Fire Research Note
No 1029

THE EARLY STAGES OF FIRE GROWTH IN A COMPARTMENT

A CO-OPERATIVE RESEARCH PROGRAMME OF THE CONSEIL INTERNATIONAL DU BÂTIMENT (COMMISSION W 14).

FIRST PHASE

by

A J M HESELDEN and S J MELINEK

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Co-operative work by:

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Centrum voor Brandveiligheid, Instituut TNO, Netherlands
Commonwealth Experimental Building Station, Australia
Factory Mutual Research Corporation, United States
Fire Research Station, United Kingdom
Forschungsstelle für Brandschutztechnik, Karlsruhe, German Federal Republic

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SUMMARY

This note analyses the data from laboratories taking part in an international co-operative research programme studying the early stages of fire spread in a compartment particularly the effects of 8 factors, comprising parameters of the compartment, fuel and ignition. All factors except the shape of compartment are statistically significant.

The contribution of wall linings is greatest when ignition is in a corner and the ventilation opening large.

Department of the Environment and Fire Offices' Committee
Joint Fire Research Organization

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1. INTRODUCTION

The rate at which a fire in one compartment of a building grows in its early stages is of profound importance because it affects escape and evacuation, the way in which the fire can be dealt with, and the chance of a small fire becoming a major catastrophe. Although there has been much work in many laboratories, some of it on a large scale, this has not always led to agreement on the importance of various factors, presumably because of the narrow range of experimental conditions imposed by an inevitably limited experimental effort, and a greater interdependence between factors than has been assumed. Nor has there been agreement between laboratories on the principles of a single test for the 'reaction to fire' of materials. A contributory cause of this is thought to be the inadequate understanding of how the many relevant factors affect the development of fire. With this background the Fire Commission (W14) of CIB began a co-operative reseach programme to study the influence on fire spread of two kinds of factors:

a) The different kinds of flammable and insulating linings covering all or some of the internal surfaces of the compartment.

b) The other factors that influence the spread of the fire and the contribution to it of the linings. These include the size, shape and ventilation of the compartment, the amount and distribution of the fuel other than the linings themselves and the size and position of the igniting source.

Clearly in an initial programme considerable simplification and idealisation could be introduced.

The experimental work for the first phase of this programme[1], 256 experimental fires carried out by 8 laboratories in a balanced statistical design, has been completed and this note gives the results of statistical and other analyses made on these data, together with data for compartments of two scales, provided by a ninth laboratory.

The participating laboratories are listed in Appendix 1.

2. SCOPE OF THE PROGRAMME

The first phase of the programme was intended to investigate the practicability of conducting this kind of experiment, the reproducibility within and between laboratories, and the relative importance of various factors on the spread of fire.

A design for the programme[1] was provided by the Fire Research Station and experiments were allocated to the various participating laboratories with a suggested random order.

The programme was designed to obtain the effect of the following eight factors on the spread of fire, each factor being included at two levels (Appendix 2).

1. Shape of compartment (s)
2. Position of ignition source (p)
3. Fuel height (f)
4. Ventilation (window opening) (v)
5. Bulk density of fuel (related to stick spacing) (b)
6. Continuity of fuel (c)
7. Lining of walls and ceiling (l)
8. Area of ignition source (a)

A statistical design was adopted in which tests were carried out at one half of all the possible $2^8 = 256$ conditions. Each test was repeated, so that each of the 8 laboratories carried out 32 tests.

In each experiment of this phase, cribs of wood in a compartment 1 m high were lit by an ignition source of alcohol and various measurements were made up to the time of 'flashover'.

The measurements and observations made were reported by laboratories in summary tables and in graphs. The quantities measured are listed in Appendix 3.

Before commencing the allotted experiments of the first phase each laboratory was asked to carry out and report the results obtained in a short series of preliminary experiments designed to test that the ignition of the first crib and the subsequent spread between cribs would be satisfactorily repeatable.

Most laboratories had the practical troubles usually encountered in work of this kind, particularly instrument failure. Notes given in Appendix 4 summarise the most important of these experimental details.

Several laboratories were able to manage comprehensive smoke density and gas composition measurements – these had been specified as desirable, but not essential – and one laboratory carried out five supplementary tests with additional lining materials.

3. STATISTICAL ANALYSES

3.1. General

Analyses have been made by means of multiple regression of the time for flames to touch the ceiling (t_f), the time for final transition from a slow to a fast rate of spread (t_2) (see Appendix 3), and the time for flaming over the whole of the tops of all the cribs (t_3).

It was assumed that the dependent variable y (usually $\log_e t$) varied linearly with the independent variables so that

$$y = \bar{y} + \sum_i a_i x_i \tag{1}$$

where x_i are the independent variables and their products and a_i are the corresponding regression coefficients.

The data formed a balanced orthogonal set so that taking the values of the independent variables to be ± 1 gives

$$a_i = n^{-1} \sum_j y_j x_{ij} \tag{2}$$

where n is the number of runs

y_j is the value of y for run j

x_{ij} is the value of x_i for run j.

The method of analysis is further discussed in Appendix 5.

The dependent variables were transformed by taking logarithms (to base e) to hold the variance more constant over the whole range of the data – a requirement of the significance tests.

Air temperature, water vapour pressure and fuel moisture content were omitted from the analysis since a previous analysis using four sets of data had shown that the effects of these variables were negligible. This does not mean, however, that in general fuel moisture content has no effect on the rate of spread, indeed experiments[2] to supplement an earlier co-operative study of fully-developed fires showed that the initial fire growth could be closely related to moisture content when this was in the range 4 to 13 per cent. In the present experiments the moisture content of the fuel lay between narrower limits.

3.2. Results and discussion

Statistically significant regression coefficients obtained for t_f, t_2 and t_3 are given in Table 1. Means and standard deviations were obtained from the differences between the replicates.

3.2.1. First order effects

All the first order effects except shape are significant but the effects of ventilation opening and area of ignition source are confounded with laboratory interactions. The latter effect is very plausible and the former small.

The results for t_3 are expressed as percentages in Table 3. The effects of fuel continuity and ventilation opening are not large. It is noteworthy that the lining material has by no means the largest effect on t_3.

The effects found can be considered in terms of a simple qualitative model for fire spread. This postulates that the fuel bed alone controls the rate of spread of fire in its early stages but at a later stage control is taken over by the compartment, as this is heated by the fire. In the earliest stage the horizontal rate of spread is set only by the bulk density and configuration of the fuel so that the fire spreads through the fuel with a more or less vertical fire front. As the compartment, particularly perhaps the ceiling, heats up, and a body of flame builds up under the ceiling, then the rate of spread accelerates to a high value and fire spreads rapidly over the top surfaces of the fuel. The experimental work showed that sometimes this acceleration was sharp, sometimes gradual and in some cases an intermediate stage could be identified when spread appeared to depend both on the compartment and fuel, especially on the direction of the top layer of sticks[3].

With this model in mind it is not surprising that increasing the fuel height, increasing the spacing of sticks within the cribs, or moving the ignition source from the corner to the centre shortened the time of fire development since all these increased the rate of heat release in the compartment.

Plates 1 and 2 illustrate the two modes of fire spread. In Plate 1, with tall stacks of fuel, there is a clearly marked change from slow spread of fire through the fuel stacks to a rapid spread over the tops of the stacks, and flaming over the tops of all the stacks is attained in only $6\frac{1}{2}$ minutes. In Plate 2, with low fuel stacks, the initial rate of spread is very similar to that of the tall sticks but since the rate of heat release is smaller the ceiling is heated less and this, together with the smaller flames from the smaller stacks, means that the downward radiation to the top of the fuel stacks is less than with the tall stacks.

This is why in Plate 2 there is a much more gradual change-over to fire spreading over the top of the fuel. This spread is in any case slower and takes place later than with the tall stacks. It takes nearly twice as long for flaming to extend over the top of all the fuel

This view of fire spread is shown diagrammatically in Fig.2.

Effect of size of ignition source

The larger ignition source gave values of t_3 on average 22 per cent shorter than those of the smaller ignition source (Table 3) and with an overall average for t_3 of 12.7 min this amounts to 2.7 minutes.

The larger source (120 x 120 mm) could be expected to cause ignition at distances of 80 mm or 40 mm (average 60 mm) ahead of the smaller source (40 x 40 mm) depending on whether the ignition was at the corner or at the centre, see Fig.3, and for an average rate of spread of about 20 mm/min this corresponds to an advance of about 3 min, which is about the reduction in t_3 actually found.

Effect of continuity of fuel

Dividing the fuel into a number of separated cribs of the same height (which lowers fire load density) gave a slight delay in the time of spread. This result could not have been predicted in advance since the spread of fire across a small gap might conceivably be more rapid than through a fuel bed. A simple reduction of fire load density at constant fuel height can also be effected by increasing the stick spacing and this ordinarily increases the rate of spread except near extinction.

Effect of lining

Inserting a hardboard lining gave shorter times of spread. Ignition of the lining usually resulted in rapid subsequent spread because the rate of heat output of the fire was thereby increased and because spread of flame took place rapidly over the preheated lining. The effect of the thermal properties of lining materials is discussed in Section 4.6.

Effect of ventilation opening

The larger ventilation openings apparently caused slightly longer times of spread although this result must be treated with some caution in view of the confounding with the laboratory effect. It is hard to see what substantial effect the size of the opening could have on the earliest stages of the fire but as the fire increases in size there would be greater convective heat loss with the larger opening as the $\frac{1}{4}$ opening would increasingly form a constriction on the air flow into the compartment.

The experiments in 1 and 2 m compartments described in Section 4.7 give an unconfounded ventilation opening effect of between 3 and 10 per cent.

It is interesting to note that the effect on t_f, the time for flame to touch the ceiling, is also small but is in the opposite direction.

With a larger opening flame apparently touches the ceiling sooner (at t_f), but the fire spreads over the tops of all the cribs later (at t_3). If this is not due to a laboratory effect, it reflects a difference between early and late stages.

Effect of shape

It is perhaps surprising that there is no significant effect of shape since the absolute size of the ventilation openings is different between the two shapes and there appears to be a small but significant ventilation effect. Possibly some other factor such as the geometry of the flow is operating in opposition.

3.2.2. Interaction terms

The first order effects are modified to a greater or less extent by interactions. Table 1 shows that the significant second order effects on t_3 are: pf, pb, pl, pa, fb, fc, fa, vl, va. When both variables of one of these pairs are at the higher level or the lower level (eg p_2 f_2 or p_1 f_1) then the corresponding independent variable, $x_{ik} = x_i\ x_k = 1$. From equation (2) the mean value of $\log_e t_3$ is increased by the regression coefficient a_{ik}, which is given in Table 1 (0.04 for pf). When one variable is at the upper level and one at the lower level (eg p_1 f_2) then $x_{ik} = -1$ and the mean value of $\log_e t_3$ is reduced by a_{ik}.

The largest unconfounded interaction pl is readily explained qualitatively - with ignition at a corner where the lining can be ignited most readily there is more difference in t_3 between linings. The vl interaction probably appears because when there is a hardboard lining it is this which controls the speed of fire growth and the ventilation opening is of less importance than with an unlined asbestos millboard compartment.

The fc interaction means that taller cribs give less difference between continuous and separated fuel, which is plausible. The va interaction probably owes its apparent existence to confounded laboratory interaction terms, since the size of the ignition source should affect the earliest stages of the fire and the ventilation opening the stage later on just before the fire becomes fully developed so that it is hard to see how these can interact. The reasons for most of the other interactions between p, f, b, c, a are obscure.

3.2.3. Sensitivity of lining effect to other factors

Although the average difference in t_3 between the fires with hardboard linings and those with asbestos millboard is only 23 per cent, there are situations where t_3 is more sensitive to the lining because the pl and vl interactions are significant.

From equation (2) the mean value of $\log_e t_3$, taking account of first and second order interactions, is given by

$$\log_e t_3 = \bar{y} + x_p a_p + x_v a_v + x_l a_l + x_p x_v a_{pv} + x_p x_l a_{pl} + x_v x_l a_{vl} \qquad (3)$$

where $\bar{y}$ is the mean value of $\log_e t_3$ for all the data

x are the independent variables ($= \pm 1$)

a are the regression coefficients.

Table 4 shows the deviation of $\log_e t_3$ from the mean for different conditions. These values were obtained from equation (3) using the regression coefficients given in Table 1. It can be seen that with corner ignition and full ventilation opening t_3 would be expected to be 37 per cent lower for hardboard-lined compartments, much larger than the overall average difference of 23 per cent. Conversely, with centre ignition and $\frac{1}{4}$ ventilation t_3 is insensitive to the lining material.

In the light of Table 4 the supplementary experiments by the National Bureau of Standards discussed in 4.6 are seen to have been carried out under conditions sensitive to the lining material (corner ignition, $\frac{1}{4}$ opening), though not quite the most sensitive (viz corner ignition with full ventilation opening).

3.2.4. Repeatability of tests

The standard deviations of replicate tests for t_f, t_2 and t_3 are given in Table 2 with the means. t_3 has a standard deviation of 11 per cent. This is somewhat larger than that of the time scale in fully-developed fires based on rate of burning but for a transient situation is probably realistic. t_f is much less repeatable (standard deviation of 22 per cent), presumably because the time at which flames are seen to touch the ceiling is harder to measure objectively.

4. OTHER ANALYSES

4.1. Time of spread

There is no single measure of the time for the fire to spread to a stage broadly representing 'flashover' which is entirely satisfactory and unambiguous. In most experiments t_3 is the best available time representing a 'fully spread' condition, but in some experiments with the 211 shape and $\frac{1}{4}$ opening and a fire spreading from the corner the fire spreads up to the opening and large flames emerge from it before spread has taken place over the rest of the crib.

The flames invariably first touch the ceiling before t_3, in the majority of experiments well before t_3. On the other hand the times at which the lining ignites (t_{L1}), flames emerge from the opening (t_w) or cover the whole of the ceiling (t_{L2}) and the time of the final transition (t_2), when clearly defined, are all much closer to t_3.

4.2. Initial rate of fire spread

Average rates of fire spread for the first few minutes after ignition plotted for each laboratory in Fig.4 show that the initial rate of spread parallel to the long side of the crib is very close to that parallel to the short side, but that the rates of spread vary widely between the different laboratories. These differences do not arise from a bias in the experimental design since each laboratory carries out half its experiments with each level of each factor. However, Fig.5 shows that laboratories having a high rate of spread for 3 spacing also have a high rate of spread for 1 spacing, which has twice the bulk density. The constant of proportionality is $\frac{1}{2}$ as predicted from the known relationship between the rate of spread of fire in cribs in the open air and bulk density. The TNO point falls some way off the expected line, perhaps because two batches of wood were used in the construction of the cribs (Appendix 4).

It would be interesting to know why there are such differences in the initial rates of spread between the various laboratories. There is no well defined correlation between the rate of spread and the density and moisture content of the wood, taken either separately or together so that other factors must have affected the rate of spread in these experiments, eg the thermal conduction properties or some systematic differences in the way the experiments were conducted - for example differences in the time a conditioned crib is allowed to remain in the laboratory before being burned could affect the moisture content of the outer layer of the sticks. t_3 falls as the initial rate of spread increases (Fig.6).

4.3. Ceiling temperature

The ceiling temperatures at t_2, the time at which the final transition in the rate of spread occurs, are given in Table 5 as averages over all levels of v, c, and a, for an asbestos millboard lining (l_1). These values are generally between about 450°C and 700°C. The trend giving higher temperatures with corner ignition for the 121 shape and centre ignition with the 211 shape is the only statistically significant effect and is probably due to the position of the thermocouple measuring ceiling temperature in relation to the position of ignition. Some of the highest values might be unduly influenced by thermocouples becoming detached from the ceiling, though there is no special note of this having happened in the test data.

It must be remembered that t_2 is not always well defined and the ceiling temperature is at this time changing rather rapidly, so that the temperatures in Table 5 must be treated with some caution. There were some systematic differences between laboratories.

4.4. Oxygen, carbon dioxide and carbon monoxide concentrations

No special analyses have been made of the O_2, CO_2 and CO measurements. Generally, the concentrations changed smoothly with time, changes becoming very rapid just before t_3.

4.5. Optical density of smoke

Generally, both the optical density of the smoke and the rate of flow of the effluent gases increase as the fire grows in size. Unlike the other variables the optical density does not always increase smoothly, often exhibiting sudden drops and rises and in some cases rising to a peak and then falling to a very low value well before t_3. (See for example tests 8, 13, 17 and 25 of the CEBS, or tests 18, 21 and 23 of the FFB. These are not the only tests with this feature - they are given only as examples).

4.6. Tests with various lining materials

The tests with various lining materials by the National Bureau of Standards laboratory are of considerable interest as foreshadowing a possible second phase of the programme. It has been known for some time that two properties may affect the influence of a lining material on the rate of growth of fire. Firstly, the 'thermal inertia' of the material, ie that combination of thermal constants which determines how rapidly the temperature of the surface can rise when heated, and secondly some property describing the ability to ignite, burn and contribute to the heating of the compartment. The latter property is not likely to be independent of the first. Figure 7 gives a plot of the values of t_3 obtained in the NBS tests using for the above properties the product $K\rho c^4$.

where K is the thermal conductivity

ρ is the density

c is the specific heat

and the flame spread index (ASTM E162) quoted in the report. Neither of these is entirely satisfactory, for example some of the materials are much too thin for the effect of the backing material to be neglected, yet nevertheless the results form an ordered pattern where t_3 can decrease either with increasing insulation or with increasing flame spread index. The plot shows which flammable materials can yield times for fire development (taken as t_3) similar to particular inert materials.

It would be of great interest to see whether this or some similar presentation of the data remains valid for many different kinds of materials.

4.7. Scaling of fire spread

The experiments carried out by the Factory Mutual Research Corporation at 1 and 2 m scales permit revealing comparisons to be made between scaling possibilities. They were carried out in 121 shape compartments with corner ignition of one large crib with 60 mm stick spacing and the large ignition source. With a 1 m high compartment the fuel height was 160 mm and four experiments were carried out in a balanced design with $\frac{1}{4}$ and full ventilation openings, with and without a hardboard lining. Two similar groups of experiments were carried out in a 2 m high compartment, the conditions being identical apart from scale to those of the 1 m high compartment for one group, and the fuel height being increased to 320 mm for the other group, the other conditions remaining identical. Thus comparisons can be made of fires in which the fuel height remained constant as compartment height was varied, and those in which the fuel height was increased in proportion to the compartment height.

Part of the summary data are given in Table 6 and other data obtained from the graphs are given in Table 7.

We note from Table 6 that the times for the 1 m compartment fires are closer to those of the 2 m fires with the 320 mm high fuel than with the 160 mm high fuel. However increasing fuel height in proportion to compartment height still leaves a systematic residual difference in times, we suppose because the various processes of radiation, convection etc do not all scale in the same way. As the scale is increased, holding the ratio fuel height/compartment height constant keeps the flame height/compartment height constant, but not the ceiling temperature rise (Table 7).

The Factory Mutual Research Corporation data also enable estimates to be made of the effects of ventilation opening and lining. The data give values of t_3 10 per cent higher for full ventilation than for $\frac{1}{4}$ ventilation, but only 3 per cent higher if the result for test 5, which might be anomalous, is omitted. The average value for the ventilation opening effect, obtained from the complete programme, is 11 per cent, neglecting the va interaction which probably does not exist.

The FMRC data give an average lining effect of about 50 per cent, and this can be compared with an average figure for the complete programme of 33 per cent with corner ignition (Table 4). The vl interaction for both 1 m and 2 m compartments is in the direction of that found in the analysis of the complete programme.

5. DISCUSSION

Although this preliminary phase of research has been directed to studying the effect of the context in which linings are installed in rooms rather than the effect in detail of various linings, a number of important observations can be made. Firstly, changing the lining even when installed over all the walls and the ceiling by no means produces the greatest effect on the time of development to flashover. Changes in other factors such as the position of ignition can make a comparable change. However, apart from the shape of the room, none of these other factors are or could as easily be subject to building control. Window sizes are in principle or in fact controllable but how much of the glass breaks to form an opening in a fire is not. Thus, the control of lining can reduce the average or median flashover time but the distribution of such times for any one lining could spread as widely. The implication of the substantial effect of ignition position must be considered in relation to the variation of probability of ignition. Power sources tend to be near walls, though ignition sources associated with social habits like smoking materials, spilt heaters, may be more evenly distributed.

Consider two compartments statistically equal in all respects, one being partitioned. Even partitioning having little formal fire resistance may be expected to delay fire spread to other parts of a compartment, but its presence may hasten the local development of fire since even non-combustible linings have heat-insulation properties that aggravate fire growth. At present we do not know the relative importance of assisting local growth and retarding spread to distant areas.

The larger an enclosure the more of it is 'middle' as opposed to 'edge' and the risk of ignition near the corner - or wall - relative to the total risk probably decreases. Although the total risk of ignition increases with size (for a given usage) the risk of a fire breaking out and developing to flashover per unit compartment area may well be less. It is not necessarily more. Regulation penalties or relaxation for size cannot readily be argued a priori.

The comparison of two scales shows that to a first approximation time scale is preserved by increasing heights of fuel in proportion to height of compartment. There is a small but systematic departure from this rule and temperatures at corresponding times differ significantly. Substantially more work needs to be done in the field of scaling to develop scaling laws for fires spreading within enclosures but the evidence of the results obtained so far suggests that for practical purposes it may be realistic <u>for some purposes</u> and within limits to scale geometrically on the gross dimensions of the fuel bed and the compartment. However, the theory and detailed consideration of scaling is outside the scope of this paper.

6. RECOMMENDATIONS FOR FURTHER WORK

6.1. Effect of lining

The effect of linings in respect of flammability, thermal inertia and resistance should be explored in more detail over a wider range. Only two interactions involving the lining (vl and pl) were found significant in the analysis of t_3 and it is suggested for these tests that the combination giving the greatest sensitivity of lining (viz corner ignition and large opening) should be used and other linings tested in this discriminating condition.

The experiments might include fires in a brick or gravel concrete compartment having very large thermal inertia.

6.2. Analysis of existing data

Little analysis of the existing data has so far been attempted. More needs to be done to see how far the data support various possible reasons for the acceleration in fire spread occurring at the transition point. Regression analyses for the total quantity of smoke, radiation from the opening (at t_2 and at t_3) and the weight loss (at t_2 and t_3) could be made.

The Factory Mutual Research Corporation data for 1 and 2 m compartments form a balanced group which can be split into normal factorial designs and analysed conventionally by analysis of variance.

6.3. Experiments to resolve difficulties of present analysis

Some experiments, by one laboratory, should be made with different ventilation openings and sizes of ignition source to obtain reliable v and a effects and the va interaction (at present confounded with laboratory effects). Whilst this is being done it would be interesting to obtain the effect of varying the ventilation opening over a very wide range.

7. CONCLUSIONS

7.1. Over the range of these experiments, the time (t_3) at which flaming has spread over the top of all the fuel,

a) did not differ significantly between the two shapes of compartments used (121 and 211)

b) depended to only a small extent on continuity of fuel and ventilation opening

c) depended to a much large extent on all the other effects viz. position and area of ignition source, fuel height, stick spacing, and lining, the lining effect not being the largest.

Most of these effects can be explained qualitatively in terms of a simple qualitative model of fire spread.

7.2. All the significant main effects on t_3 are modified by interactions. The largest interactions which have a plausible explanation are the (position of ignition source) x (lining) and the (fuel height) x (stick spacing).

7.3. t_3 is most sensitive to changes in lining material with corner ignition and with the large ventilation opening.

7.4. Values of t_3 for 6 tests with various lining materials suggest a correlation with the thermal inertia and a flame spread or propagation index of the material which would be worth exploring further.

7.5. Experiments with 1 and 2 m scale compartments have shown that t_3 remains more constant as scale is increased if the fuel height is also increased in proportion. However there is a small residual effect of scale.

7.6. Further work is recommended, viz:

a) The influence of lining materials in respect of both flammability and thermal inertia should be explored over a wide range of linings and comparisons made with their performance in small-scale tests for reaction to fire.

b) Further analysis of the existing data.

c) Exploration in more detail of the ventilation opening effect, particularly for small openings.

8. ACKNOWLEDGEMENTS

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The statistical design for the programme was devised by Mr G Ramachandran.

Thanks are due to Messrs H Wraight and S Fink for assistance with these analyses

9. REFERENCES

1. THOMAS, P H, HESELDEN, A J M and WOOLLISCROFT, M J. Revised proposals for a research programme. Paper A. Supplementary reports of work for the CIB International Co-operative Research Programme on the early stages of fire growth in a compartment.

2. SMITH, P G and HESELDEN, A J M. The influence of moisture content of wood fuel on fire in a model compartment. Paper J. Supplementary reports of work for the CIB International Co-operative Research Programme on fully-developed fires. Joint Fire Research Organisation FR Note 923 (Appendix).

3. HESELDEN, A J M and WOOLLISCROFT, M J. Pilot experiments: Measurements of rate of spread. Paper C. Supplementary reports of work for the CIB

International Co-operative Research Programme on the early stages of fire growth in a compartment.

4. LAWSON, D I and SIMMS, D L. 1952, Brit. J. Appl. Phys., 3, 288, 394.

APPENDIX 1

LABORATORIES PARTICIPATING IN THE PROGRAMME

1.	Centrum voor Brandveiligheid, Instituut TNO, Netherlands	(TNO)
2.	Building Research Institute, Ministry of Construction, Japan	(BRI)
3.	Commonwealth Experimental Building Station, Australia	(CEBS)
4.	Fire Research Station, United Kingdom	(FRS)
5.	Forschungsstelle für Brandschutztechnik an der Universität, Karlsruhe, German Federal Republic	(FFB)
6.	National Bureau of Standards, United States	(NBS)
7.	National Research Council, Canada	(NRC)
8.	Statens Provningsanstalt, Sweden	(SPA)
9.	Factory Mutual Research Corporation, United States	(FMRC)

Laboratories 1 to 8 took part in the statistically designed part of the programme.

Laboratory 9 carried out experiments at two scales.

Laboratory 6 carried out additional experiments with a number of lining materials.

APPENDIX 2

LEVELS OF THE 8 FACTORS

For further details see reference (1)

s Shape of compartment

s_1 121 (1 m wide, 2 m deep, 1 m high)

s_2 211 (2 m wide, 1 m deep, 1 m high)

p Position of ignition source

p_1 Corner (away from ventilation opening)

p_2 Centre

f Fuel height

f_1 160 mm

f_2 320 mm

v Ventilation (window opening), full height of compartment

v_1 $\frac{1}{4}$ of width of compartment

v_2 Full width

b Bulk density of fuel (related to stick spacing)

b_1 20 mm spacing between sticks (20 mm square)

b_2 60 mm spacing between sticks (20 mm square)

c Continuity of fuel

c_1 One large crib 1.70 m x 0.70 m

c_2 21 small cribs each 200 mm x 200 m separated by 50 mm gaps

l Lining of wall and ceiling

l_1 Unlined asbestos millboard

l_2 Asbestos millboard lined with hardboard

a Area of ignition source

a_1 16 cm^2

a_2 144 cm^2

APPENDIX 3

DATA REPORTED FOR EACH EXPERIMENT

Summary tables containing the following:

Fuel density
Fuel moisture content
Room temperature
Relative humidity of room air
Time to ignite lining
Time for flames to touch ceiling (t_f)
Time for flames to emerge from window
Time for flames to cover the whole of the ceiling
Time for final transition from a slow to a fast rate of spread (t_2) (see note below)
Time to ignite the first of the adjacent cribs
Time for flaming over the whole of the tops of all the cribs (t_3)
Weight loss at t_3

Graphs containing the following data plotted against time:

Distance spread in direction parallel to long side of crib
Distance spread in direction parallel to short side of crib
Height of flame
Weight of fuel (or loss in weight of fuel)
Intensity of radiation from opening received at radiometer
Temperature of ceiling
Concentration of CO_2, CO and O_2 in exit gases
Optical density of the smoke

Note: The initial rate of spread was always much less than the rate of spread of flame over the last areas of fuel, to involve the whole of the top of the fuel. The transition between these phases was usually fairly well marked; sometimes there were two transitions with an intermediate rate of spread (Fig.1). Analyses have been made using the time of the final transition (t_2)

APPENDIX 4

Notes on data supplied by laboratories

Laboratory	Notes on data	Smoke density measured	Gas composition measured
Fire Research Station, U.K.	Some temperature data missing due to failure of recording instruments	Some	Yes
C.E.B.S., Australia	Moisture content of cribs carefully adjusted to 10 per cent by a drying process	Yes	Yes
T.N.O. Netherlands	1. Difficulty with supply of wood, which was obtained in two batches. Small cribs made of 1st batch. Large cribs made partly of 1st and partly of 2nd batch. 2. In tests 3, 4, 6 and 8 ceiling thermocouples on the asbestos millboard were covered by the hardboard lining. 3. Ignition had to be repeated for tests 12, 13, 14 and 24. 4. Tests 17 and 20 produced very large quantities of smoke.	Yes	No
National Bureau of Standards, U.S.A.	1. 5 supplementary tests with additional lining materials. 2. t_2 sometimes taken as time at which flame spread rate exceeded 100 mm/min. 3. Two tests allowed to progress through fully developed stage. 4. Two radiometers (one shielded from flame above compartment).	No	Yes
Forschungsstelle für Brandschutz-technik, Karlsruhe	-	Yes	Yes

Laboratory	Notes on data	Smoke density measured	Gas composition measured
National Research Council, Canada.	A few tests made later with a new batch of wood which gave development times in very good agreement with those of the first batch.	No	No
National Institute for Materials Testing, Stockholm	1. 3 extra tests with window boards lined with hardboard. 2. Narrow angle pyrometer used to measure radiation from compartment. 3. 3 spacing cribs measured 0.68 x 1.64 m 1 spacing crib measured 0.68 x 1.68 m	No	No
Building Research Institute, Japan	-	Yes	Yes
Factory Mutual Research Corporation, U.S.A.	Scaling experiments with 1 m and 2 m high compartments	No	No

APPENDIX 5

METHOD OF ANALYSIS

1. Procedure

The results were correlated against chosen independent variables and their products to give first order and higher order interactions. The regression coefficients were obtained from equation (2) by computer, average values being substituted for any missing quantities.

Combinations of independent variables were chosen which were not functions of each other. For each laboratory the number of runs excluding replicates was 2^4 so that four independent variables could be taken. For two laboratories, five variables could be taken, and so on.

The more important relationships between the independent variables and their products were worked out. In this way all possible interactions could be obtained.

The effect of the laboratory on the data appears in the results as an additional interaction, L. For example, if $x_i\, x_k$ is always 1 for laboratory A and −1 for B then the laboratory interaction is confounded with ik and is included in the value obtained for a_{ik}.

The use of orthogonal independent variables has the advantage that if any interactions are omitted the regression coefficients of the remaining reactions are unaltered. The method of analysis used can be applied only to 1, 2, 4 or 8 sets of data.

2. Confounding

For n runs with different values of the independent variables there are n equations corresponding to equation (1). It is therefore possible to obtain only n−1 unknowns, ie $\bar{y}$ and n−1 regression coefficients. If there are k independent variables then there are 2^k unknowns including higher order regression coefficients. If 2^k is greater than n then some of these quantities must be confounded so that independent variables and the products are functions of each other, there being n−1 independent quantities. If, for example, $x_{ij}\, x_{kj} = x_{hj}$ for all j , then the interaction h is confounded with the higher order interaction ik . If $n = 2^k$ then there are k independent variables which are not functions of each other.

3. Variance

Two experiments were carried out for each set of values of the independent variables. An estimate, s , of the standard deviation of the results is given by the differences d_j between the results of these duplicate runs.

$$s^2 = (\sum_j d_j^{\,2})/n-1)$$

where there are $2n$ runs (ie n different sets of values of the independent variables).

From equation (2)

$$a_i = n^{-1}\sum_j y_j\, x_{ij}$$

where $x_{ij} = \pm 1$

The standard deviation of a is therefore

$$\sigma = n^{-1} .\, n^{\frac{1}{2}}s$$
$$= n^{-\frac{1}{2}}s$$

From this quantity the confidence limits and the significance of a_i can be assessed. Values for 5, 1 and 0.1% significance were taken to be 1.96, 2.58 and 3.29 times this standard deviation respectively.

Another indication of the accuracy is the root mean square of the values obtained for the regression coefficients. This method can be used when comparing results from different laboratories.

$$a_i' = a_i + \varepsilon_i$$

where a' is the observed regression coefficient and a the true value.

$$\sum a_i'^{\,2} = \sum (a_i + \varepsilon_i)^2$$
$$= \sum a_i^{\,2} + 2\sum a_i\,\varepsilon_i + \sum \varepsilon_i^{\,2}$$
$$= \sum a_i^{\,2} + \sum \varepsilon_i^{\,2} \quad \text{approximately}$$
$$= \sum a_i^{\,2} + n\sigma^2$$

KEY FOR TABLE 1

t_f	–	time at which flames first touch ceiling
t_2	–	time of final transition
t_3	–	time of flaming over tops of all cribs
		All times are in minutes
s	–	Shape of compartment (121/211)
p	–	Position of ignition source (corner/centre)
f	–	Fuel height (160 mm/320 mm)
v	–	Ventilation opening ($\frac{1}{4}$/full)
b	–	Stick spacing (20 mm/60 mm)
c	–	Continuity of fuel (one crib/21 cribs)
l	–	Lining of wall (unlined/hardboard lined)
a	–	Area of ignition source (16 cm^2/144 cm^2)
L	–	Laboratory interactions

The levels of these independent variables were coded as −1 and +1 respectively. The regression coefficients are therefore half the total change from one level to the other.

All the coefficients given are significant at 0.1 per cent except those in brackets, which are significant at 1 per cent.

A negative sign for the regression coefficient of any of the independent variables s to a implies that the dependent variable (t_f, t_2 or t_3) decreases as the independent variable is increased from lower to higher level.

<u>Table 1</u>

<u>Regression coefficients</u>

See key , page 23

Independent variable	Statistically significant Regression coefficients for $\log_e t_f$	$\log_e t_2$	$\log_e t_3$
s			
p	-0.17	-0.15	-0.16
f	-0.27	-0.14	-0.14
v aL	-0.04	0.06	0.05
b	-0.25	-0.27	-0.25
c		0.05	0.04
l		-0.11	-0.13
a vL	-0.22	-0.13	-0.12
sp fL			
sf pL			
sv			
sb			
sc			
sl			
sa			
pf sL	0.09	0.04	0.04
pv			
pb	-0.08	(-0.02)	-0.03
pc			
pl		0.07	0.07
pa	0.08	0.03	0.03
pv bL			
fb vL, aL	-0.19	-0.07	-0.08
fc	-0.07	-0.04	-0.03
fl			
fa bL	-0.06		-0.02
vb fL			
vc		0.03	
vl		-0.03	-0.03
va L	-0.13	-0.08	-0.08
bc lL			
bl cL	(-0.03)		
ba fL			
cl bL			
ca			
la			

Table 1 (cont'd)

Independent variable		Statistically significant Regression coefficients for $\log_e t_f$	$\log_e t_2$	$\log_e t_3$
spf	L		(0.02)	
spv	bL		0.03	
sbc		(0.04)	0.03	0.02
pbc		0.05	0.03	0.03
fvb	L	-0.14	-0.10	-0.09
fbl				-0.02
bcl	L			
fca	lL		(0.02)	0.03
fba	L		0.02	
sva	sL	0.06	0.03	0.03
spa			-0.04	-0.04
sfv		(0.03)		
svl				(-0.02)
sla			(0.02)	(0.02)
fcl	vL, aL			(-0.02)
spfc	cL		-0.03	-0.02
spvb	L	0.08		
svbl			-0.03	-0.02
sbcl	sL	0.04	0.03	0.03
fvbl	lL		0.03	0.03
fvcl	L		0.04	0.05
fbcl	fL	0.05		
spfv	vL, aL	(0.04)		
spfb	bL	(-0.03)		(-0.02)
spvc	lL		(-0.02)	
sfvb	sL			(-0.02)
pfvb	pL	(0.03)		
pfbc			(0.02)	
pfcl			(-0.02)	
pvbc				(0.02)

Table 2

Means and standard deviations of variables in regression analyses

	$\log_e t_f$	$\log_e t_2$	$\log_e t_3$
Mean	1.83 (6.3 min)	2.45 (11.6 min)	2.54 (12.7 min)
Standard deviation	0.20 (22%)	0.11 (12%)	0.10 (11%)

Table 3

Main effects of variables on t_3

Factor	Average effect on t_3	Significant low order interaction terms	
		Unconfounded	Confounded
Stick spacing (b)	40 per cent shorter for 60 mm than for 20 mm spacing	pb	fb
Position of ignition source (p)	27 per cent shorter at centre than at corner	pb, pl, pa	pf
Fuel height (f)	24 per cent shorter for 320 mm than for 160 mm fuel	fc	pf, fb, fa
Lining (l)	23 per cent shorter for hardboard lining	pl, vl	
Area of ignition source (a)	22 per cent shorter for larger source (but confounded with a laboratory interaction)	pa	va, fa
Ventilation opening (v)	11 per cent longer for full opening than for 1/4 opening (but confounded with a laboratory interaction)*	vl,	va
Continuity of fuel (c)	8 per cent longer for 21 cribs than for 1 large crib	fc	-
Shape (s)	No significant effect	-	-

*An unconfounded estimate of between 3 and 10 per cent can be obtained from the data of section 4.7

Table 4

Interaction of position of ignition source and ventilation opening with lining

Conditions		Deviation of $\log_e t_3$ from mean		Difference between linings	
		Asbestos millboard lining	Hardboard lining	$\log_e t_3$	%
Corner ignition	$\frac{1}{4}$ ventilation	0.28	- 0.06	- 0.34	- 29
	full ventilation	0.44	- 0.02	- 0.46	- 37
Centre ignition	$\frac{1}{4}$ ventilation	- 0.18	- 0.24	- 0.06	- 6
	full ventilation	- 0.02	- 0.20	- 0.18	- 16
Overall average		0.13	- 0.13	- 0.26	- 23

Table 5

Mean values for ceiling temperature in ^oC at t_2.

121 shape (s_1)								211 shape (s_2)							
Corner ignition (p_1)				Centre ignition (p_2)				Corner ignition (p_1)				Centre ignition (p_2)			
160 mm fuel (f_1)		320 mm fuel (f_2)		160 mm fuel (f_1)		320 mm fuel (f_2)		160 mm fuel (f_1)		320 mm fuel (f_2)		160 mm fuel (f_1)		320 mm fuel (f_2)	
b_1	b_2	b_1	b_2	b_1	b_2	b_1	b_2	b_1	b_2	b_1	b_2	b_1	b_2	b_1	b_2
610	545	600	615	455	525	475	450	485	455	420	485	515	480	675	690

b_1 = 20 mm stick spacing

b_2 = 60 mm stick spacing

Table 6

Summary data for fires in 1 and 2 m compartments

(Factory Mutual Research Corporation experiments)

Ventilation opening	Lining	Scale m	Fuel height mm	Test No.	Lining ignited t_{L1} (min)	Flames touched ceiling t_f (min)	Flames from opening t_w (min)	Final transition t_2 (min)	Flaming over tops of cribs t_3 (min)	Weight loss at t_3 kg
$\frac{1}{4}$	None	1	160	12	–	3.8	7.5	7.6	8.4	6.3
		2	160	11	–	12.8	18.6	17.6	19.3	44.0
		2	320	9	–	4.9	9.5	8.9	10.4	31.8
	Hard-board	1	160	3R	6.2 Top	4.9	7.5	6.4	7.7	5.9
		2	160	6	9.2 Side	8.7	9.7	9.7	10.0	24.1
		2	320	10	7.0 Side	4.8	7.7	7.8	8.2	25.4
Full	None	1	160	2	–	4.2	9.5	9.9	10.4	7.7
		2	160	5	–	9.5	–	26.8	29.7	74.9
		2	320	8	–	4.7	10.3	11.6	11.9	39.5
	Hard-board	1	160	13	5.4 Back	4.0	5.8	5.7	6.4	5.4
		2	160	7	8.2 Back	8.7	9.2	9.8	10.2	30.4
		2	320	4	6.9 Side	5.0	7.5	7.5	7.9	27.2

Table 7

Data at 5 min after ignition

(Fires in 1 and 2 m compartments)

Ventilation opening	Lining	Scale m	Fuel height mm	Test No.	Values 5 min after ignition: Spread distance (parallel to long side) mm	Average rate of fire spread mm/min	Flame height m	Weight loss kg	Ceiling temperature rise: °C	Ceiling temperature rise: Relative
¼	None	1	160	12	300	60	1.00	1.3	95	1
		2	160	11	320	64	1.20	3	20	0.21
		2	320	9	340	68	2.00	6	50	0.53
	Hard-board	1	160	3R	290	58	1.00	1.4	60	1
		2	160	6	280	56	0.80	2.5	15	0.25
		2	320	10	350	70	1.90	4	30	0.50
Full	None	1	160	2	310	62	1.00	0.9	65	1
		2	160	5	370	72	1.15	1.0	20	0.31
		2	320	8	350	70	2.00	3.7	60	0.92
	Hard-board	1	160	13	340	68	1.00	0.9	65	1
		2	160	7	290	58	0.95	1.3	15	0.23
		2	320	4	320	64	2.00	2.8	25	0.38

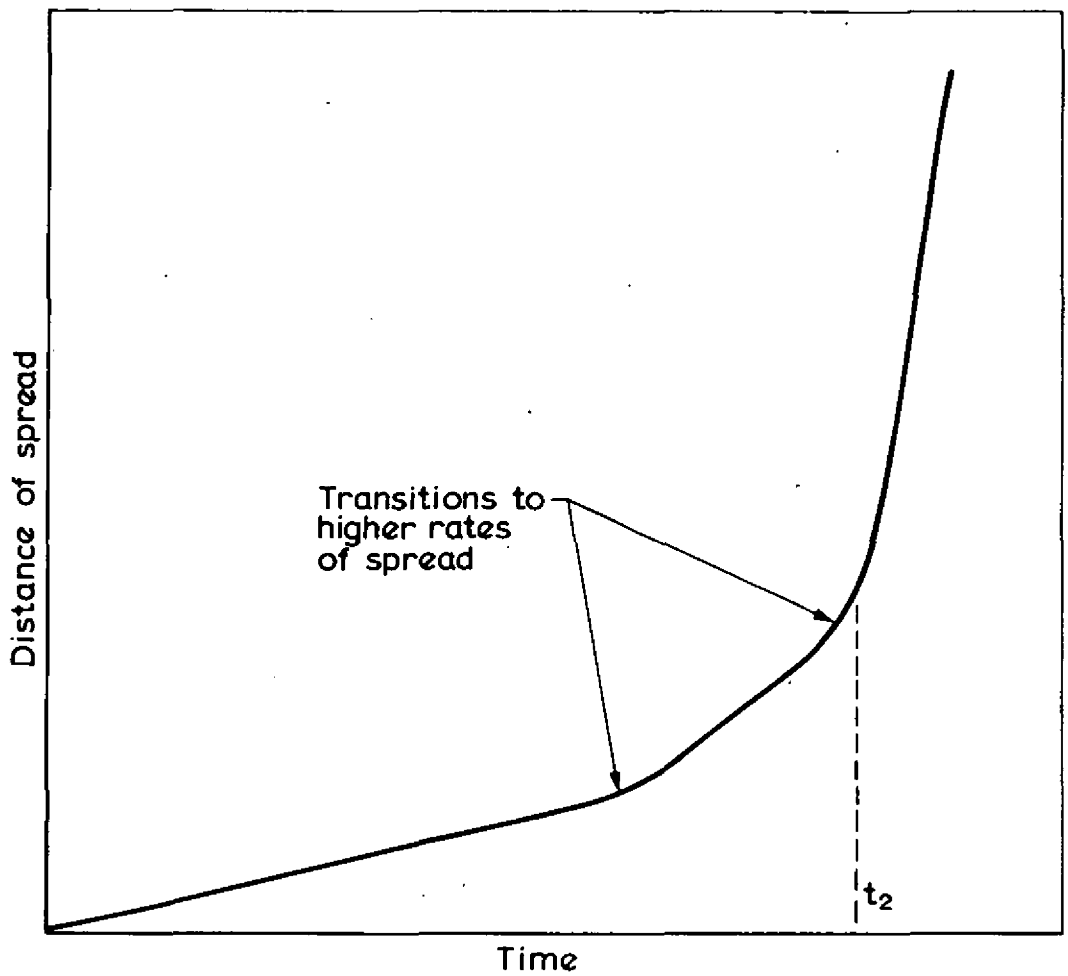


Figure 1 Idealised variation of distance of flame spread with time

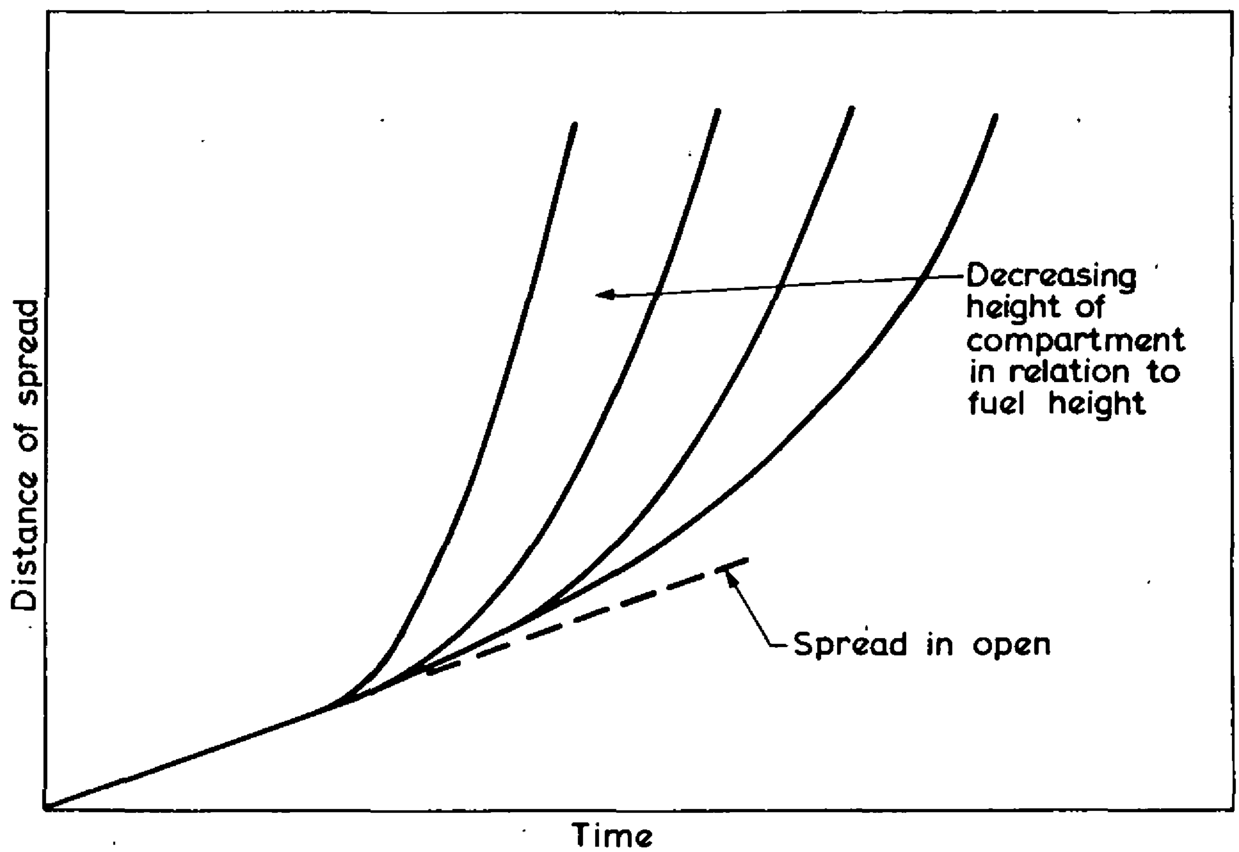
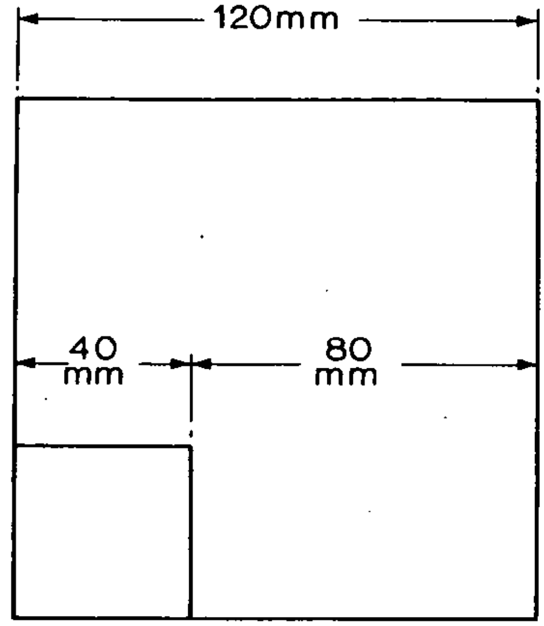
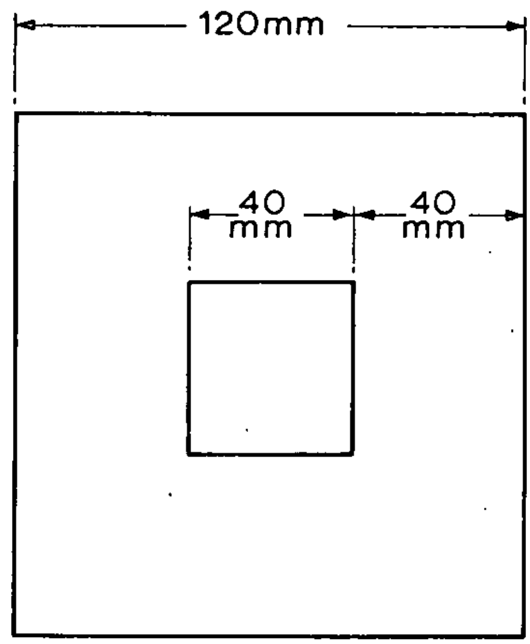


Figure 2 Diagrammatic view of fire spread



With corner ignition the large source causes ignition 80mm ahead of the small



With centre ignition the large source causes ignition 40mm ahead of the small

Figure 3 Effect of size of ignition source

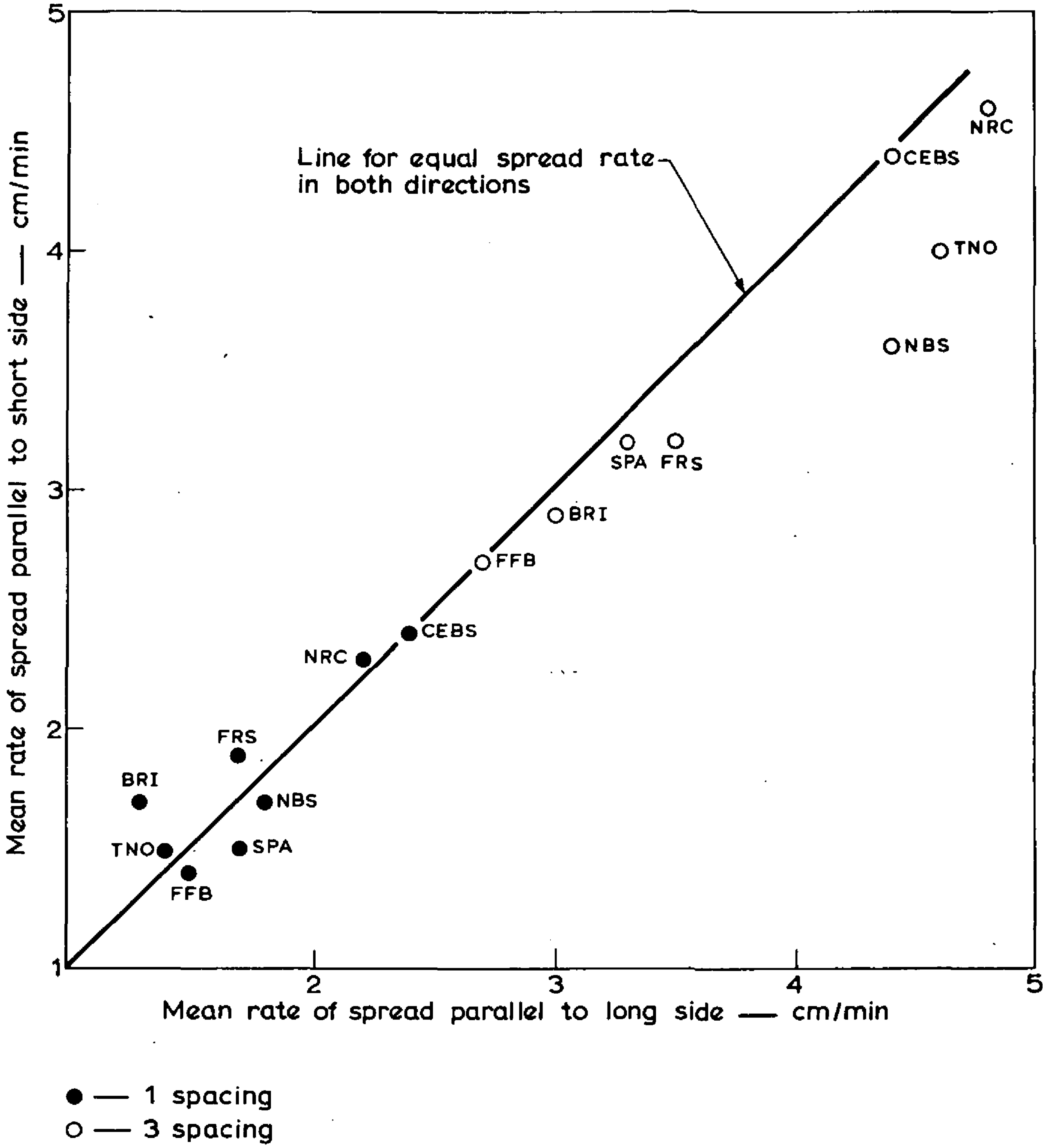
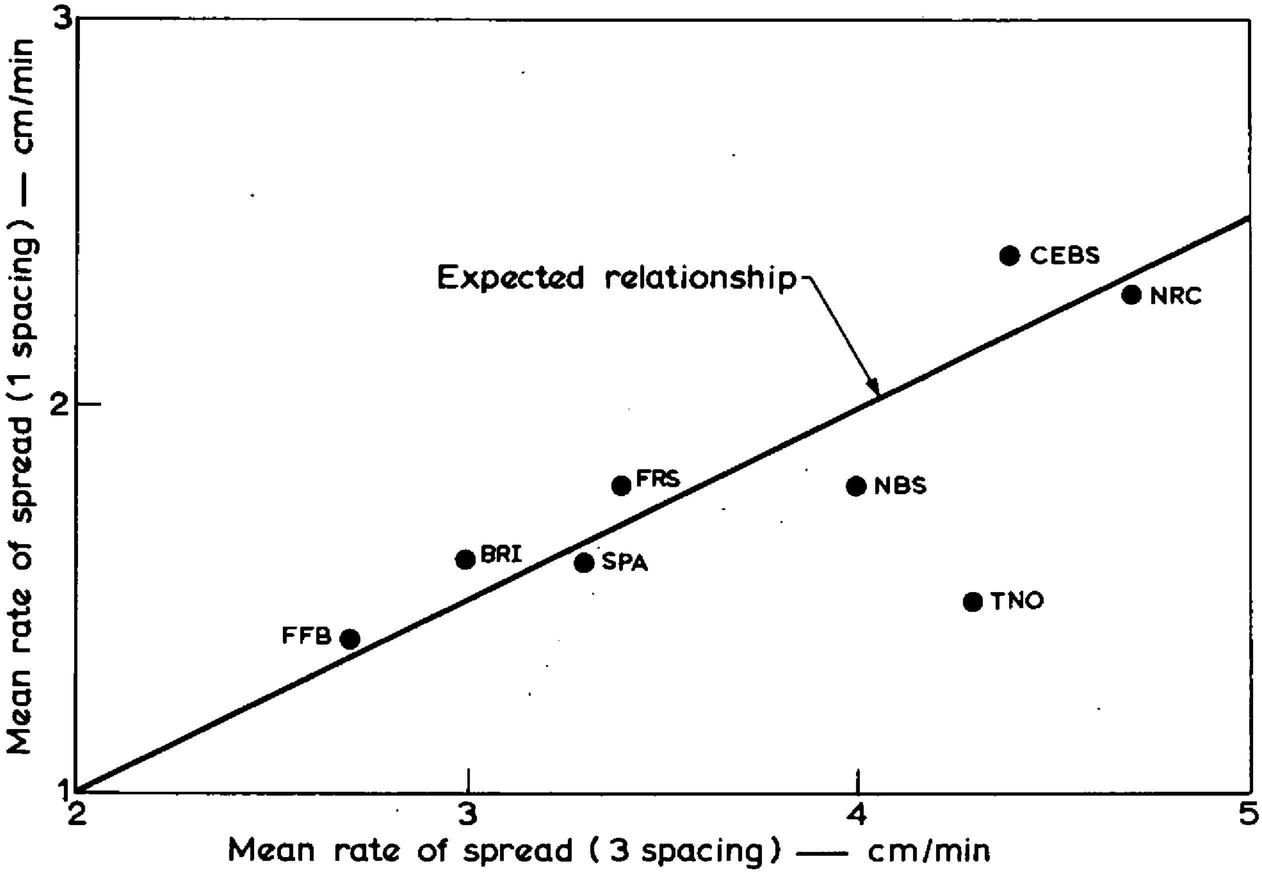


Figure 4 Rates of fire spread in two directions (one large crib).



Each plotted point is the mean of spread rates in 2 directions at right angles for 8 tests (one large crib)

Figure 5 Correlation between rates of spread in 1 and 3 spacing cribs

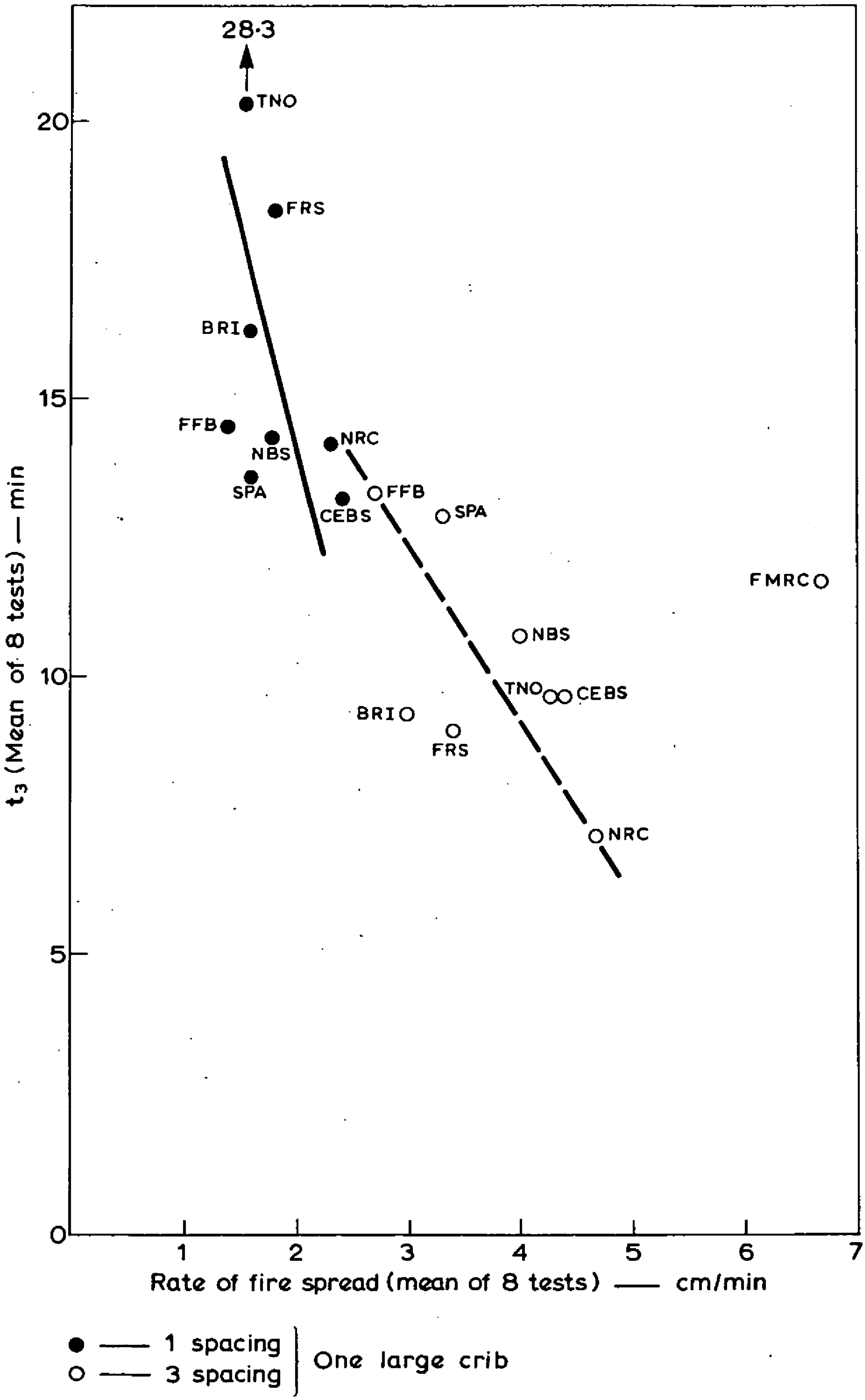
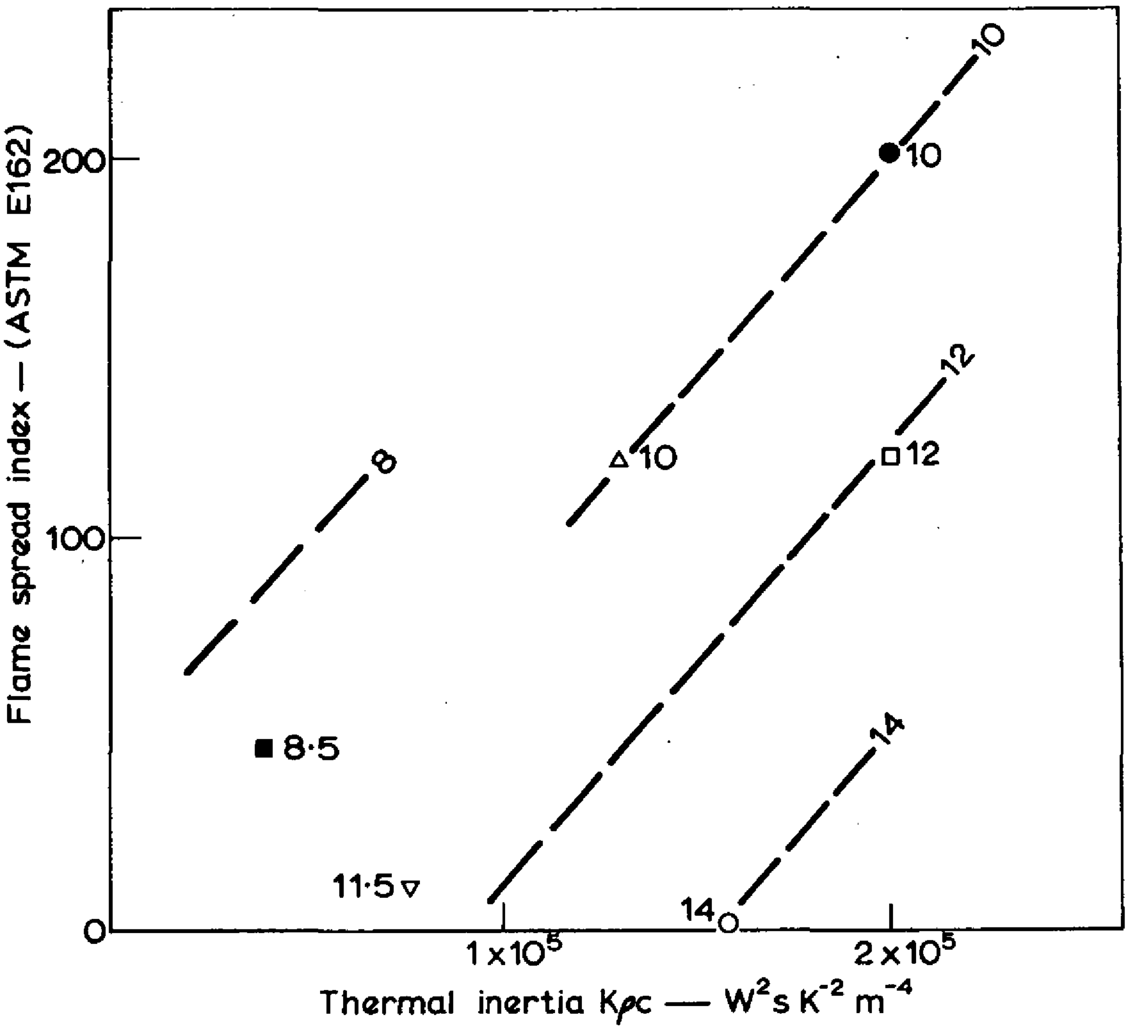


Figure 6 Initial rate of fire spread and t_3
(no lining)



○ Asbestos millboard (Kρc taken as $1{\cdot}57 \times 10^5 W^2 s K^{-2} m^{-4}$ Flame spread index assumed zero)

● Hardboard

■ Fibreboard

□ Plastic-coated hardboard

▽ Gysum board

△ Plywood, exterior grade

Numbers against each point are values of t_3 to the nearest $^1/_2$ minute
Dashed lines are contours of constant t_3 (approx)

Figure 7 t_3 as a function of the thermal inertia and flame spread index of the lining material

Conditions for test shown in Plate 1:

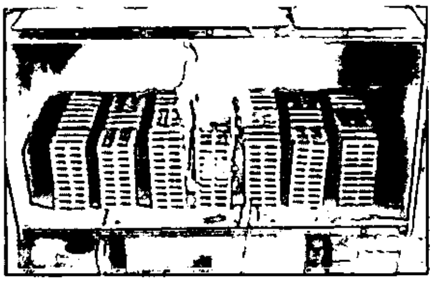
Shape 211	Stick spacing 3
Centre ignition	21 cribs 18 cm square
Fuel height 40 cm	Unlined compartment
Full ventilation opening	Large ignition source

This was a preliminary test and the conditions differed slightly from those of the main programme, but this does not affect the principles being illustrated.

Conditions for test shown in Plate 2:

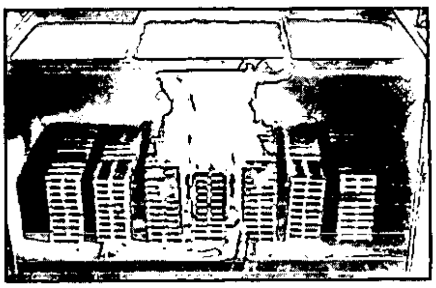
Shape 211	Stick spacing 3
Centre ignition	21 cribs 20 cm square
Fuel height 16 cm	Unlined compartment
Full ventilation opening	Large ignition source

1 min 30 s



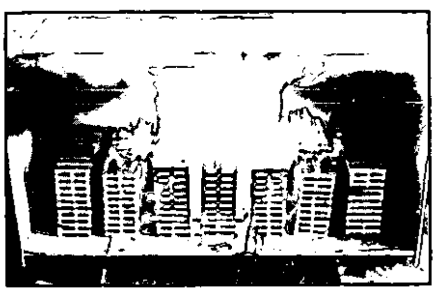
4 min 30 s

Fire spreading slowly from stick to stick through fuel stacks



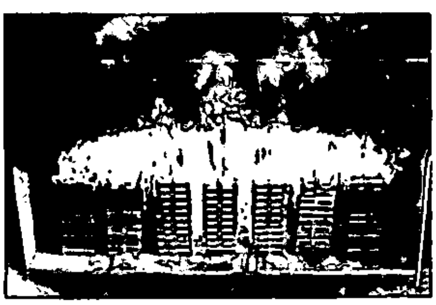
5 min 30 s

Flame spreading out under ceiling. Heat radiated downwards is causing fire to spread over the tops of the stacks of fuel



6 min

Fire spreading rapidly over the tops of the stacks of fuel



6 min 30 s

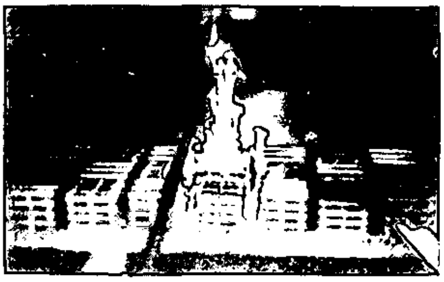
'Flashover'. Lower parts of side stacks of fuel not yet affected

Times given from ignition

Stages in fire spread with tall stacks of fuel

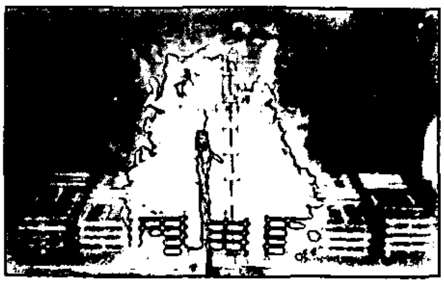
PLATE 1

3 min



4 min 35 s

Fire spreading slowly from stick to stick through fuel stacks at about the same rate as for the tall stacks

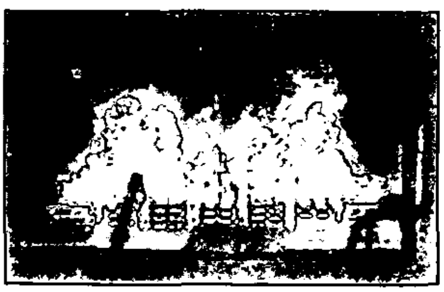


10 min 10 s

Flames do not reach ceiling. Downward radiation is less than for the tall stacks and spread is slower

11 min 40 s

Fire spreads through and over the fuel stacks



12 min 10 s

'Flashover' has taken about twice as long as for the tall fuel stacks

Times given from ignition

Stages in fire spread with low stacks of fuel

PLATE 2

Printed in England for Her Majesty's Stationery Office by Studio Trade Plates Ltd., Watford, WD1 8SA. 7/75