MINISTRY OF TECHNOLOGY

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NO. 599

FIRE SPREAD IN WOODEN CRIBS
PART II HEAT TRANSFER EXPERIMENTS IN STILL AIR

by

P. H. Thomas, D. L. Simms and H. G. H. Wraight

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F.R. Note No. 599

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SUMMARY

The assumption that fire spread in cribs is the result primarily of the radiation transmitted forward from the burning zone is confirmed by experimental data which show a correlation between heat transfer rates in the burning zone and the rate of spread.

The report also discusses some other aspects of crib behaviour such as the effect of stick size and bulk density.

June, 1965.

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1. Introduction

The spread of fire through cribs of wood in still air has been correlated by means of a dynamic heat balance for the fuel bed(1). As a result of the observation by Fons that the front of the burning zone was vertical and the rate of spread was independent of the height of the crib(2) the unburnt fuel was presumed to be heated to ignition by the radiation transmitted directly through the crib. The heat transferred forward from the burning zone i_B was estimated from the rate of spread to be about 2.0 cal $cm^{-2}s^{-1}$. It has now been shown that the value chosen originally for the Newtonian cooling constant (8×10^{-4} cal $cm^{-2}s^{-1}$ $degC^{-1}$) probably overestimated its value by 25 per cent(4) but inserting the lower value makes only a small difference to the value calculated for i_B, reducing it to about 1.7 cal $cm^{-2}s^{-1}$.

The assumption that radiative transfer through the fuel bed controlled the rate of spread of fire was recently confirmed by McCarter and Broido(3) in an ingenious series of experiments. Both by quenching the flame and by shielding the fuel bed from the flames above the fuel bed they showed that radiation from these flames had little effect on the rate of spread. They also measured the total heat output from the fire and the radiative and convective components from the flame and the fuel bed and showed by differences that the heat transfer by radiation through the fuel bed must be the important factor in heating up the fuel bed although they did not actually measure its value directly.

The experiments described in the present paper were undertaken primarily to obtain experimental values for the heat transfer within the burning zone.

2. Experimental work

2.1. Experiments carried out

The individual tests are listed in Table I; they provide some guidance to the effects on:-

(a) the rate of fire spread, R, flame length, L, and length of the burning zone, D_W

and (b) the rates of heat transfer per unit area within the burning zone, and from the flames,

as a result of:-

(i) enclosing the crib sides and doubling the crib width (test No's 1, 8, 7)

(ii) varying the bulk density, stick size and spacing with the crib sides covered (test No's 65, 66, 90-93)

(iii) varying the horizontal gradient of the crib by ± 5° (test No's 87, 88, 90)

(iv) including inert materials within the crib by substituting asbestos rope for every third stick in each row. This lowered the bulk density of the wood in the bed without changing the crib configuration (test No's 112, 113)

(v) sealing the ends of the sticks with a fire retardant paint to prevent the escape of volatiles before the arrival of the burning zone, using two species of different permeabilities, European Whitewood (Picea abies) and European Redwood (Pinus sylvestria) (test No's 120-123).

2.2. Details of cribs

Most of the cribs (a typical one is shown in Plate I) were built to a length of 91 cm (3 ft), a width of 30 cm (1 ft) and a height of 15 cm (6 in). This length of crib was found to be sufficient for a steady rate of fire spread to be maintained for a period long enough to make observations. The cribs were constructed of square section sticks of thickness 2.5 cm (1.0 in), 1.3 cm (0.5 in) and 0.6 cm (0.25 in) cut from a common variety of unplaned softwood. The spacing between the sticks in the vertical direction was always the same as their thickness, a 1 : 1 spacing ratio, but in the horizontal direction it was varied from 3 to 11 times the stick thickness, so enabling the bulk density of the crib to be varied by a factor of 3 for any given value of the density of the wood itself. The sticks were secured by the least amount of nailing necessary to make the whole crib portable. The moisture content of the cribs measured before the test varied from 8 to 14 per cent of the dry weight.

2.3. Heat transfer instruments

Radiation from the flames and from the burning zone was measured by a total radiation pyrometer placed behind the ignition plane and sighted in the direction of fire spread. The heat transfer within the burning zone was measured by a continuous water flow calorimeter in the form of an inverted U-tube of 0.6 cm (0.25 in) external diameter mounted so that it projected about 15 cm (6.0 in) into the crib. The heat transfer at the far end was measured using a disc calorimeter with a concentric guard ring placed with its receiving surface vertical(5). Temperatures within the burning zone were measured with thermocouples (28 S.W.G. chromel-alumel) placed along the central axis of the crib in the direction of fire spread. Figure 1 shows the arrangement of crib and instruments.

2.4. Experimental procedure

In the majority of the experiments the crib sides were protected with Fletton bricks to reduce heat losses and air inflow at the sides, and thus make the crib represent a wider fuel bed. The cribs were placed on a sheet of asbestos wood and ignited at one end with thin strips of fibre insulating board about 15 cm long soaked in paraffin and placed underneath; this ignited the first 10-15 cm of the crib. The position of the front of the burning zone, the height of the flames, the length of the burning zone and the outputs of the pyrometer, heat flux meters and thermocouples were recorded.

2.5. Experimental results

The experimental results are listed in Table I. The flame front remained vertical in all the experiments.

3. Discussion of results

3.1. Effect of crib width

Increasing the crib width from 30 to 61 cm increased the rate of spread from 0.049 to 0.083 cm/s (Tests 1 and 8) while covering the sides of a 30 cm wide crib increased the rate to 0.074 cm/s (Test 7). On the other hand Fons et al(2) showed that a crib 30 cm wide and 15 cm high was large enough to be representative of a fire burning on a wide front, whether the sides were covered or not, a result confirmed by Anderson and Rothermel(6) for beds of pine needles. Clearly some further investigation of the effect of width is desirable. The difference between tests No's 1 and 8 is consistent with the effect of width found for non-spreading fires by Byram et al(7) who obtained a correlation in terms of

Table I

Experiments on fire spread in cribs

Length of crib - 91 cm

Test No.	Stick thickness - cm	$\frac{\text{Stick spacing}}{\text{Stick thickness}}$	Moisture content - per cent by wt.	Bulk density of crib - mg/cm^3	Wood density at given moisture content - g/cm^3	Crib Dimensions cm		Rate of spread - cm/s	Mass spread rate mg cm^{-2}s^{-1}	Length of burning zone - cm	Flame length from top of crib - cm	Radiation from flames - cal cm^{-2}s^{-1}	Maximum temperature rise in burning zone - deg C	Heat transfer from burning zone cal cm^{-2}s^{-1}				Permeability of wood along grain (where known) cm^2 s^{-1} atm^{-1}	Remarks All crib sides covered with Fletton bricks unless otherwise stated
	d	x	M	ρ_b	ρ_m	Width D_c	Height h	R	$R\rho_b$	D_w	L	q''_f	T_B	Normalised Residence Time $\frac{D_w}{R\rho_f d^{1.5}}\left(\frac{10}{M}\right)^{0.26}$	Total Radiation Pyrometer i_p	U - tube calorimeter i_u	Disc calorimeter i_D		
91	0.6	11	10	48	0.58	30	15	0.130	6.2	13	68	-	-	300	2.5	2.4	1.5	-	
92	0.6	11	10	48	0.58	30	15	0.130	6.2	13	77	-	-	300	2.4	2.4	1.4	-	
93	0.6	5	9	94	0.56	30	15	0.064	6.0	6	83	-	970	302	2.6	1.9	2.0	-	
65	0.6	5	13	113	0.68	30	15	0.058	6.6	8	81	-	-	339	-	1.7	-	-	)Crib sides covered with asbes-
66	0.6	5	13	109	0.65	30	15	0.072	7.9	10	89	-	-	354	-	1.6	-	-	)tos wood boards 1.0 cm thick
Gradients																			
90	1.3	3	8	120	0.48	30	15	0.090	10.8	18	99	-	-	342	2.6	-	2.0	-	
87	1.3	3	8	120	0.48	30	15	0.070	8.4	23	105	-	-	562	2.9	-	2.3	-	Burning downhill on 5° slope
88	1.3	3	8	120	0.48	30	15	0.080	9.6	20	99	-	-	427	2.6	-	2.0	-	Burning uphill on 5° slope
Restricting air flow and reducing heat loss																			
1*	1.3	3	14	115	0.46	30	15	0.049	5.6	11	49	-	900	367	-	-	-	-	*
8*	1.3	3	12	113	0.45	61	15	0.083	9.4	23	101	-	1000	467	-	-	-	-	*
7	1.3	3	12	116	0.46	30	15	0.074	8.6	19	91	-	1060	427	-	-	-	-	1.0 cm asbestos wood sideboards
Inert Material																			
112*	2.5	3	10	73	0.44	53	15	0.044	3.2	17	28	-	900	293	1.3	1.1	1.3	-	*1/3 sticks of asbestos
113*	2.5	3	9	126	0.50	53	15	0.082	10.3	33	126	-	900	273	1.9	2.2	2.6	-	*
Permeability																			
120	1.3	3	10	104	0.42	30	14	0.079	8.2	15	92	0.35	1010	355	2.1	2.1	2.0	0.42	European Whitewood) stick ends) not
122	1.3	3	10	123	0.49	30	14	0.074	9.1	15	100	0.37	960	320	2.8	2.0	2.2	2.10	European Redwood) sealed
123	1.3	3	10	110	0.44	30	14	0.084	9.2	15	96	0.39	1070	317	2.6	2.1	2.2	0.42	European Whitewood) stick ends
121	1.3	3	10	128	0.51	30	14	0.071	9.1	15	106	0.48	1100	325	2.4	2.2	2.0	2.10	European Redwood) sealed

*Crib sides left uncovered

convection. If the rate of spread were air controlled then increasing the width or enclosing the sides would be expected to decrease the burning rate per unit area of crib section; since the opposite was the case the results are therefore more consistent with thermal control. Increasing the crib width both reduces the heat lost from the sides and has a geometric effect on the radiation transmission forwards, while covering the sides merely reduces the heat losses. Thus the effect of covering the sides shows that the spread is influenced by heat loss from the sides quite apart from any geometric effect of crib width. However, the heat loss from the sides is expected to become a negligible fraction of the heat balance for very wide cribs so that the power law correlation obtained by Byram et al between a dimensionless burning rate and a Grashof number might break down for wide cribs even if it applies for the non-spreading square fires they examined. The choice of terms in these variables leads to coefficients between the two groups of order 10^2 and 10^3 which suggests they are not the fundamentally appropriate variables. The use of a heat release instead of mass burning rate only worsens this and the coupling of the gravitational acceleration and a horizontal dimension in their correlation which does not contain a vertical dimension is ambiguous since it implies relationships between the dimensions which are not explicitly stated. While it is very probable that the flames in the burning zone transfer heat to the sticks mainly by convection and that tightly packed cribs (e.g. those with spacings less than twice the stick size) are air controlled it is not clear how convection would affect the rate of spread. Instead it is suggested that the increase of burning rate with crib width is the result of a lower heat loss increasing the radiation transmitted forward. In tests 1, 7 and 8 the temperature data tends to support this view but clearly more extensive heat transfer data are required to substantiate any views on this question.

The retarding effect of a narrow crib is expected to be more pronounced with thick sticks since these produce greater lengths of burning zone and consequently greater edge loss for a given width of crib. This is thought to be the reason why the data reported by Fons et al(2) for thick sticks lies below the trend calculated theoretically(1).

3.2. The effect of bulk density

The change of a factor of just over 2 in Tests 65, 66, 90-93 for a given stick size led to a corresponding increase in the rate of spread.

3.3. Effect of slope

Changing the slope by 5° up or down did not appear to make a significant difference to the flame height or the rate of spread in the experiments carried out. This is consistent with the view that convection through the cribs is not an important source of heat transfer to the unignited fuel.

3.4. Heat flux measurements within the burning zone

The peak values of heat transfer obtained from the two continuous flow calorimeters are compared in Fig. 2 and are in reasonable agreement except for two experiments where the disc calorimeter gave much lower values than the U-tube calorimeter and the pyrometer. This may have been due to the early collapse of that end of the crib. The values of heat transfer range between 1.1 and 2.6 cal $cm^{-2}s^{-1}$ with a mean value of 2.0 cal $cm^{-2}s^{-1}$. They are on average somewhat lower than those given by the total radiation pyrometer sighted on the rear of the burning zone (Fig. 3). This was unexpected since the calorimeters measure the convective as well as the radiative heat flux. One reason for this discrepancy may be that the pyrometer was sighted on the glowing embers.

3.5. Emissivity of the burning zone

The maximum temperature, T_B recorded in the burning zone varied from 900°C to 1100°C in the experiments. The effective emissivity of the burning zone, ϵ_B, can be calculated from the Stefan-Boltzmann law if the heat flux measured is assumed to be radiative

$$i_B = \epsilon_B \sigma_s T_B^4 \qquad \text{..........(1)}$$

where σ_s is the Stefan-Boltzmann constant

The values of ϵ_B calculated in this way from the heat transfer measurements and the radiation pyrometer measurements are given below. The second set are slightly higher but even for those obtained from the heat transfer measurements the value is never less than 0.40 and the mean value is about 0.6. Table II also shows the number of horizontal gaps between sticks in the burning zone. x is the ratio of stick spacing to stick thickness.

TABLE II

Values of emissivity

Experiment No.	Stick thickness d-cm	Length of burning zone D_w-cm	Number of gaps in burning zone $\frac{D_w}{d(1+x)}$	From heat transfer measurements ϵ_B	From pyrometer ϵ_B
93	0.6	6	1.4	0.63	0.81
112*	2.5	17	1.7	0.47	0.50
113	2.5	33	3.3	0.95	0.76
120	1.3	15	2.9	0.58	0.57
122	1.3	15	2.9	0.67	0.91
123	1.3	15	2.9	0.50	0.58
121	1.3	15	2.9	0.41	0.47
Mean value excluding No. 112				0.62	0.68

*Contains inert material

There is not a sufficient range of data to detect any relation between the value of the emissivity and the width of the burning zone or the stick thickness. The last column is a measure of the length of the burning zone as a ratio of the mean free path of the radiation transfer*, i.e. the optical thickness of the burning zone. This ratio is about three except for tests 93 and 112 which is indicative of high emissivities.

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*The radiation attenuation coefficient α in a randomised bed(1) is $\frac{\sigma}{4(1+\sigma\lambda)}$ where σ is the specific surface of the solids and λ is the volume of voids per unit area of solid. For cribs $1/\alpha$ the mean free path is readily shown from the definitions of σ & λ to be the distance between stick centres, i.e. d(1 + x).

3.6. Comparison between heat transfer from flames above the crib and through the burning zone

The maximum radiation levels from the flames, where measured, were 0.35 to 0.48 cal $cm^{-2}s^{-1}$, the mean value being 0.40 cal $cm^{-2}s^{-1}$. The ratio of the radiation transfer per unit width of crib from the flames $\dot{q}'_F$ to that from the burning zone $\dot{q}'_B$ is given by

$$\frac{\dot{q}'_F}{\dot{q}'_B} = \frac{i_F \; L \; F}{i_B \; h} \qquad \ldots\ldots\ldots\ldots(2)$$

where i_F = radiation intensity from flames

L = height of flames from top of crib

F = radiation exchange factor between flames and top of crib

and h = crib height

The flame heights from cribs 15 cm high vary from about 70 to 125 cm (Table 1), hence the exchange factor F for a crib 30 cm wide varies from about 0.13 to 0.17(9). Taking mean values of 0.4 cal $cm^{-2}s^{-1}$ for i_F, 2.0 cal $cm^{-2}s^{-1}$ for i_B and 95 cm for L and substituting in equation (2) gives a value of about 0.2 for the ratio $\dot{q}'_F/\dot{q}'_B$.

Hence the radiation from the flames even at the top of the crib is much less than that transferred through the crib. This was a conclusion drawn by Fons from the fact that the fire front was vertical.

3.7. Heat transfer and mass burning rate ($R\rho_b$)

The theoretical model shows that the mass burning rate, $R\rho_b$ should be a function of the total heat transfer rate per unit area Q" viz.:

$$R\rho_b.\Delta H = f\left(\frac{Q''}{a\theta_o}\right) \frac{a\,d}{K_m}) \qquad \ldots\ldots\ldots\ldots$$

where f is a calculated function

a is the Newtonian cooling constant

θ_o is the ignition temperature of wood in the presence of a pilot flame

ΔH is the enthalpy rise necessary to raise 1 gm of wood to ignition temperature

d is the stick thickness

and K_m is the thermal conductivity at the appropriate moisture content.

Thomas(1) assumed that there was no variation of Q" with $R\rho_b$, or with ad/K but the results in Table 1 show this is only an approximation since i_B varies.

Figure 4 shows the heat transfer data plotted against the mass burning rate. The theoretical line corresponds to the heat balance of the unburnt material derived in reference(1)

$$R\rho_b.\Delta H = i_B - 2.67\,a\theta_o \qquad \ldots\ldots\ldots\ldots(3)$$

ΔH has been taken as 180 cal/gm for nominal 10 per cent moisture content.

The heat loss $a\theta$ has been taken as 0.24 cal $cm^{-2}s^{-1}$ from $a = 8 \times 10^{-4}$ cal $cm^{-2}s^{-1}\,{}^{o}C^{-1}$, θ equal to 300°C.

The heat transfer rates are much higher than those reported by Byram et al(7) for a calorimeter just before the approaching flames reached it. The agreement here with a theoretical line is fortuitously good since no account has been taken in equation (3) of the non-uniform heating of the thicker sticks throughout their cross section. The cribs of thicker sticks burn more slowly than expected from the more detailed theory allowing for non-uniform heating.

McCarter and Broido(3) gave the mean radiation levels 209 cm away from the centre of the burning zone for 4 cribs of $\frac{1}{2}$ in wood and we can calculate the value of i_B assuming the burning zone to be radiating uniformly in all directions. To do this, a value has been taken for D_W the length of the burning zone, and this was obtained indirectly from the correlation obtained by Thomas, Simms and Wraight(9) for the residence times (see below). i_B was estimated from this and the width and the height of the crib and is shown in Fig. (4) where it is seen that the agreement with theory is very satisfactory.

3.8. Effect of permeability

The mass burning rate of the European Redwood (Pinus sylvestria) was unchanged while that for the European Whitewood (Picea Abies) was slightly increased by sealing the ends of the sticks, whereas the reverse might have been expected. The heat transfer rates and the flame heights were unchanged. Permeability over this range and on the basis of these four experiments with these two woods does not appear to affect the rate of fire spread.

3.9. Residence times

In a previous report(8) the data of Fons et al(10) on residence times was correlated by the equation

$$t = 380\rho_f \, d^{1.3} \left(\frac{M}{10}\right)^{0.26}$$

where $t = {}^{D_W}/R$

and ρ_f is the density of dry fuel.

This correlation, which was used to estimate D_W for the experiments of McCarter and Broido(3), is less satisfactory from a purely numerical point of view than was Fon's own(10) but it is thought to be physically more meaningful. The values of $\frac{D_W}{R\rho_f \, d^{1.3}} \left(\frac{10}{M}\right)^{0.26}$ are tabulated in Table 1 but the differences are not necessarily significant. Enclosing the sides of the cribs increases the heat transfer (Test 1 and Test 7). It also increases the residence time which may be thought surprising if the effect were significant. The relation between residence time and heat transfer is however not necessarily inverse because, although one expects a hotter fire to burn the wood faster, the residence time will depend on the amount of wood actually burnt, and data on residues were not obtained.

3.10. Effect of inert material

The presence of the inert material reduced the heat transfer rate, the rate of spread and the length of the burning zone by about half, whilst the flame height was reduced to one-quarter. The total burning rate was reduced from 10.3 to 3.2 mg $cm^{-2}s^{-1}$ i.e. to about $\frac{1}{3}$. For such a change in burning rate the flame length is expected from theory to be reduced to below 0.45 instead of the fraction 0.25 that was measured. The burning zone temperature, however, remained the same as that of the completely combustible crib. The ratio of the emissivities was reduced to about one half, which roughly corresponds with the change in the length of the burning zone.

4. Conclusions

1. There is evidence that a crib with covered sides will burn like a wider crib with open sides and that with open sides a 61 cm wide crib burns faster than a 30 cm one.

2. The rate of spread increases with decreasing bulk density. The effect of stick thickness on the mass burning rate appears to be similar to that predicted by theory, and in agreement with the data of Fons et al. The effect of stick thickness for a given bulk density was presumed in the theory to be due to the lack of uniform heating throughout the cross section of thicker sticks.

3. There appears to be no significant effect on the rate of spread due to the gradient of the fuel bed when the slope is not more than 5°.

4. The presence of inert material in the fuel bed reduces the mass burning rate, heat transfer and flame size.

5. There does not seem to be any significant effect due to the permeability of the wood sticks.

6. The radiation transfer from the flames is much less than the radiation transmitted through the fuel bed.

7. The measured rates of heat transfer transmitted through the cribs vary with the burning rate as predicted from the theory based on a heat balance of the unburnt fuel

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APPENDIX I

Definitions of terms used in expressing results of crib fires.

(1) Basic data

Stick thickness (d) - cm

Stick spacing ratio ($1 : x$) $\therefore$ gap between sticks = dx

Percentage moisture content (M) = $\frac{\text{weight of water}}{\text{weight of dry wood}} = 100$

Bulk density (ρ_b) - mg/cm^2 = $\frac{\text{Total weight of crib}}{\text{Total volume of crib}}$

Rate of spread (R - cm/s)

Length of burning zone in direction of spread (D_w) - cm

Width of crib (D_c) - cm

Height of crib (h) - cm

Length of flame from top of crib (L) - cm

Heat transfer from burning zone (i_B) - cal cm^{-2}s^{-1}

Heat transfer calculated from max. temp. in burning zone ($\dot{i}_T$) = $\sigma_s (T_B + 273)^4$

Heat transfer to U-tube calorimeter ($\dot{i}_U$) = $R_w \; \Theta$ where R_w = rate of water flow in g/s and Θ temp. diff. in water in degC.

Heat transfer to disc calorimeter ($\dot{i}_D$) = $R_w \; \Theta$

Radiation to pyrometer ($\dot{i}_p$) = $\epsilon_B \, \sigma_s (T_B + 273)^4$

(2) Derived data

Specific surface of wood sticks (σ) = $4/d$ cm^{-1}

Volume of voids per unit surface area (λ) $= \frac{\rho_m - \rho_b}{4\rho_b} d = \frac{\rho_b (1 + x) - \rho_b d}{4\rho_b} = \frac{dx}{4}$

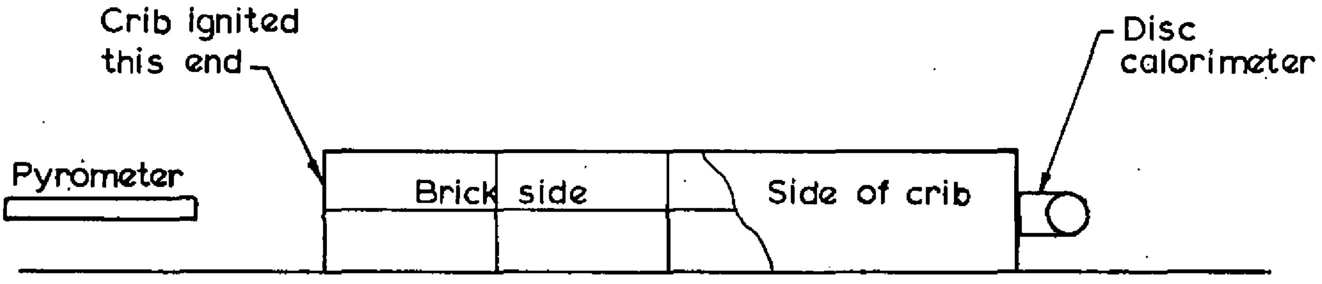
Mean density of solid fuel (ρ_m) = $\rho_b (1 + x)$ mg/cm^3

$$\sigma \lambda = x$$

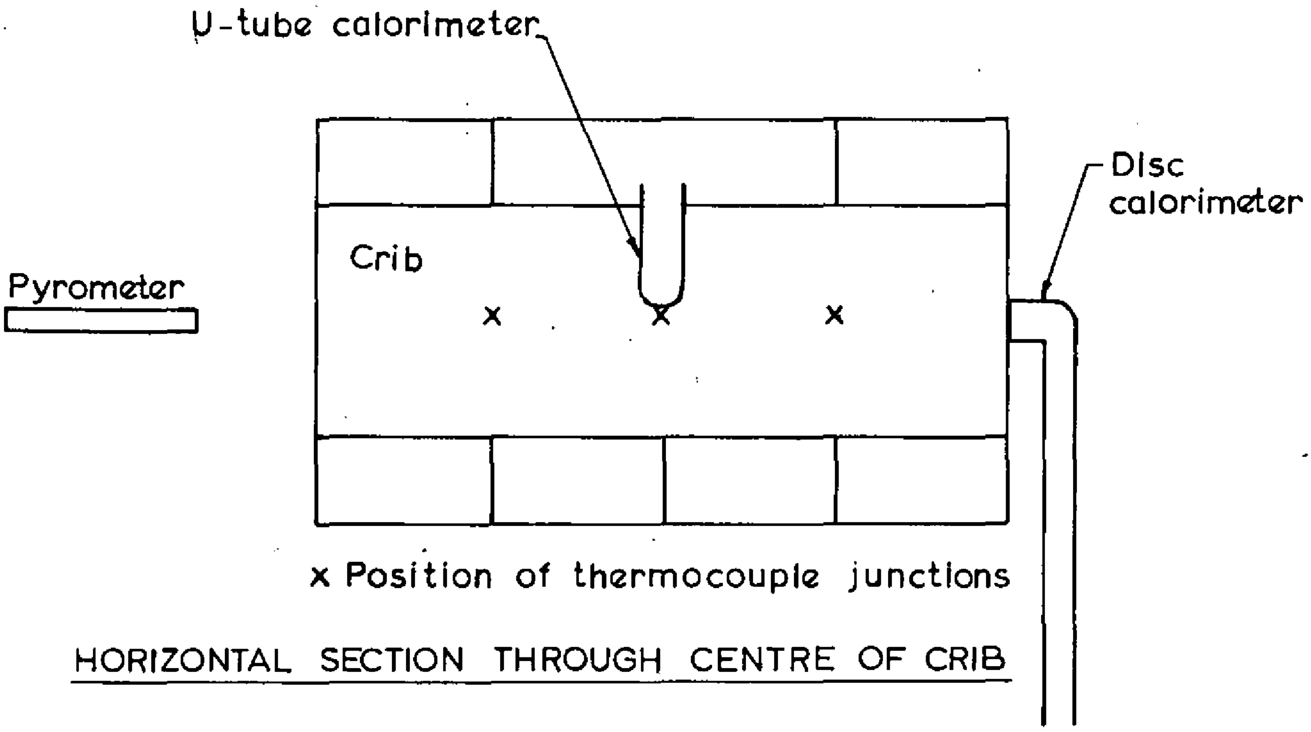
Density of fuel when dried $\rho_f = \rho_m \left(1 + \frac{M}{100}\right) = \rho_b (1 + x)/\left(1 + \frac{M}{100}\right)$

Burning rate per unit base area ($\dot{m}''$) = $\frac{R \rho_b h_c}{D_w}$ mg cm^{-2}s^{-1}

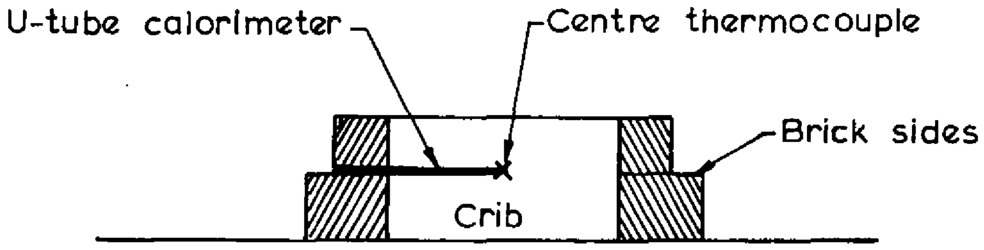
$$\frac{1}{\alpha} = \frac{4(1 + \sigma\lambda)}{\sigma} = d(1 + x)$$



SIDE ELEVATION



HORIZONTAL SECTION THROUGH CENTRE OF CRIB



VERTICAL SECTION THROUGH CENTRE OF CRIB

FIG.1. DIAGRAMS OF EXPERIMENTAL LAYOUT

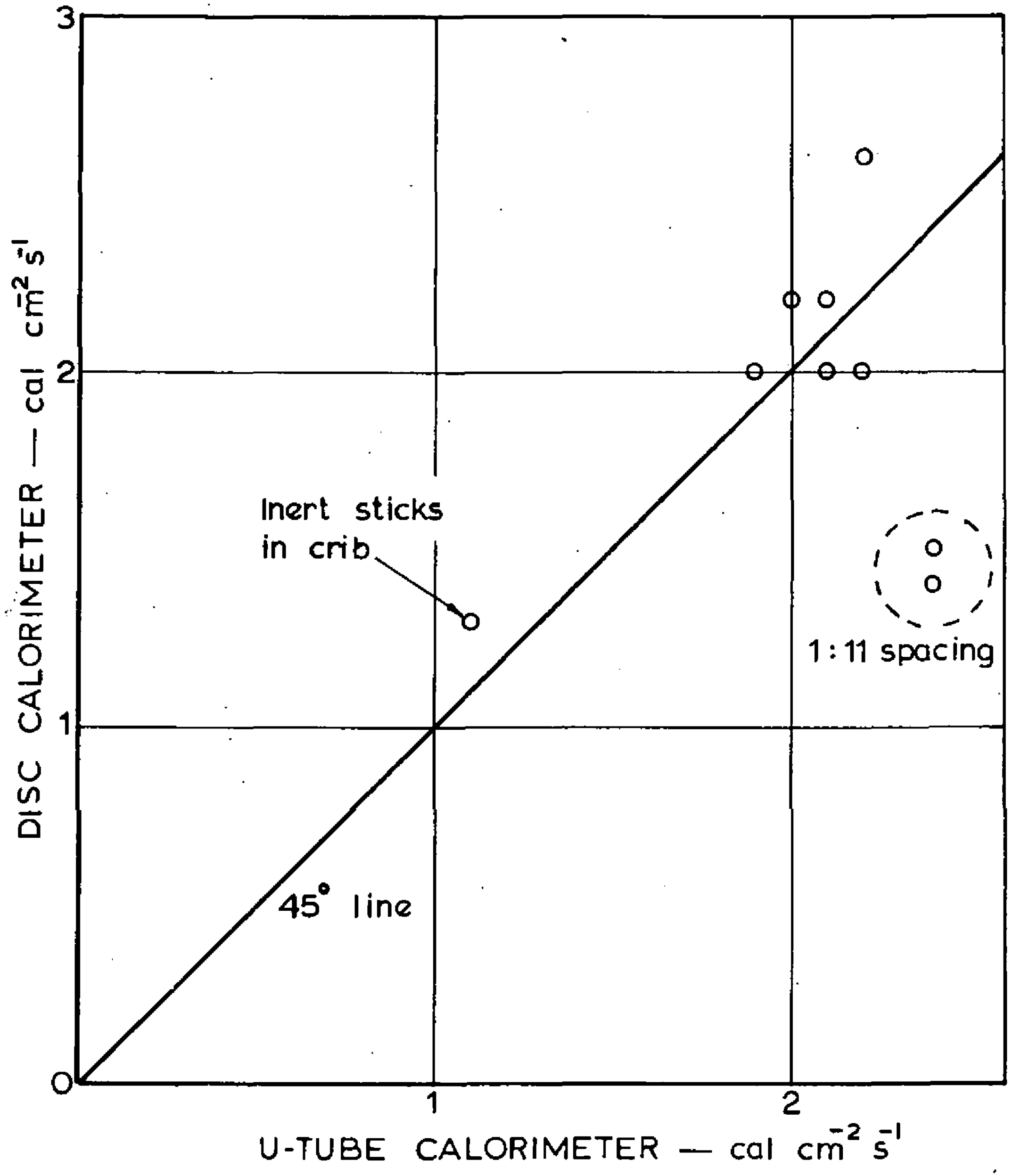


FIG. 2. COMPARISON OF TWO HEAT FLUX CALORIMETERS

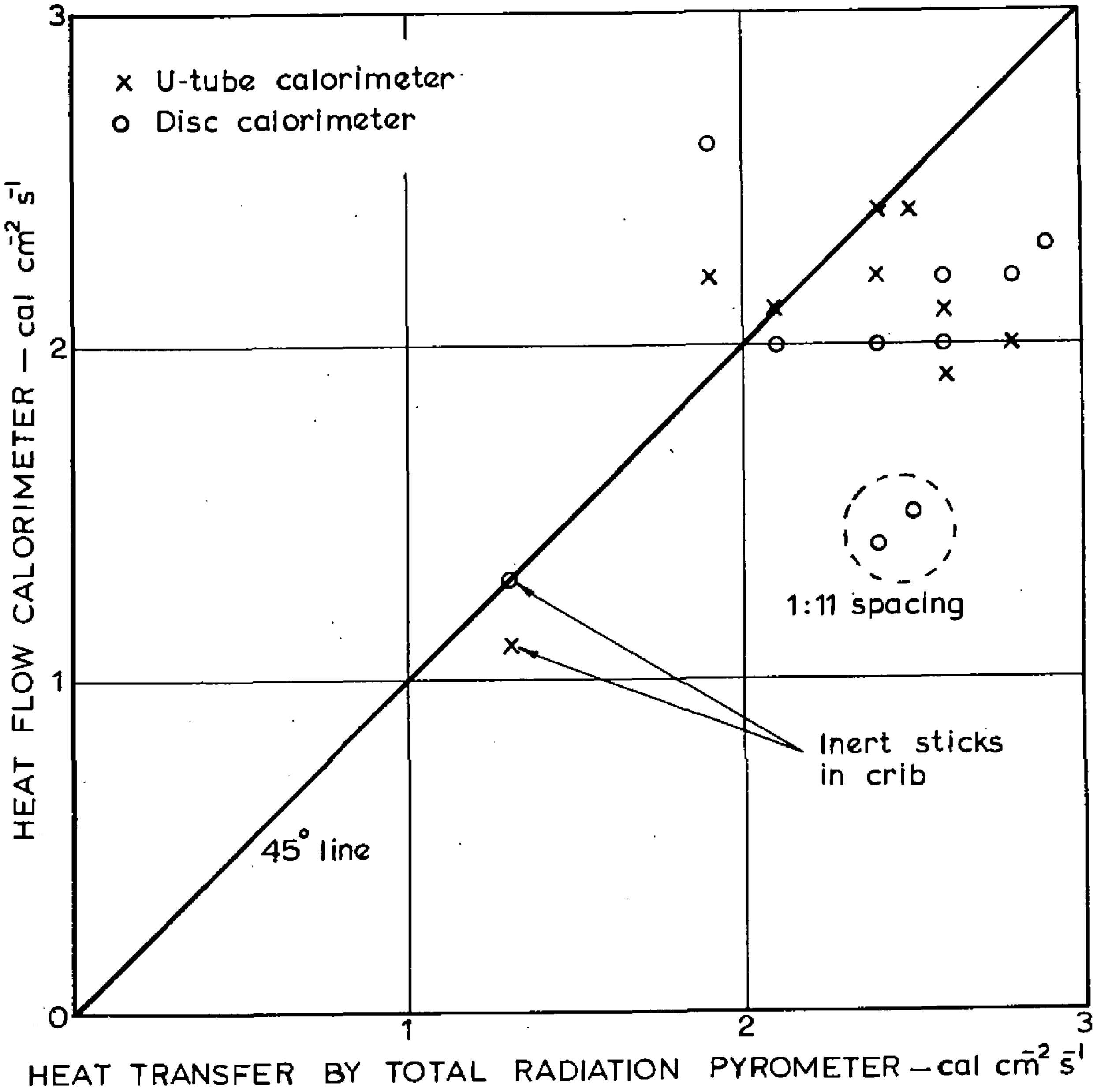
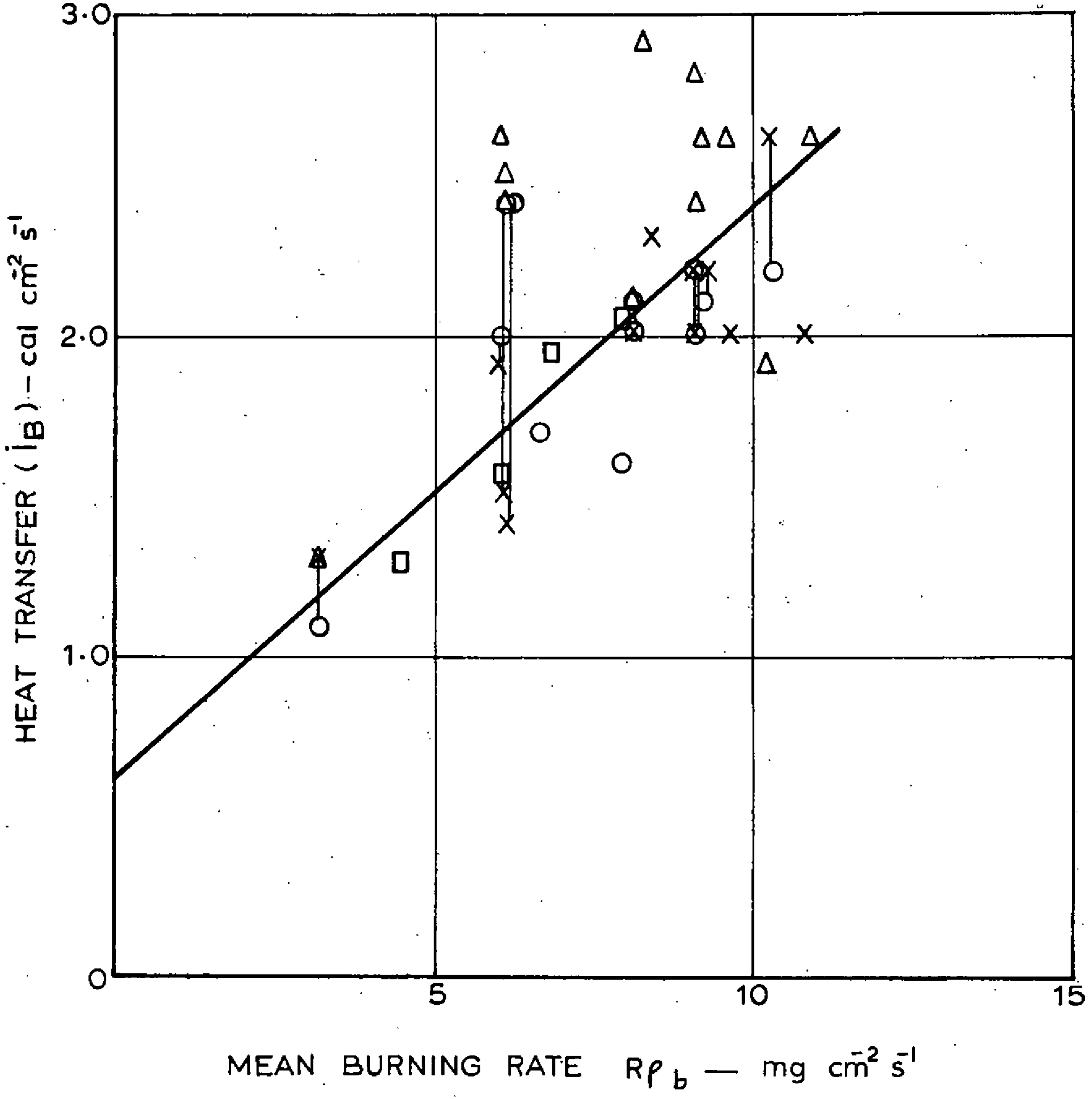


FIG. 3. COMPARISON OF HEAT FLUX CALORIMETERS AND PYROMETER



——— $R\rho_b\ \Delta H = i_B - 2{\cdot}67\ \alpha\theta$

X Disc calorimeter

O U-Tube calorimeter

Δ Radiation pyrometer

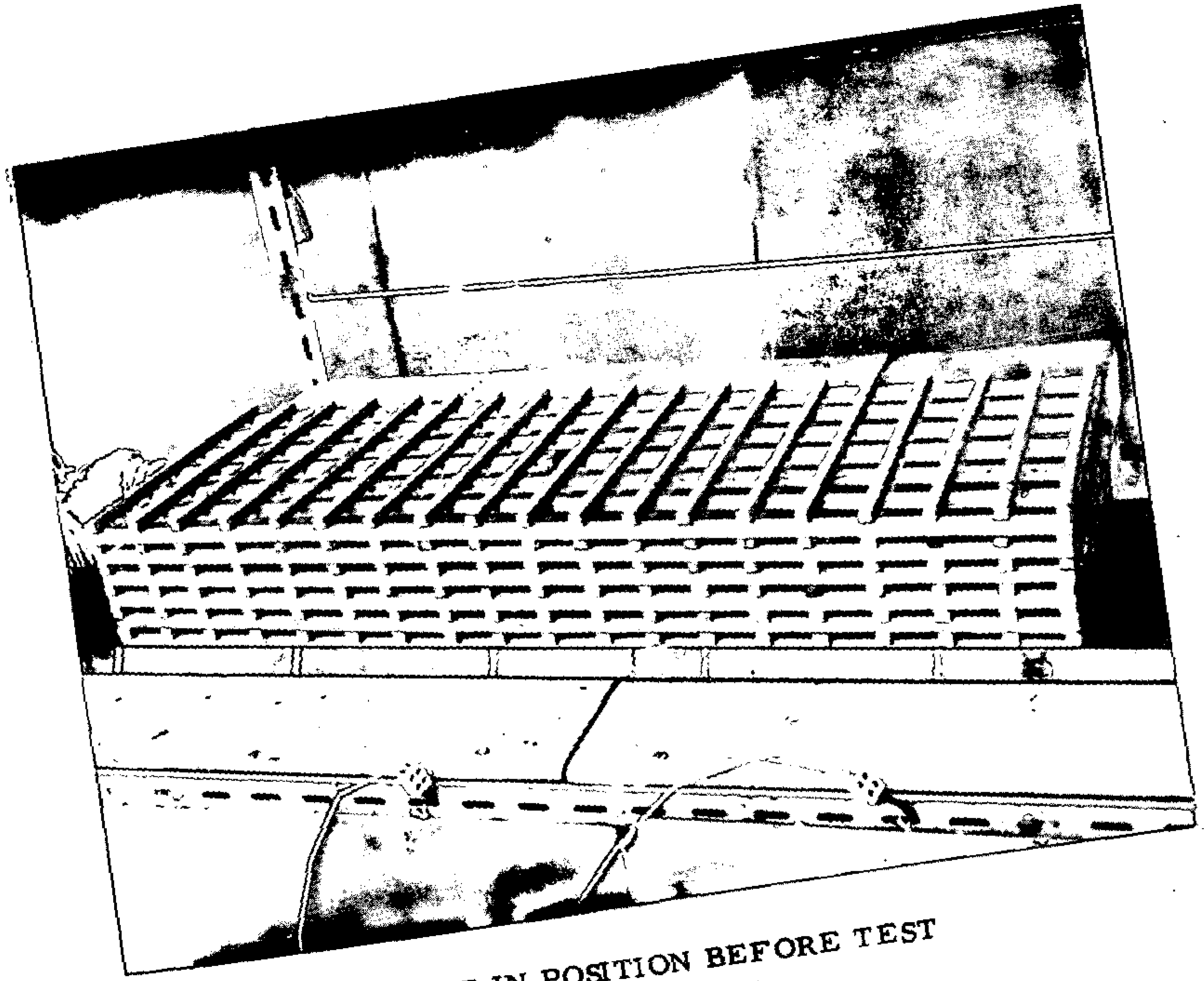
□ Calculated from radiation measurements by Mc Carter and Broido

ΔH For nominal 10% moisture content approximately 180 cal/g

$\alpha\theta$ Taken as 0·24 cal cm^{-2} s^{-1}

No account taken of fact that larger sticks are not thermally thin

FIG.4. HEAT TRANSFER RATES IN CRIBS



CRIB IN POSITION BEFORE TEST

PLATE 1