from these references in Tables (1) and (3).

Values of i_B lie between 30 and 80 Kw/m^2 and apart from fire 1967/7 and 1968/3 where ϕ is 0.5, ϕ lies between 0.73 and 0.87, according to the observations made by Woolliscroft of flame deflection.

Fig.8 shows how the flame radiation per unit width of fire front is correlated with the wind speed. There is a general - but scattered - upward trend; Uh being better than U. It is perhaps noteworthy that the three fires lying furthest from the trend with U are the two gorse fires 1967/6 and 1968/4 with tall fuel, and 1967/3 which is anomalous in most correlations.

It is this correlation that allows Fig.3 to correlate the data empirically in terms of U irrespective of whether it is the convection or flame radiation that is responsible but it is only the lack of complete correlation that could be used to separate the effects of convection and flame radiation in the heat balance. The data are too few in number to allow this to be effected successfully.

From Table 4 one can see how $RW'\Delta H$ everywhere exceeds $i_B h$ (except for the fire 1967/2 which had continually to be relit as it tended to go out owing to the unevenness of the fuel). We now plot in Fig. 9 the excess, viz

$$RW'\Delta H \; - \; i_B h \quad \text{against} \quad R^{5/3} W'^{2/3} \phi \; t_B \; i_f$$

and the line with the "expected" slope based on $k' = 0.1 \bar{m}^{1}$ and $\frac{L}{(RW')}^{2/3} = 18.6$ passes through the body of the data. Fig. 9 is not suitable for predicting R because R appears on both axes. It simply indicates that broadly the value of R appears to be reasonably self consistant with a heat balance based on the radiation through the fuel bed and from the flames. However we cannot accept this correlation: such spread is not necessarily stable, since values of 1.86 $R^{5/3} W'^{2/3} \phi \; t_B \; i_f$ substantially exceeds 1.5 $i_B h$ for several of the fires. If for any reason one were to suppose that flame radiation had been over-estimated e.g. the flame was not continuous, then there could be a contribution from convection because of its correlation with flame radiation (Fig. 8).

The inclusion of some convection increases the effective forward flux and enables the stability criterion to be satisfied.

Fig. 10 shows $RW'\Delta H - i_B h$ against Uh from which it is seen that (neglecting flame radiation) we could take a wind dependant flux (regarded here as convection) as

$$q''_c = 130 \;\; U \;\; \text{Kw/m}$$

This gives an upper limit to q''_c

The equation

$$RW' \Delta H \;\; = \;\; i_B h \; + \; 130 \;\; Uh$$

may be written as

$$R \rho'_b \; = \; \frac{i_B}{\Delta H} \; + \; \frac{130 \;\; U}{\Delta H} \qquad \text{———— (7)}$$

where $\frac{i_B}{\Delta H}$ is of order 0.05 kg $m^{-2} s^{-1}$

and $\frac{130}{\Delta H}$ is of order 0.11 kg m^{-3}

This latter value is about 50% greater than the comparable value in Fig. (3)*

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*Equation (3) may be regarded as an approximation to equation (7) neglecting variation in $i_B h$ and ΔH.

Unlike Fig. 9, Fig. 10 (and Fig. 3 to which it is closely related) has R only on one axis. However we can no more dismiss flame radiation than dismiss convection. There is therefore some uncertainty in the relative contribution of flame radiation and convection. We can presume that flame radiation is less than calculated because it has been calculated on the assumption that the flame is continuous.

Let the actual flame radiation be a fraction α (<1) of that calculated, and convection a fraction β (<1) of the upper limit to q_c''. Hence

$$i_B h + \alpha\, 18.6\; k'\; R^{5/3}\, W'^{2/3}\, \phi\;\; t_B\, i_f \;+ \beta\, 130\, U h = R W' \Delta H$$

where $\quad \alpha + \beta \approx 1$

and $$\frac{\alpha \cdot 18.6\;\; k'\;\; R^{5/3}\, W'^{2/3}\;\; \phi\;\; t_B\;\; i_f}{i_B h \;+\; \beta \cdot 130\, U h} < 1.5$$

We neglect q_L' (see Appendix 2).

Using the largest ratios of $18.6\, k'\;\; R^{5/3}\, W'^{2/3}\, \phi\;\; t_B\, i_f' / i_B h$ (Test 1968/2) viz 12.4, this inequality is satisfied so long as $\alpha < 0.50$. Without convection ($\beta = 0$) and using measured values of L we would still require $\alpha < 0.50$.

Thus flame radiation cannot be more than about 50% the value calculated assuming the flame is continuous, and convection cannot be less than $65\, U h$. If this is identified with the flux

$$V_o\, K_p \rho_g\, \theta \doteq 65\, U$$

where $\quad V$ is the effective velocity of the gases in the fuel bed

we have $$\frac{V}{U} \doteq 0.17 \;\frac{T_o + \theta}{\theta}$$

θ is somewhat uncertain but 500°C would be a reasonable estimate so that, approximately $\frac{V}{U}$ is of order 0.2 - 0.3.

This is about 2-3 times the minimum estimate in Appendix I which is at least consistent with the main convective effect being (as might be expected) short range where the flow is mainly upward and faster than the value obtained a long way downwind which is what has been estimated in Appendix I.

In Fig. 9 the line is drawn from a prioriconsiderations - viz, the value of k' and the relation between flame length and burning rate. In Fig. 10 the line is fitted. The graphs are essentially different in that R appears on both sides in Fig. 9. Fig. 11 shows a heat balance, similar in form to Fig. 9 and 10 but where the horizontal axis is based on taking $\alpha = 0.5$ and $\beta = 0.5$ as discussed above; little difference is observed with $\alpha = 0.3$ and $\beta = 0.7$.

Short of a full statistical analysis - complicated by the presence of R in two terms in an equation which does not give R explicitly, by tolerances on the values of all the measured and estimated qualities e.g. fuel bed height, fuel burnt, and by inhomogeneity in the data - one cannot readily obtain the best values of α & β.

However we can calculate values of R for selected values of α and β for comparison with the observed data.

Consider equation (5) with ϵ_f retained in its original form, i.e. equation (4) with $q''_c \propto U$ and introduce the two disposable constants α and β.

viz

$$i_B h + \beta (130\ Uh) + \alpha (1.86\ i_f\ \phi\ R^{2/3}\ W'^{2/3}\ (1 - e^{-k' t_B R}) = RW' \Delta H \quad (8)$$

which may be rewritten as

$$\frac{A}{x} + \frac{B}{x^{1/3}} (1 - e^{-x}) = 1 \quad (9)$$

where $A = \frac{i_B h}{\Delta H} \left(1 + \frac{\beta\ 130U}{i_B}\right) \left(\frac{kt_B}{W'}\right)$

$$B = \frac{\alpha\ 1.86\ i_f\ \phi}{\Delta H} \left(\frac{kt_B}{W'}\right)^{1/3}$$

and $x = kt_B R$.

Figure (12) shows the A-B plane and some values of x.

For any test result A and B can be calculated and x found. Within the shaded area two values of x can be obtained for given A and B i.e. both slow (thin flame) and fast (thick flame) spread are possible there. At the apex of the area the two equilibria merge into one.

The simplest method of evaluating x is to draw a line through the point A, B determined from experimental data to touch the (b) curve tangentially: x is then the intercept on the A axis.

Comparison between observed and calculated rates of spread

Values of A and B have been calculated for the experimental data and Fig. (12) used to calculate x and hence R. These are shown in Table 5 for $\alpha = 0.3$, $\beta = 0.7$ and $\alpha = \beta = 0.5$.

Table 5

Year	Test No.	R observed m/s	R calculated $\alpha = 0.3$	$\alpha = 0.5$
1966	2	0.067	0.056	-
	4	0.146	0.068	0.065
1967	1	0.045	0.048	0.048
	2	0.018	0.12	-
	3	0.063	0.22	-
	5	0.086	0.13	0.12
	6	0.30	0.36	0.32
	7	0.015	0.008	0.008
1968	1	0.088	0.12	0.13
	2	0.21	0.28	0.24
	4	0.15	0.13	0.14

The calculations show that three fires would have no 'slow' mode of spread for $\alpha = 0.5$* and for $\alpha = 0.3$, two have still unrealistically high values.

Fires 1966/2 and 1968/1 can spread in both modes, the former being just on the critical condition above which no slow mode is possible. The intermittent behaviour of 1967/2 may be associated with this well defined theoretical lack of a slow mode.

By and large the results for the head fires are reasonably satisfactory. Fire 1967/3 appears to spread much slower than expected. The fires 1966/4 and 1967/7 spread somewhat faster than expected.

Even though 1966/4 has been treated as a grass fire the discrepancies cannot readily be removed by adjusting α and β within a realistic range, but appear to be associated with the estimated value of ΔH.

*The previous statement that the stability criterion was satisfied by $\alpha \ll 0.5$ was based on observed values of R.

It is noteworthy that these three fires 1966/4, 1967/7 and 1967/6 all lying above the line in Fig. 11, have the wettest fuels and accordingly have been given values of ΔH by Woolliscroft substantially higher than the others because of high measured moisture contents. It will be recalled that we have previously commented that the inclusion of ΔH in the correlation in Fig. 3 worsens it.

With such few data it is difficult to pursue discussion of apparent anomalies nor to optimize the values of α and β.

Discussion

It should be recalled that we have assumed the wind dependent flux (other than flame radiation) varies linearly with wind speed and that Fig. 8 shows an upward trend of flame radiation with wind speed, but with considerable scatter. Several experiments on the effect of wind on fires in beds of pine needles[9,10] have shown a more than proportional increase in spread rate with increasing wind and this suggests that the correlation obtained here is perhaps limited to wind speeds only up to about 4 m/s.* If more data are collected from controlled burns it might be possible to establish theories on a firmer physical basis, but it is doubtful if it is profitable to do so at present.

If the flame length correlation were maintained at high rates of spread and t_B, ϕ i_B and i_f, are treated as constant, equation (9) gives R in terms of U. R increases more than proportionately to U over a substantial practical range even if the effect is relatively not as great as reported for pine needles. These parameters cannot strictly be regarded as insensitive to wind speed and to treat them other than as measured parameters (which strictly a full theory needs to do) would be well beyond the scope of this paper. However it is probable that treating them as relatively insensitive to wind speed and reserving the main effect of wind for the indirect effect of rate of spread on flame radiation and on convection is a useful first approximation.

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*Boundary layer convection from the bent over flame to the fuel bed may be important in spread over pine needles and insignificant for fires discussed here. The inclusion of a convection term depending on LU would increase the dependance of R on U.

The analysis has not resolved the question of when one should base rates of spread on all the fuel in a mixture and when only one component carries the fire, though if there is a large difference in the moisture content of the thin and the thick fuel, i.e. if drying weather has not persisted long enough to dry out thicker fuel, one may perhaps expect that the burning of only the thin fuel is more likely. Nor has it resolved the role of moisture. In the range $U < 4$ m/s and $M < 60\%$, W' should be taken, provisionally, as $0.45\,W$ or $\rho_b' \doteq 0.45\,\rho_b$. The dependence of the rate of spread on U is suggested as partly a direct dependence on convection and partly on flame radiation which is correlated with U.

In reporting data on fires, controlled burns or wildfires, information on fuel height is necessary. To prepare for analyses (presumably statistical) in the future the description of the fuel and weather condition should include information on the extent of thin fuels, especially grass, in the fuel bed and information which either gives the moisture content of such fuel separate from the other fuel or from which it could be inferred, e.g. the fire danger index for preceding days to which the moisture contents of thin and thick fuels would be expected to be related in different ways.

Conclusions

Although theory at present cannot specify whether the total fuel or the part burnt is the more useful term for correlation purposes nor resolved the roles of moisture content and the effect of mixtures of fuels, we have found

(a) a provisional empirical correlation between rate of spread, fuel bulk density and wind speed up to 4 m/s

(b) a correlation between the fraction of fuel burnt and moisture content

(c) that flame radiation is controlled by an effective attenuation coefficient of $0.1\ m^{-1}$ but is, from stability arguments, $\frac{1}{2}$ or less than that calculated for a continuous flame

(d) that a term which appears to represent convection heating can be accommodated into heat balance equations for the spread.

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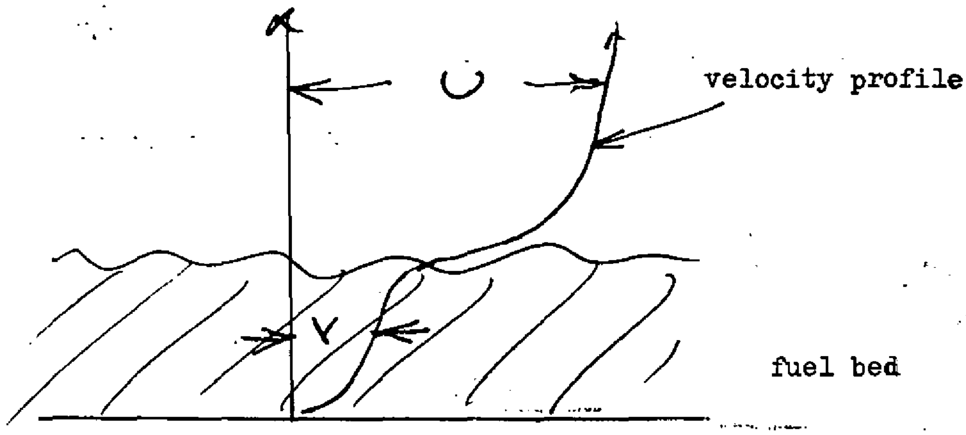
APPENDIX I

Horizontal flow of gases in fuel bed



The following treatment to estimate the velocity downwind in the fuel bed is highly simplified. We assume all the drag of the free stream wind is taken up by the fuel bed and thence to the ground.

The resistance in a bed of randomly packed spheres is given by Ergum as[12]

$$\frac{dp}{dx}\,\frac{\varepsilon^3}{1-\varepsilon}\,\frac{d_p}{\rho_g V^2} = \frac{150\,(1-\varepsilon)\nu}{d_p V} + 1.75$$

where $\frac{dp}{dx}$ is the pressure gradient

ε is the porosity

d_p is a characteristic dimension = $6/\sigma$

where σ is the specific surface

ρ_g is the gas density

$\rho_g V$ is the mass flow per unit total bed cross section

and ν is the kinematic viscosity.

This expression refers to spheres and the effect of cylindrical type obstructions would be to alter the coefficients 150 & 1.75 but by little relative to order of magnitude changes in σ, U etc.

In terms of our previous notation we have

$$\frac{\rho_b}{\rho_s} = 1 - \varepsilon$$

Also $$S = \frac{\sigma}{4}\frac{\rho_b}{\rho_s} = \frac{\sigma}{4}(1-\varepsilon) = \frac{3}{2}\frac{(1-\varepsilon)}{d_p}$$

where ρ_s is the density of the solid fuel

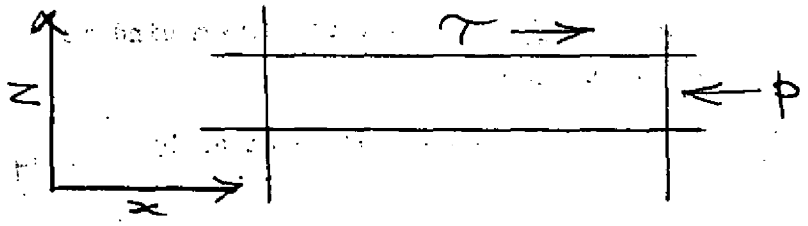
and S is the same expression as the radiation attenuation coefficient of the bed (5)

Now $$\frac{\rho_b}{\rho_s} \sim 10^{-2} - 10^{-3}$$

so $$\varepsilon \rightarrow 1$$

Hence $$\frac{dp}{dx} = \frac{2}{3} S V^2 \rho_g \left(\frac{100\nu S}{V} + 1.75\right)$$

To balance the horizontal pressure gradient by a shear force, we put



$$\frac{d\tau}{dz} = \frac{dp}{dx}$$

Treating V as constant we have

$$\tau = \frac{2}{3} S h \rho_s V^2 \left(\frac{100\nu S}{V} + 1.75\right) \text{at } z = h$$

where h is the height of the fuel bed

and we put $$\tau = \rho_g C_D \left(\frac{U - V}{2}\right)^2$$

where C_D is a drag coefficient

We take, as typical values

$$S \doteqdot 3.0 \text{ m}^{-1} \quad (1)$$

$$\nu = 0.45 \times 2\ 10^{-4} \text{ m}^2/s$$

so that $$\frac{100 S}{V} \ll 1.75$$

i.e. $$\frac{U}{V} \doteqdot 1 + \sqrt{\frac{7}{3}\frac{hS}{C_D}}$$

and since C_D is of order $10^{-2} - 10^{-1}$

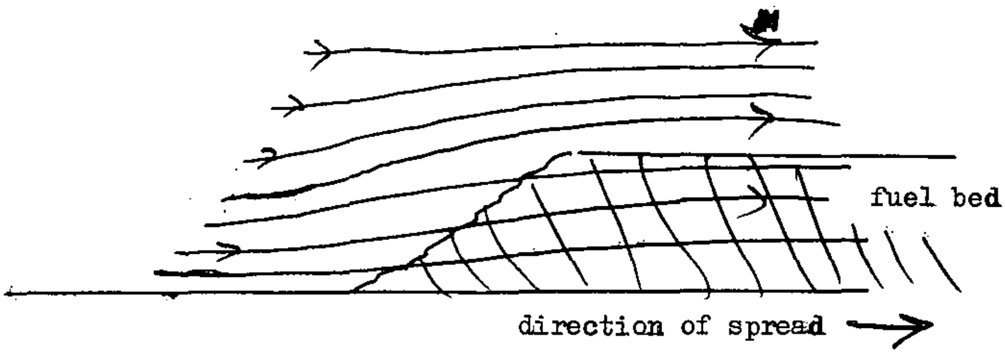
$$\frac{V}{U} \doteq \sqrt{\frac{3\ C_D}{7h\,S}} \quad \text{or} \quad \sqrt{\frac{12}{7}\ \frac{C_D\,\rho_s}{W\,\sigma}}$$

where W is the fuel loading kg/m^2

Putting $C_D \doteq 3 \times 10^{-2}$ $S = 3.0\ m^{-1}$ $h = 0.5\ m$

$$V \doteq \frac{U}{10}$$

This is representative of downwind conditions but it does not really represent the air flow near the fire front because the fuel bed, which does not exist behind the fire front, is more like a step in the path of the wind, and air must enter the fuel bed from the rear and tend to rise up through it as im the sketch below.



These upward components of the flows which are different for different fuel beds will affect the flame profile. Indeed one might consider the ratio of $\frac{S h}{C_D}$ (or $\sigma W/C_D \rho_s$) as an additional dimensionless parameter for modelling fires spreading in a wind. $\sigma W/\rho_s$ is, in effect, the surface area of fuel per unit ground area. The difference betweem the deflection of the flame front within the fuel bed and the flame above the fuel bed is a possible explanation of the inadequacy referred to by Woolliscroft of the laboratory flame deflection as a measure of field behaviour.

APPENDIX II

Heat loss

Radiation is only lost from those surfaces which "see" outside the fuel bed.

The effective distance over which the unburnt fuel is heated in the absence of flames is $\frac{1}{s}$, where s is the attenuation coefficient in the fuel, and with long flames it is of order L. Woolliscroft reports values of $\frac{1}{s}$ of 0.3 m for various fires and L is generally greater than this. The maximum effective temperature rise of this fuel is the ignition temperature 300°C. Hence the radiation component of q'_L is

$$q'_L(\text{rad}) < \alpha'' 300\ L$$

where α'' is the radiation transfer coefficient 0.02 kW/m^2°C at 300°C

$$q'_L(\text{rad}) < 6\ L\ \text{kW/m}^2$$

This represents a fraction 'f' of the total flux where

$$f = \frac{6\ L}{R \rho'_L\ \Delta H.h.}$$

This is greatest at low rates of spread and $R \rho'_L \Delta H.h.$ has a minimum value of about 40 kW/m where L has a value of about 1 m so that $f < 15\%$. L is greatest (5 m) for test 1968/4 for which $R \rho'_L\ \Delta H.h.$ is 360 kW/m so that $f < 10\%$. We shall accordingly neglect the relatively low loss of uncertain value.

Convection loss is absorbed into the estimate of q''_c which is net flux. As a consequence of these arguments no special provision need be made for heat loss.

It is likely that the higher estimate of the heat loss derived by Thomas and used by Woolliscroft is more appropriate to cribs where

(a) a large part of the surface can lose radiation to outside the cribs, i.e. the fuel bed is small compared with a radiation attenuation "mean path".

(b) there is little wind so that parts of the crib ahead of the fire front lose heat by natural convection to outside the crib and not to other parts of the crib.

Table 1

Controlled New Forest Burns

Fire reference year and number (see reference 1-4)	Fire type	'U' Wind speed m/s	Fuel	Moisture content %	t_B s	Fuel bed height m	Bulk density of fuel k/m^3	% burnt	Bulk density of fuel burnt k/m^3	Rate of spread R m/s
1966/2	Head	1.33	Heather	38	35	0.40	6.81	43	2.96	0.0675
1966/4	Head	0.425	Dwarf gorse Cross leaved heath Fine grass	59 40 25	10	0.35	5.84	56	3.27	0.146
1967/1	Head	1.25	45% Heather 49% Dwarf gorse 6% Fine grass	35	15.5	0.45	5.4	50	2.7	0.045
1967/2	Head	1.0	Heather	40*	28	0.22	3.9	33*	1.6*	0.018
1967/3	Head	3.75	80% Heather 15% Gorse 5% Bracken	40*	13	0.35	4.2	40*	1.7*	0.063
1967/5	Head	2.25	Heather	41	13	0.50	7.3	36	2.6	0.086
1967/6	Head	2.25	Gorse	60	4.7	1.40	2.9	25	0.7	0.30
1967/7	Still air	0	75% Heather 12% Grass 8% Gorse 4% Leaves	50	53	0.50	7.2	50	3.6	0.015
1968/1	Head	0.75	97% Heather 3% Grass	30	11	0.50	2.43	43	1.05	0.088

Table 1 (cont'd)

Controlled New Forest Burns

Fire reference year and number (see reference 1-4)	Fire type	'U' Wind speed m/s	Fuel	Moisture content %	t_B s	Fuel bed height m	Bulk density of fuel k/m^3	% burnt	Bulk density of fuel burnt k/m^3	Rate of spread R m/s
1968/2	Head	4.17	86% Heather 14% Grass	30 18	9	0.40	2.17	63	1.7	0.21
1968/3	Flank	(1.12)	46% Gorse 25% Heath 29% Grass	26 30 9	39	0.35	7.2	52	3.75	0.028
1968/4	Head	1.27	Gorse	35	20	1.50	3.09	48	1.5	0.15

*Estimates

For other data see references 1-4.

Values of i_f lie betweem 154 and 192 kW/m^2 except for 1967/7 where it was 123 kW/m^2.

Values of H between 1 and 1.8 x 10^6 joule/kg.

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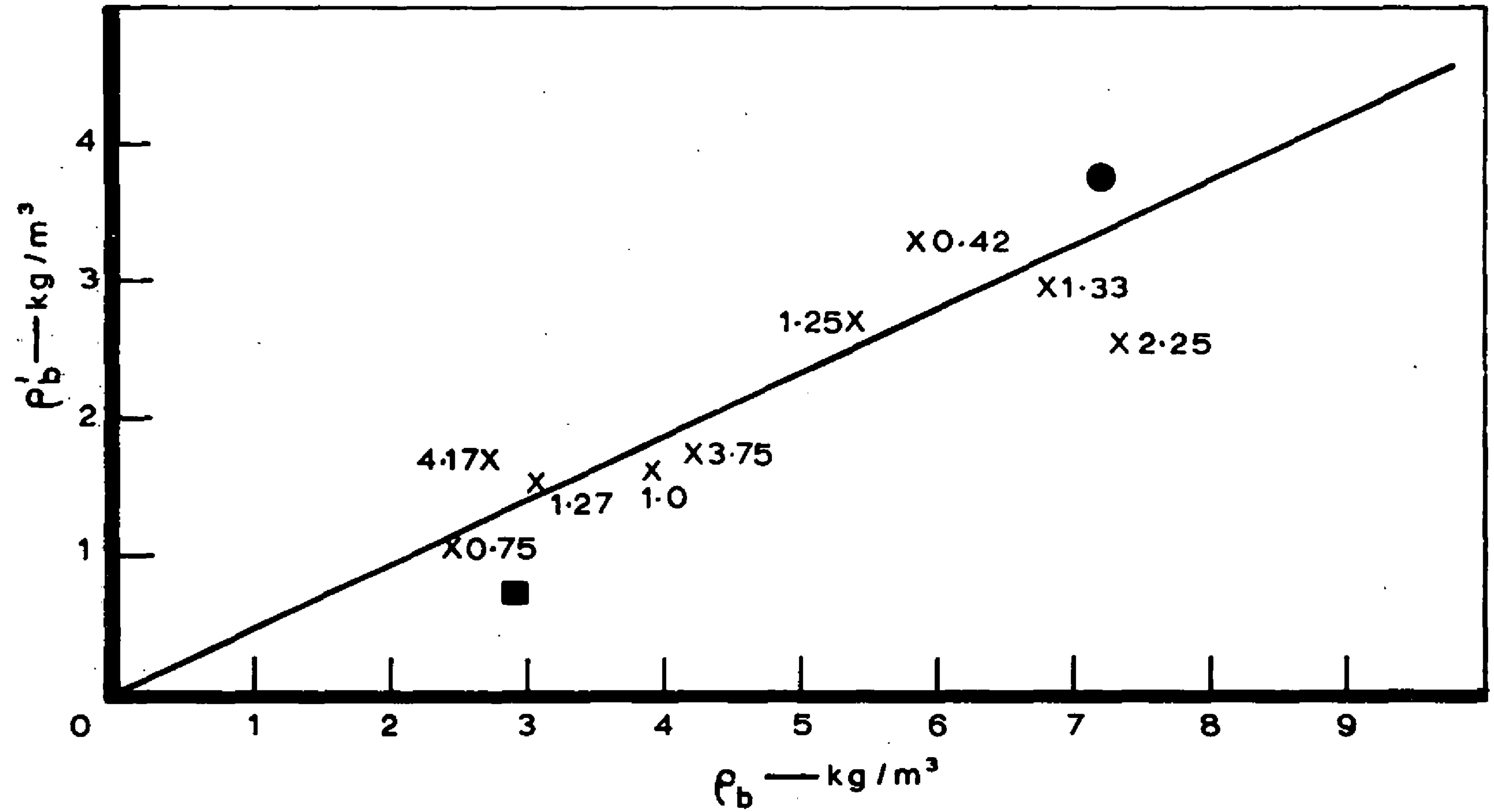

The numbers by each point are the wind speeds(m/s)

● Flank fire at 1·12 m/s (1968/3)

■ Still air fire (1967/7)

FIG.1. THE BULK DENSITY OF BURNT FUEL

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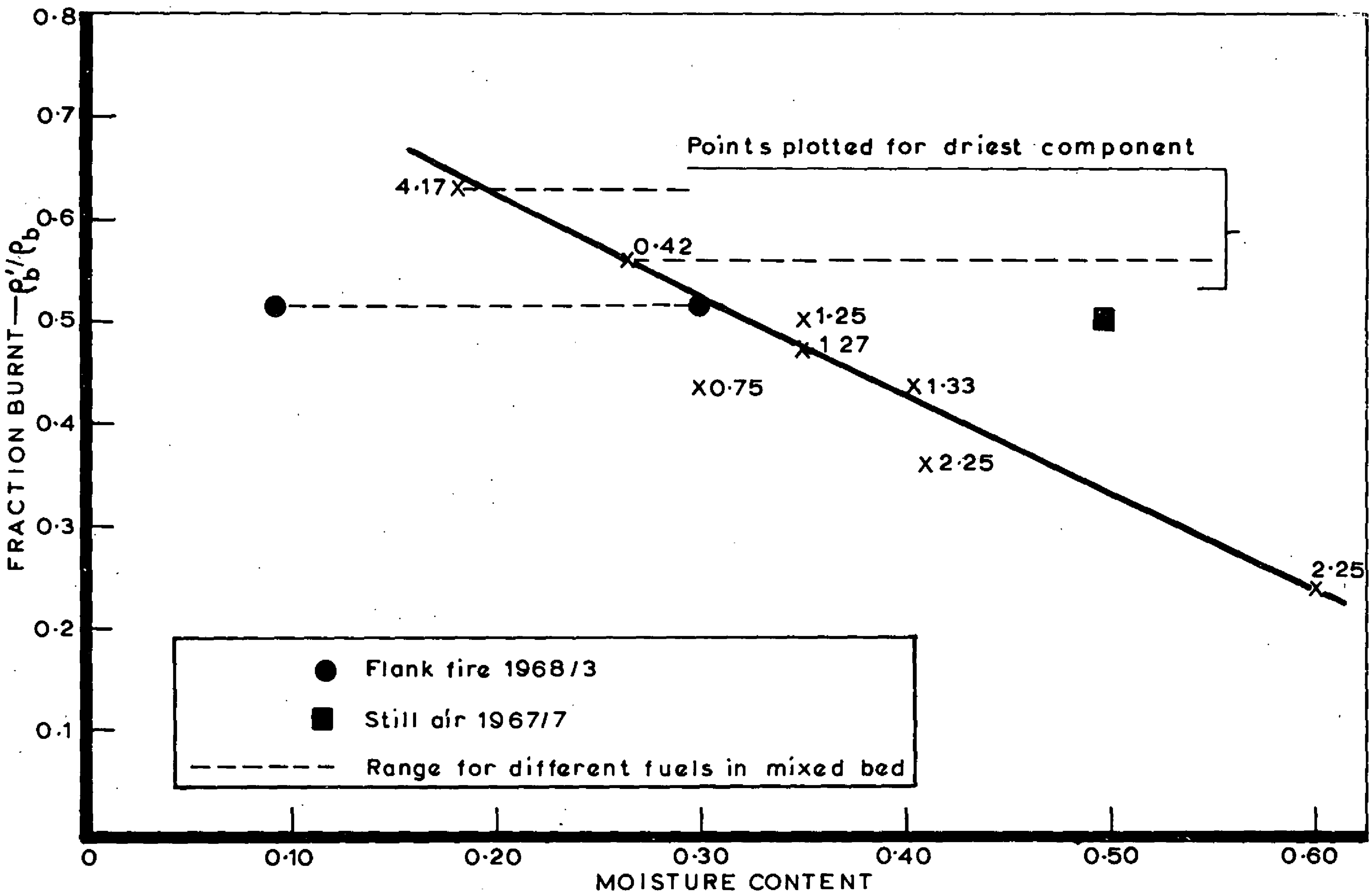

FIG. 2. THE EFFECT OF MOISTURE ON FUEL CONSUMPTION

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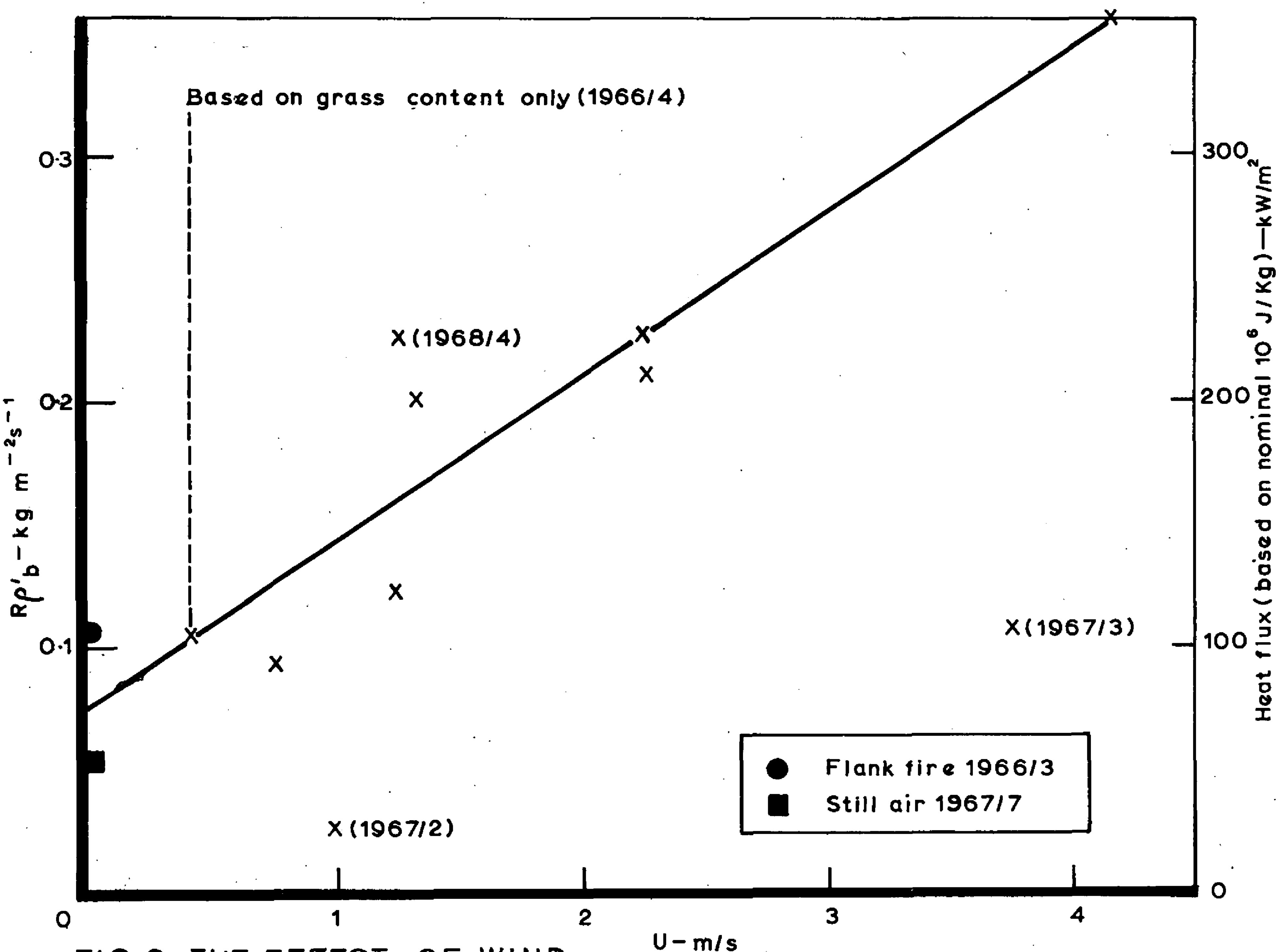

FIG.3. THE EFFECT OF WIND

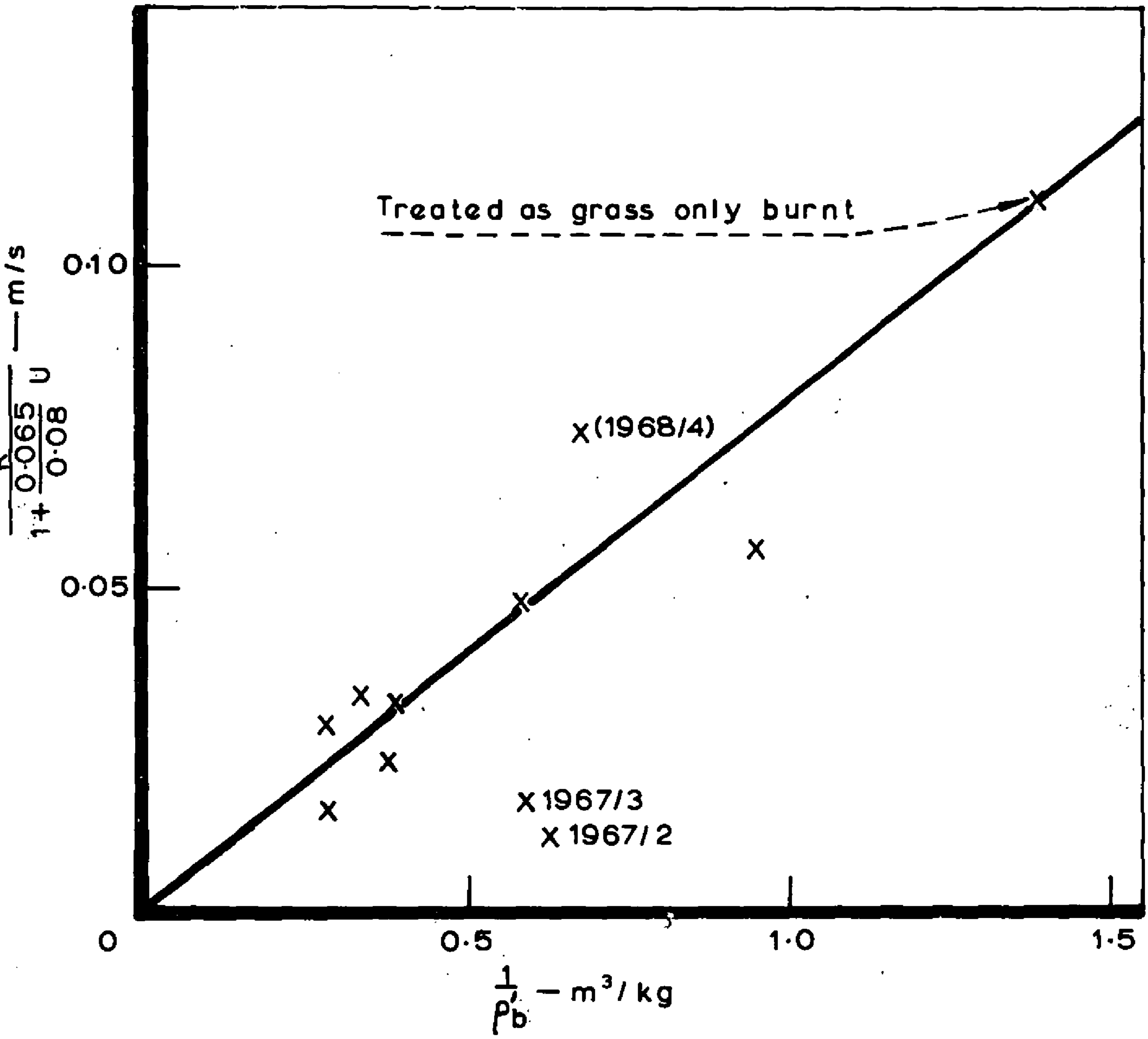

FIG. 4. THE RECIPROCITY BETWEEN BULK DENSITY AND RATE OF SPREAD

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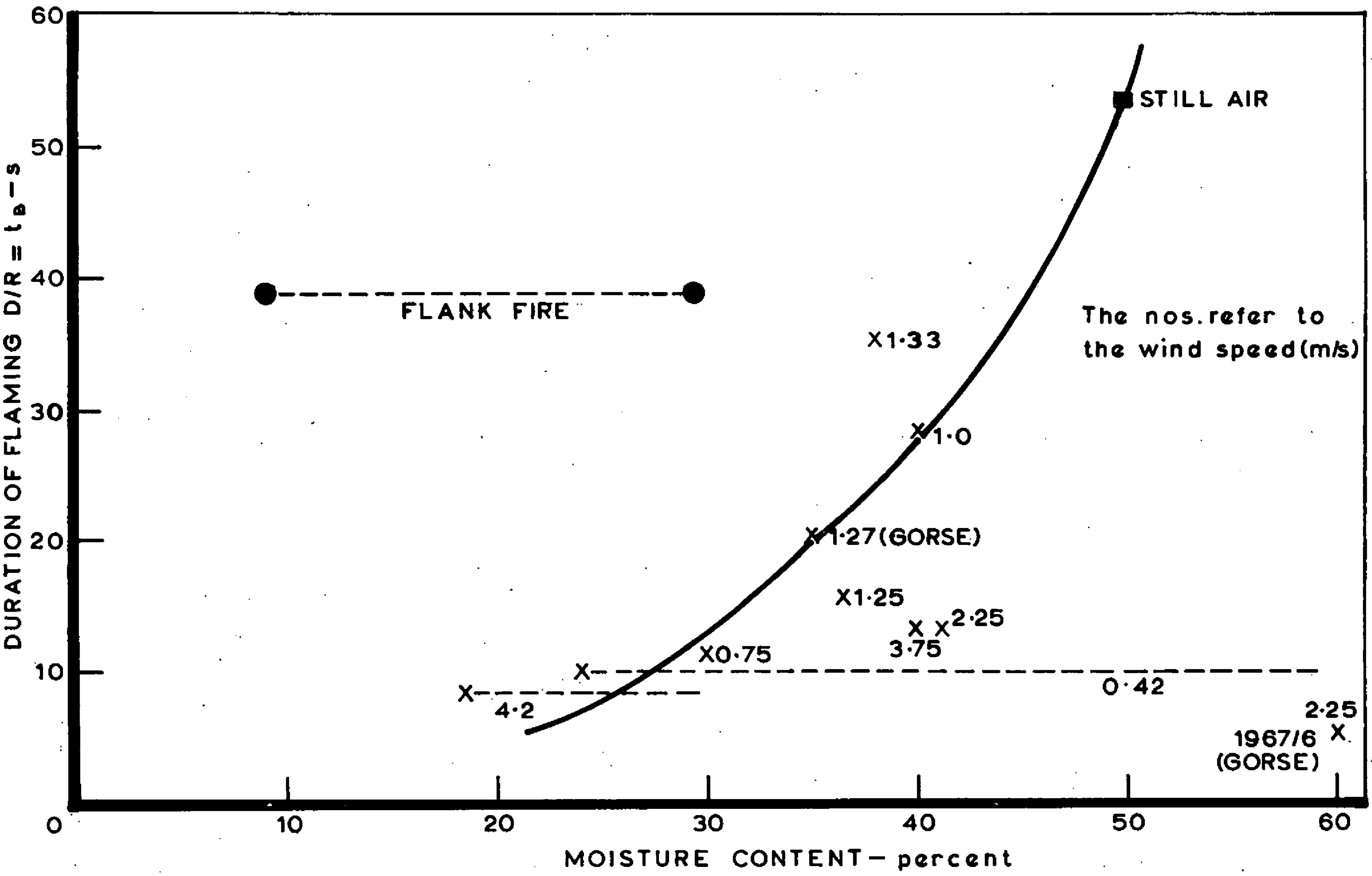
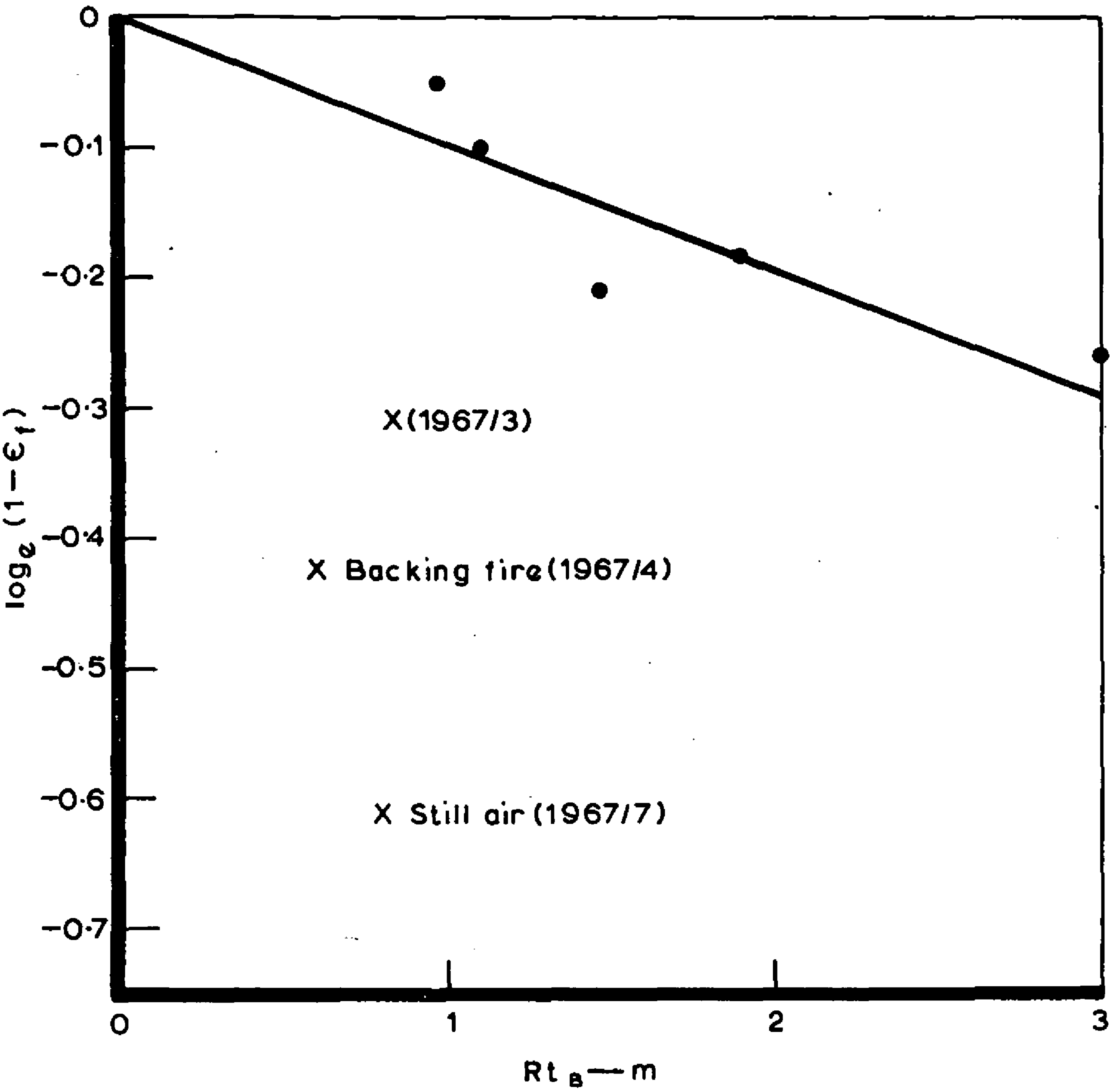


FIG.5. THE DURATION OF FLAMING (RESIDENCE TIME)



ϵ_f from measured radiation and temperature

No data for fires 1966/2, 1967/1 or 1967/2

FIG.6. FLAME EMISSIVITY

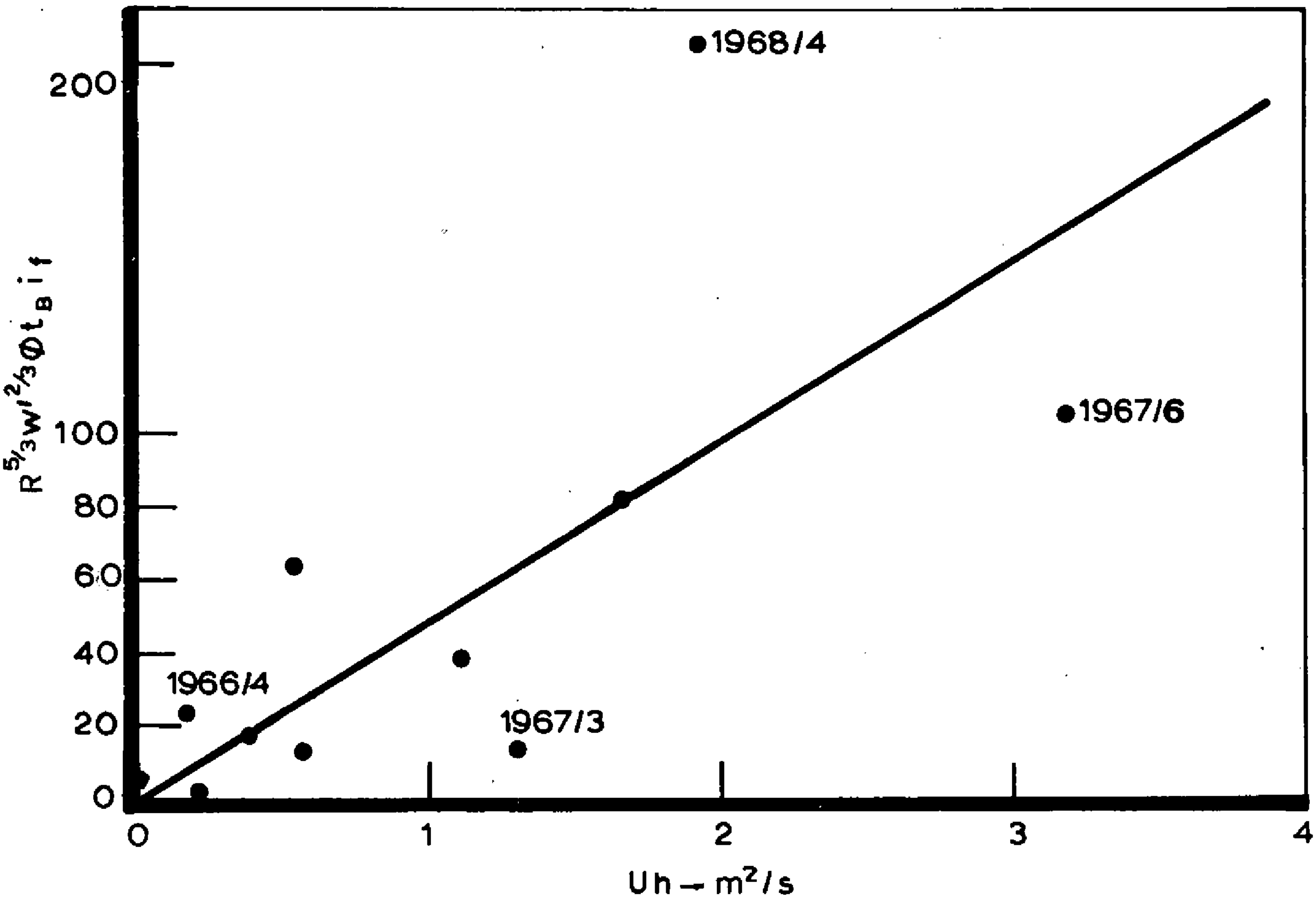


FIG.8. FLAME RADIATION AND WINDSPEED

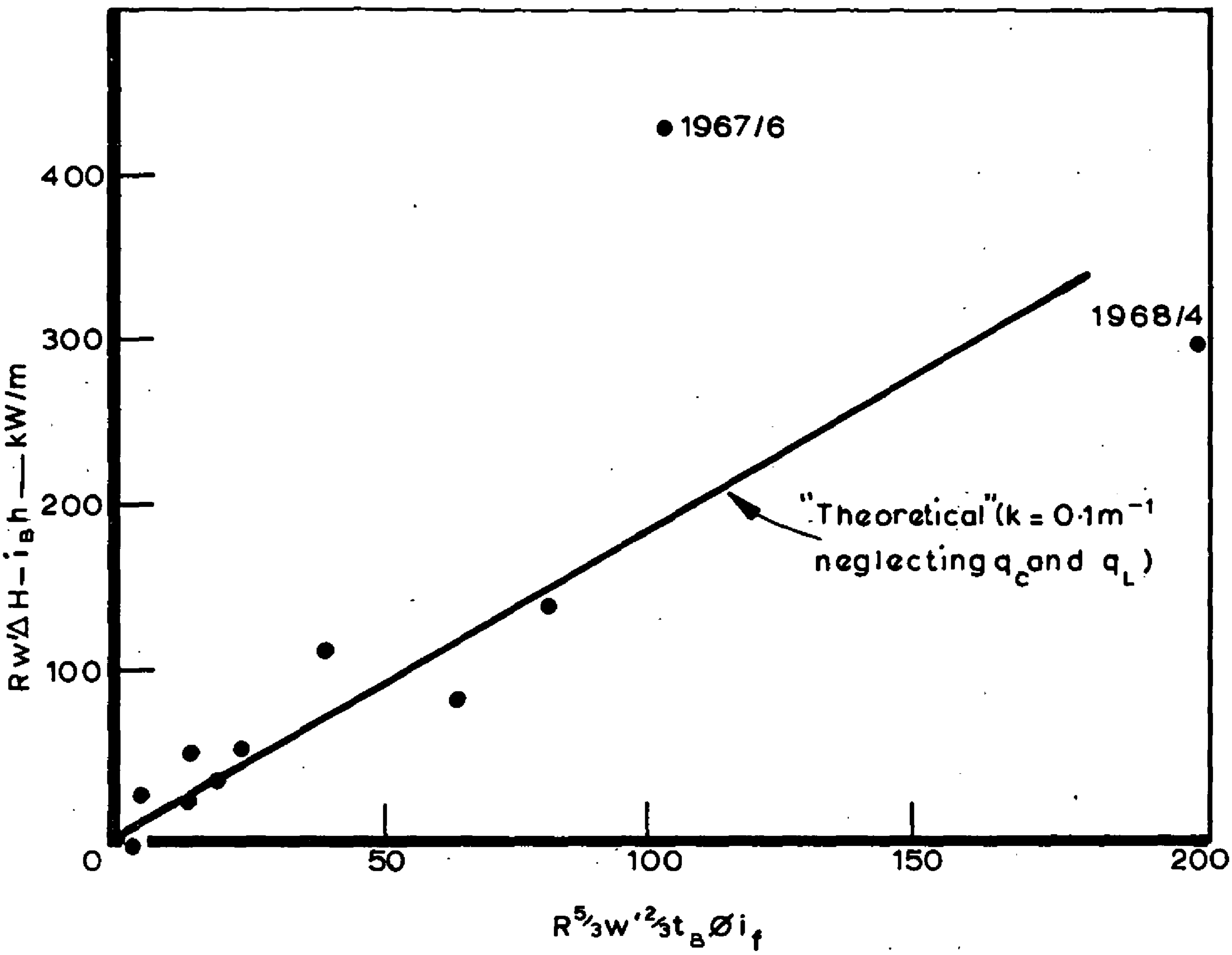


FIG.9. HEAT BALANCE (NEGLECTING CONVECTION)

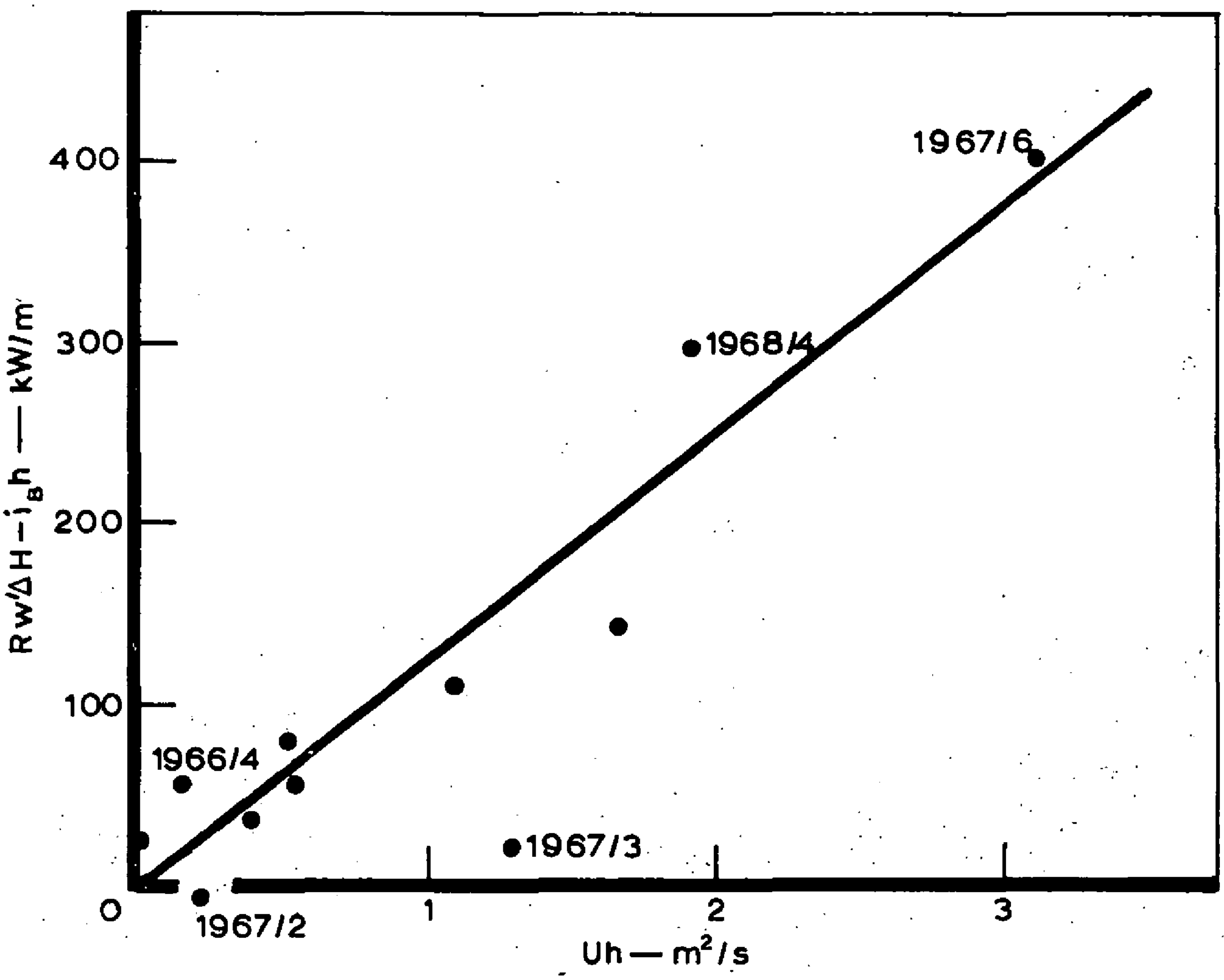


FIG.10. HEAT BALANCE (NEGLECTING FLAME RADIATION)

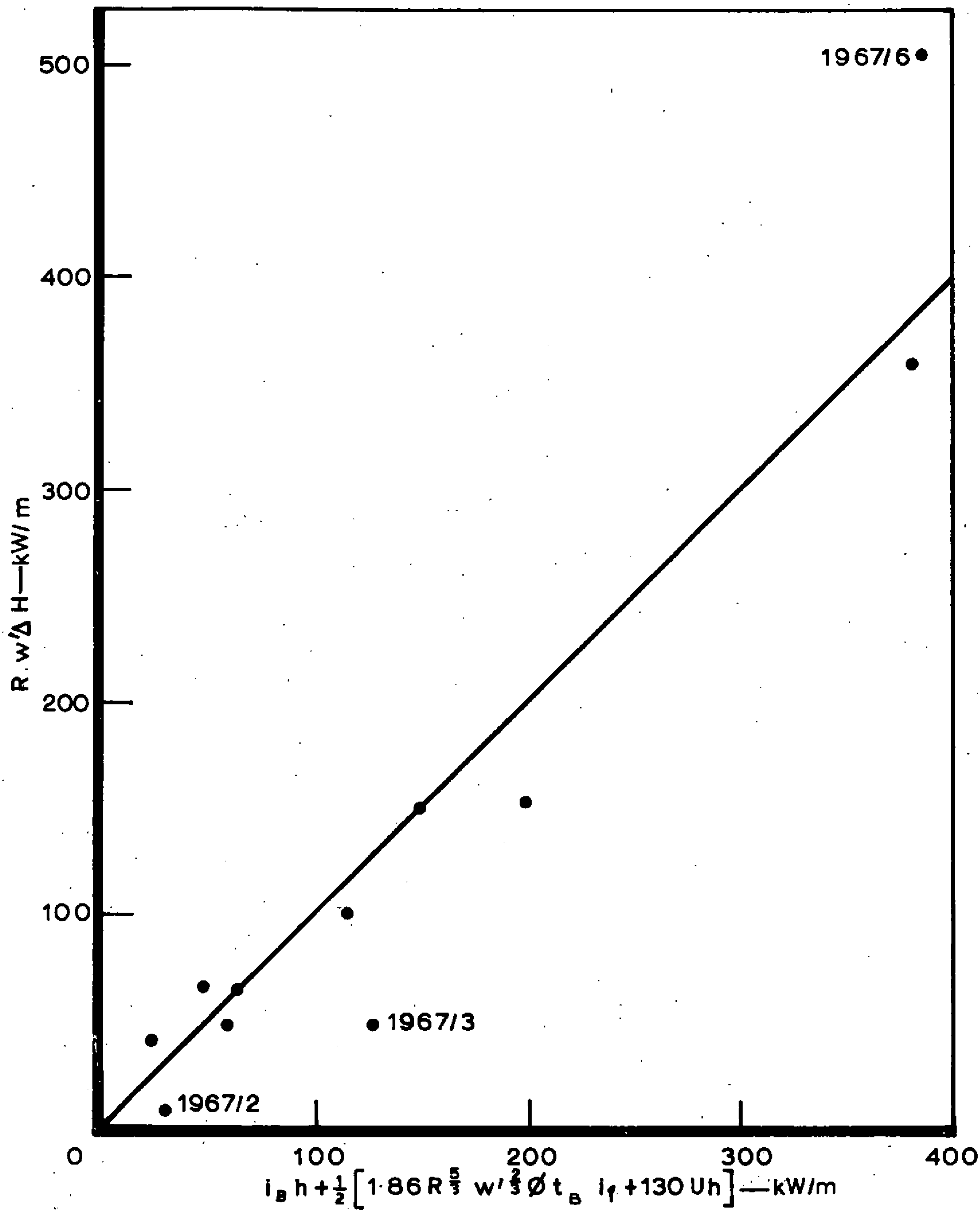


FIG.11 A HEAT BALANCE ($\alpha = \beta = 0{\cdot}5$)

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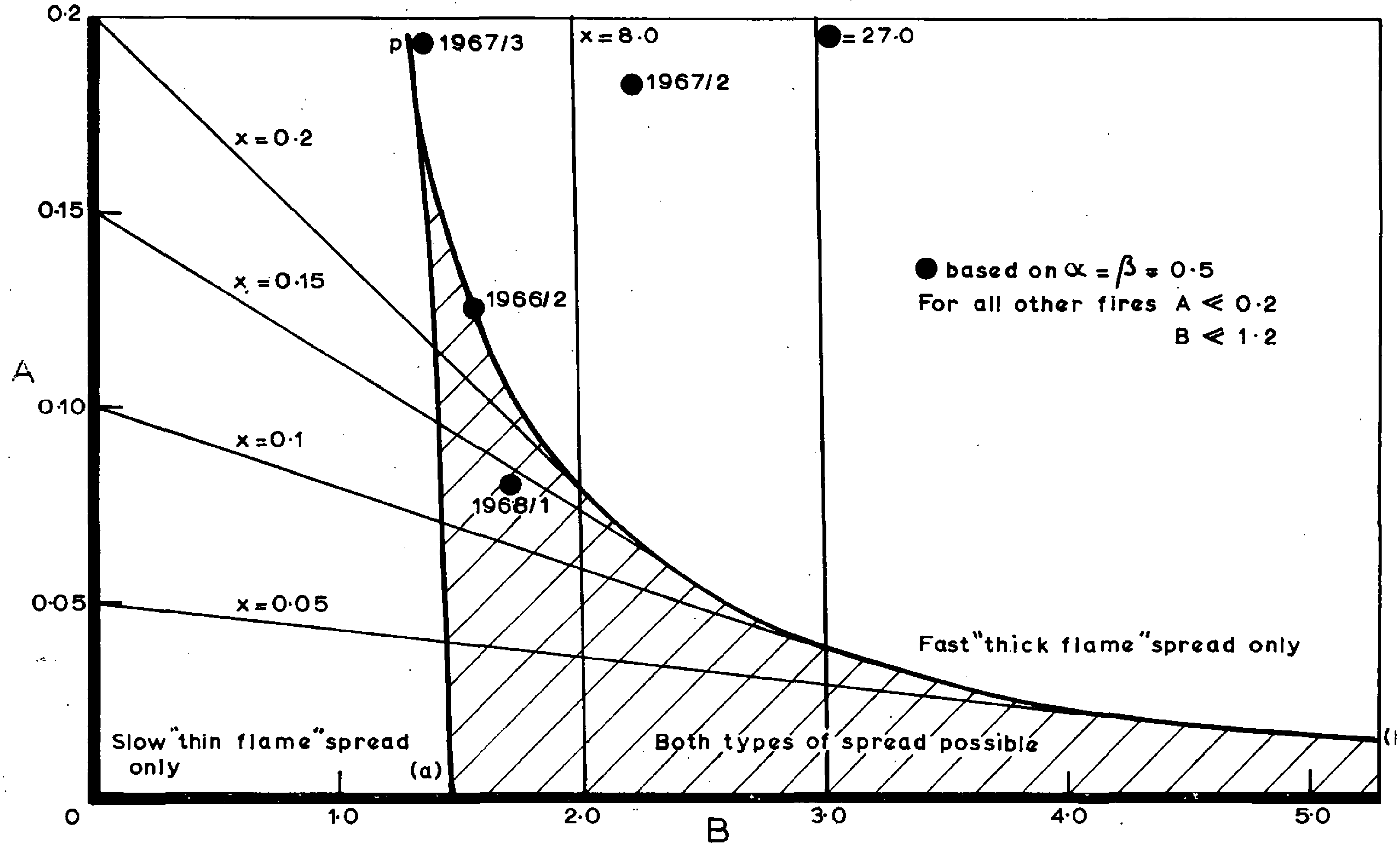

FIG.12 CALCULATION OF SLOW AND FAST RATES OF SPREAD