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FIRE SPREAD ALONG PAPER

by

P. H. THOMAS and MARGARET LAW

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Fire Research Station.
Boreham Wood.
Herts.
('phone ELStree 1341)

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Introduction.

Recently Hottel, Williams and Steward(1) and Atallah(2) have described small-scale experiments on the spread of fire that were made with a view to comparing the results with an appropriate theoretical model of fire spread. Hottel et al supplemented the heat supply to the layers of torn paper or card which constituted the fuel by adding varying amounts of radiation to the heat supplied by the fuel already burning. The effect of this was to increase the rate of spread. Atallah, on the other hand, studied the horizontal spread of fire along sheets of papers of various thicknesses and gave a theory for this based on the assumption that the major source of heating was the radiation from the flames. Hottel et al attempted to allow for convection from the flame as well as the radiation; in their case the major source of heat was usually the supplementary radiation.

Earlier work by Stott(3) had shown that flames spread across paper at a roughly constant mass rate of burning so that the lineal rate of spread was inversely proportional to the paper thickness. Simms and Law have analysed Stott's data which corresponds to a burning rate per unit width of fire front of

$$\dot{m}' = 3.5 \text{ mg cm}^{-1} \text{ s}^{-1}$$

Atallah presented his results in terms of parameters which included the flame height. This was not reported separately but in one example he took a value of 1 in which is similar to the values recorded by Stott. Using this value, Atallah's data correspond to a burning rate of

$$\dot{m}' = 5.6 \text{ mg cm}^{-1} \text{ s}^{-1}$$

i.e. of the same order as Stott's.

Physical interpretation.

The significance of $\dot{m}'$ being constant is that the heat is transferred from a source outside the paper as opposed to, say, conduction, self-heating, or radiation in or through the paper. These mechanisms would give a rate of spread which would be, to a large extent, independent of thickness except insofar as surface cooling was important. Thomas(4) et al have shown the spread of fire through cribs of wood in which the lineal burning rate is independent of the crib height can be attributed to the radiation transfer within the crib.

If paper has to be heated to, say, 300°C to produce enough volatiles to support a flame, and its specific heat is taken as 0.34 cal g^{-1} $degC^{-1}$, and a nominal moisture content of about 10% is assumed, the above values of $\dot{m}'$ correspond to a net heat transfer of 0.56 and 0.9 cal cm^{-1} s^{-1} respectively.

For a vertical flame of large width the overall exchange factor is $\frac{1}{2}$, or less if the flame was inclined back from the vertical, so that if this heat transfer arose from radiation from a flame 2.5 cm high, the effective intensity would be at least 0.45 or 0.69 cal cm^{-2} s^{-1}. These figures imply a flame emissivity of at least 0.15. Atallah, in fact, in more detailed calculations allowing for cooling, had to assume in two examples emissivities of 0.85 and 0.43 to get reasonable agreement with his measurements. To get an emissivity even as high as 0.1 would be difficult to justify for these small flames barely 1 cm thick and for this reason there are grounds for doubting that a radiation dominated spread is consistent with the experimental data. The difficulties in this view and a possible insight into an alternative explanation can be illustrated by a few simple experiments.

Experiments on spread of fire along paper and card.

Experiment 1.

If flame is allowed to spread horizontally across a sheet which is held vertically, as in Fig.1, one might expect the heat transfer by radiation to be less than when the flame in the sheet is horizontal because buoyancy keeps the flame and hot gases nearer to the surface so that the radiation falling ahead of the flame is less. However, the rate of spread was in fact faster (see Table 1) and the fire-front was not vertical. The

Table 1

Flame spread on card

Time for centre of burning front to spread 13 cm

Experiment	Position of card	Time - s
1	Horizontal	108, 124
	Vertical	89, 89
2	Horizontal with approx. 20 per cent holes	78, 89
3	Tilted 8° from horizontal Flame spread up	71, 90
	Flame spread down	132, 137

Card: Weight per unit area = 31 mg/cm^2
Width = 5 cm
Thickness = .045 cm
Length = 15 cm

fire advanced furthest at the bottom edge, as sketched in Fig.2, where the flame was thinnest; this is exactly the opposite of what one would expect of a radiation model and is quite consistent with the higher convection transfer at the bottom edge where the boundary layer of the flame is thinnest and consequently the heat transfer greatest. It may be noted that in the horizontal position the value of $\dot{m}'$ was 3.5 mg cm^{-1} s^{-1} in agreement with the results of Stott.

Experiment 2.

Punching holes in a horizontal flat sheet should slow up the fire spread if it is controlled by radiation, because the same lineal rate of spread would produce less fuel and this would result in smaller flames; in fact the lineal rate of spread was faster (see Table 1). It is suggested that the reason for this is the increased convection transfer from the gases below passing across the sharp edges of the holes.

Experiment 3.

Some experiments were made with the paper tilted slightly ($8\frac{1}{2}^{o}$) up and down from the horizontal. If the flame height and thickness remain unchanged the change in radiation is measured by the change in the "exchange factor". This exchange factor for a vertical flame is 0.42 for spread downwards, 0.5 for the horizontal and 0.56 for uphill spread. For a wide enough front these are independent of flame height. They represent a 16 per cent reduction for downhill spread and a 12 per cent increase for uphill spread. The changed rate may produce changes in the flame height and thickness and hence emissivity but the overall effect on flame radiation is expected to be approximately the same order of fractional change for the two directions although spread downwards might be reduced by rather more than spread upwards is increased. Although the upward spread was higher than the horizontal spread by an amount larger than the reduction due to spread downwards the repeatability of the experiments was not good enough to regard the difference as significant.

The mechanism of fire spread.

Atallah observed that when flames spread along a horizontal surface there was extra heat transfer from underneath, due to the carbonaceous residue curling up and radiating preferentially on to the lower surface. In fact, in our experiments this curling hardly occurred at all but a flame about 2 cm long in the direction of spread was observed beneath the paper; the thickness of the visible region of the flame normal to the paper was less than 3 mm and the charring on the underside was seen to be ahead of that on the upper side of the burning card. Clearly, if any combustion occurs beneath a flat surface, there must be a tendency for hot combustion products to flow away from the hot zone. Above the burning card there is an opposite tendency because the rising combustion products tend to induce an inward flow of air in the opposite direction to fire spread. Accordingly some experiments were made to see if the rate of spread could be influenced by factors which affect the direction and extent of this convective flow. Measurements of the rate of spread were therefore made with corrugated cardboard in the four situations illustrated in Fig.(3). Each experiment was repeated and the eight done in a random order, making in all four with the corrugations uppermost and four with the corrugations below. Of each four, two had the corrugations along and two had the corrugations across the direction of flame spread. The entire set of eight, again randomised, were repeated three times on a subsequent day, on the last occasion with cards from a different batch. In the second sixteen experiments the corrugations were crimped, i.e. pinched together, (see Fig.(3)). This was expected to affect the part of the convective flow within the corrugations. Because of the differences introduced by using cards from two batches and doing experiments on different days with different humidities, the four sets were first regarded as four separate treatments. It was thought that if convection from beneath was the main source of heating there should be little if any difference between the spread rate along and across the corrugations when these were uppermost. However by preventing hot gases being lost across the edges of the card, placing the corrugations underneath and along the direction of spread would hasten the spread of flame. The times of spread, t, for 13 cm are shown in Table 2, and the analysis of variance of Log t is given in Table 3. (It may be shown that this transformation improves the significance level of significant factors).

Table 2

Flame spread on horizontal corrugated paper

Time t for centre of burning front to spread 13 cm

	"Treatment"	Time – s				
		Corrugations on upper O_o surface		Corrugations on lower O_1 surface		Mean
		Corrugation across D_o	Corrugation along D_1	Corrugation across D_o	Corrugation along D_1	
Uncrimped C_o	1	120, 55	58, 52	92, 90	27, 37	66
	2	72, 58	47, 48	60, 45	30, 33	49
Crimped C_1	3	82, –	76, 72	64, 87	44, 52	70
	4	47, 44	57, 54	78, 62	50, 44	54.5
	Mean	70	58	72	40	
	Mean	64		56		

Paper: Weight per unit area = 30 mg/cm^2
Width = 5 cm
Length = 15 cm

Table 3

Analysis of variance on $\log_e t$

Effect	TSS	D of F	MSS
D - direction of corrugation	11,420	1	11,420
O - orientation; above or below	2,420	1	2,420
T - Treatments			
C - Crimping (treatments 1 & 2 taken together versus treatments 3 & 4)	1,460	1	1,460
T-C	4,252	2	2,126
DO	3,360	1	3,360
DC	2,530	1	2,530
DT-DC	1,327	2	663
OC	670	1	670
OT-OC	1,385	2	692
DOC	12	1	12
DOT-DOC	815	2	407
Residual between repeats including large variation in one particular pair	2,900	1	2,900
Excluding large variation in one particular pair (one result missing)	2,219	14	158

The DO interaction is significant at the 5 per cent level and DC is not quite significant at the 5 per cent level with respect to a variance obtained by pooling all other interactions, i.e. 526 with 8 degrees of freedom.

The results show that despite the significant variations between "treatments" the difference in spread rate along and across the corrugations depended on whether they were above or below because the interaction DO is significant. The DC interaction tested against the interaction involving treatments is not significant at the 5 per cent level but is large. Crimping slowed up the spread when the spread was along the corrugations showing that there was some transfer through the spaces within the corrugations. A separate analysis of the results for spread along the corrugations shows that there was a large and significant increase in the rate of spread when the corrugations were below and in the direction of spread and the effect of crimping in slowing up the spread is significant. In the analysis of spread across the corrugations there was too much variation between the treatments for results to show any significant effect of crimping or orientation of the card, though this cannot be ruled out. A separate analysis of Treatment 2 and 3 together (these being nominally under identical conditions) shows that crimping slows up the spread for all conditions. In the crimped conditions (Treatment 3) alone the only difference between the data is that the combination of corrugations on the underside and along the direction of spread produces faster spread than the other conditions in which the rates of spread are effectively the same. These results are consistent with convection from below being an important factor and are not easy to reconcile with radiation being the main mechanism of spread.

Conclusions.

Clearly, further experiments can be devised on these lines to demonstrate various aspects of the mechanism of fire spread. Even the few rather simple observations referred to here despite the inconclusive nature of some of the experiments suggest that in spread along a horizontal paper convection underneath is more important than radiation, perhaps the most significant result being that of Experiment 1. It is questionable whether such experiments have any usefulness in the study of large-scale fire spread once it has passed beyond the very early stages of growth because then the flames are thicker and radiation more important than on small-scale and the convection will be of a different kind because the flow is turbulent.

Acknowledgement

Miss L. Griffiths helped with the experiments.

References

(1) HOTTEL, H. C., WILLIAMS, G. C. and STEWARD, F. R. "The Modeling of Firespread through a Fuel Bed". Tenth Symposium (International) on Combustion. The Combustion Institute, Cambridge, 1964.

(2) ATALLAH, S. "Model Studies of a Forest Fire". A Paper at 1964 Spring Meeting of Western States Section, The Combustion Institute, Stanford University, April 1964.

(3) STOTT, J. B. "A Study of Flamespread Over Cellulosic Surfaces". Leeds University 1949 (Ph.D. thesis unpublished).

(4) THOMAS, P. H., SIMMS, D. L. and WRAIGHT, H. G. H. "Fire Spread in Wooden Cribs". Department of Scientific and Industrial Research and Fire Offices' Committee F.R. Note No.537, 1964.

The pieces of card were tested in the following positions

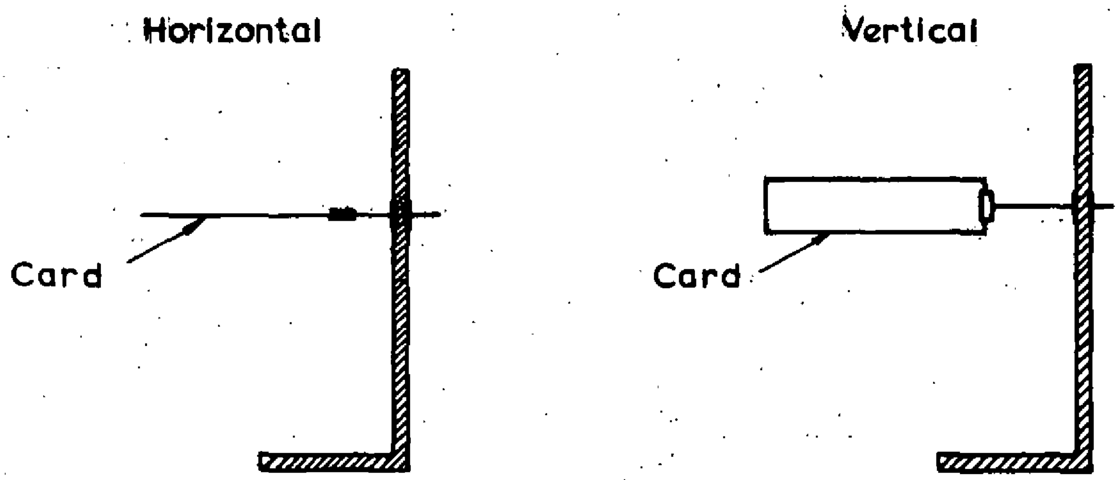

FIG.1. POSITIONS OF CARD

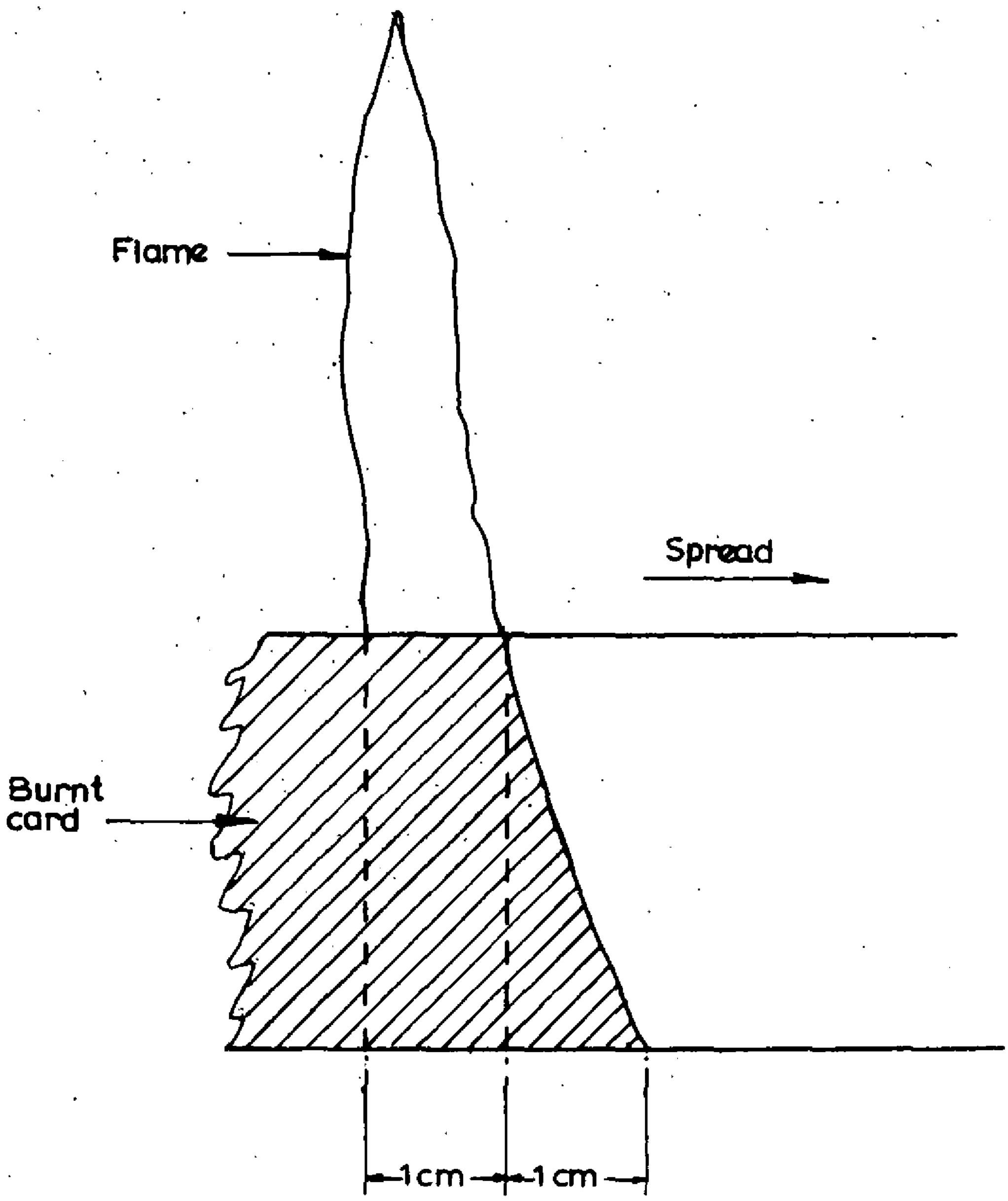

FIG.2. FLAME SPREAD ON VERTICAL CARD

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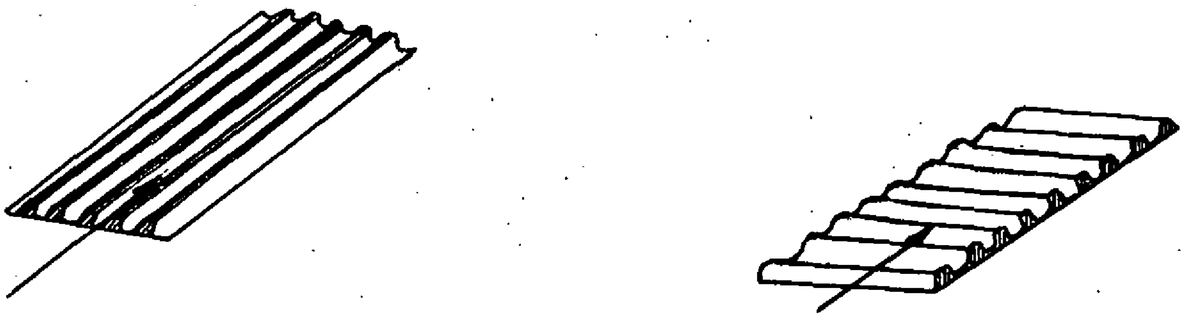
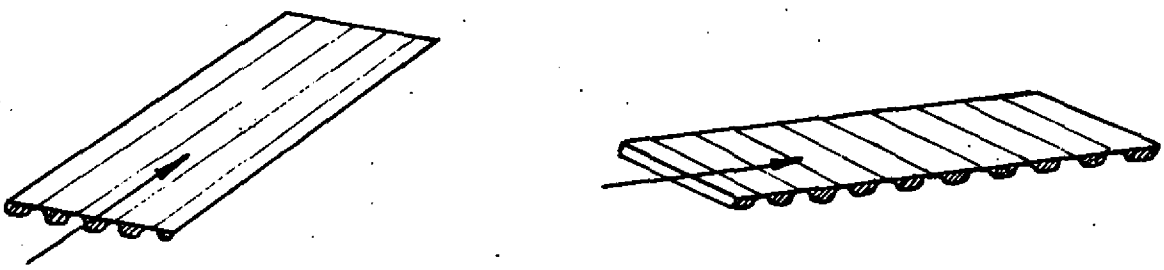
The pieces were tested in the following positions



Corrugations on upper side O_0

(a) Parallel to flame spread D_1 (b) Perpendicular to flame spread D_0



Corrugations on lower side O_1

(a) Parallel to flame spread D_1 (b) Perpendicular to flame spread D_0

These positions were repeated for cardboard with crimped corrugations

Uncrimped C_0 Crimped C_1

FIG. 3. CORRUGATED CARDBOARD