Fire Research Note

No. 923 (Appendix)

SUPPLEMENTARY REPORTS OF WORK FOR THE C.I.B. INTERNATIONAL CO-OPERATIVE RESEARCH PROGRAMME ON FULLY- DEVELOPED FIRES

by

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August 1972

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SUPPLEMENTARY REPORTS OF WORK FOR THE C.I.B. INTERNATIONAL CO-OPERATIVE RESEARCH PROGRAMME ON FULLY-DEVELOPED FIRES.

Edited by A J M Heselden

In this report, the most important of the reports prepared during the course of the programme are gathered together for reference. Very little editing has been done beyond correcting a few errors and misprints, modifying titles and references and eliminating some parochialisms.

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INTERNATIONAL CO-OPERATION IN MODELLING FIRES - A SUGGESTED PROGRAMME

by

D. I. Lawson Director, Fire Research Station, England.

SUMMARY

This paper describes a suggested series of model experiments in which the effects of the following parameters are to be investigated:-

(1) Shape of compartment

(2) Size of compartment

(3) Area of window opening

(4) Amount of fuel

(5) Dispersion of fuel

(6) Dimensions of fuel

(7) Wind orientation

(8) Wind velocity

June 1959

INTERNATIONAL CO-OPERATION IN MODELLING FIRES - A SUGGESTED PROGRAMME

by

D. I. LAWSON Director, Fire Research Station, England

INTRODUCTION

During the last few years there has been a growing realization that if progress is to be made in research into fires it will be necessary to enquire into the effect of various parameters on the development of fire, particularly in respect of fires in buildings which account for the bulk of fire loss.

The factors influencing the development of a fire are so numerous and fire experiments are so variable that it is unthinkable

to carry out a programme of this kind at full scale and some kind of recourse to modelling is therefore essential. In any case, however large the so called full scale fires are, the ones occurring in practice may be bigger so that the issue is not between full scale and model fires, but whether we tackle the problem of fire development with a proper understanding of what is really taking place.

A fire is such a complex happening that it would be quite impossible to formulate a modelling technique from a consideration of the heat and mass transfer processes taking place; in fact different modelling techniques may be applicable to different stages of development of the fire. The approach most likely to yield results is to carry out a graded series of small scale experiments in a simple structure and from these experiments to try to identify the dominant transfer processes for a series of pre-arranged and different conditions. The simplest unit is the single compartment which would represent a factory, warehouse or the fire resisting compartment of a building. The development of fire in such a unit is of international interest. This paper sets out detailed proposals for a graded series of experiments which would break down into a number of easily related programmes of work in which various countries could participate. It is suggested that all results should be freely interchanged through the Secretary of the C.I.B. Working Party on Fire Research, who will arrange for their distribution in participating countries.

PARAMETERS AFFECTING THE DEVELOPMENT OF A FIRE

The following parameters may be assumed to affect the growth of a fire and the communication of fire from one building to another:-

Table 3

Correlation matrix showing correlations between the variables

	I_o/ϕ	$R/AH^{\frac{1}{2}}$	θ_c °K	Scale	Fire load density	Fuel spacing	Fuel thickness	Width/height	Depth/height	Distance between stick centres
I_o/ϕ	1.00									
$R/AH^{\frac{1}{2}}$	0.08	1.00								
θ_c °K	0.75	-0.08	1.00							
Scale	0.59	-0.33	0.55	1.00						
Fire load density	0.21	-0.30	0.05	0.32	1.00					
Fuel spacing	-0.18	0.14	-0.51	-0.04	-0.08	1.00				
Fuel thickness	0.08	0.02	0.25	0.01	0.03	-0.56	1.00			
Width/height	0.45	0.51	0.27	0.05	-0.04	-0.05	0.02	1.00		
Depth/height	-0.50	-0.03	-0.61	-0.21	0.01	-0.03	-0.04	-0.21	1.00	
Distance between stick centres	-0.08	0.16	-0.21	-0.03	-0.04	0.33	*	-0.03	-0.07	1.00

Notes

Each value in the table is the correlation coefficient between the logarithms of the variables named on the same line and column.

$\frac{1}{3}$ spacing data is omitted.

* Not obtained.

(1) Shape of compartment

(2) Size of compartment

(3) Area of window opening

(4) Amount of fuel

(5) Dispersion of fuel

(6) Dimensions of fuel

(7) Wind orientation

(8) Wind velocity

(9) Thermal properties of the compartment

In order to reduce at this stage the number of experiments it is not proposed to investigate in this series the effect of changing the thermal properties of the compartment but rather to investigate this separately with a few critical experiments.

(1) Shape of compartment

The shape of a rectangular compartment may be designated by a three figure code representing the three principal dimensions (a b c) as shown in Figure 1. Thus a (111) type of compartment would be a cubical box; a (441) compartment would be a box with a square ground plan area and having a height equal to $\frac{1}{4}$ that of one of the sides.

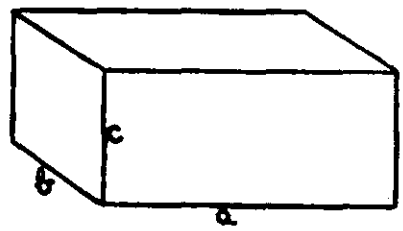


Figure 1.

Using this nomenclature it is suggested that the following shapes of buildings be explored initially:-

(111) (121) (211) (221) (441)

(2) Size of compartment

The size of the compartment is to be determined by the smallest linear dimensions and this to be either $\frac{1}{2}$, 1 or $1\frac{1}{2}$ metres.

(3) Window opening

Windows to extend from the floor to the ceiling and always be placed in the 'a c' side of the box. It is suggested that the following window openings be explored:-

(a) Side a c fully open

(b) Side a c half open

(c) Side a c quarter open.

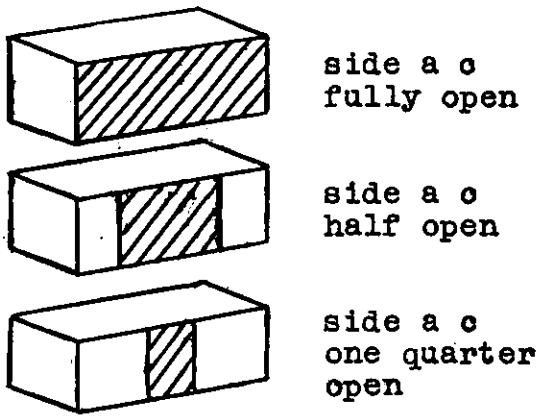


Figure 2.

(4) Amount of fuel

Square section wood fuel should be used, the amount should be expressed in kilograms per square metre, and experiments should be carried out at 20, 30 and 40 Kg/m^2 on the model scale. These figures should cover all normal occupancies, warehouses excepted.

(5) Dispersion of fuel

Fuel should be arranged in cribs with a cubic lattice formation (not face centred) as shown in Figure 3. The density of packing to be indicated by the gap between two consecutive sticks in both horizontal dimensions expressed in terms of the section of the stick, e.g. ½ packing would mean that the sticks were closer together than 2 packing as illustrated in Figure 4.

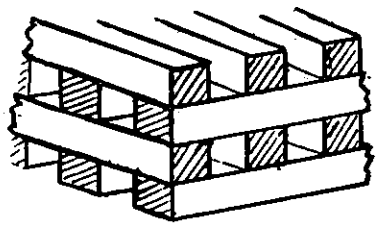


Figure 3.

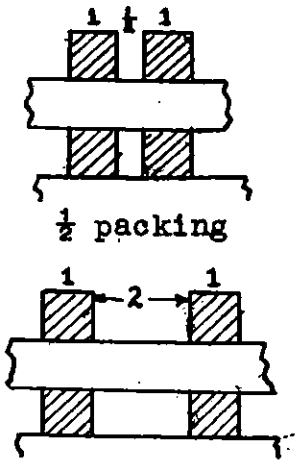


Figure 4.

Three dispersions should be investigated:

⅓ packing

1 packing

3 packing.

(6) Dimensions of fuel

The sticks should have cross-sectional dimensions of 1, 2 and 4 cm.

(7) Wind orientation

This should be taken in three directions; cross wind, following wind, and head wind relative to the 'a c' dimensions as illustrated in Figure 5.

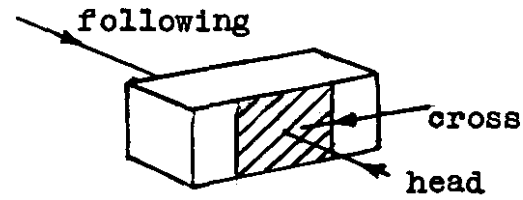


Figure 5.

(8) Wind velocity

Winds to be investigated at the following levels:-

0, 12 and 24 Km/hr.

EXPERIMENTAL PROCEDURE

It is proposed that the experiments be carried out in a non-combustible compartment (so far the compartments have been constructed of asbestos wood, $\frac{3}{8}$ in. thick, at the Joint Fire Research Organization and this appears to have a reasonable life) and that the following quantities be recorded at 2 minute intervals:-

(a) Weight of fuel consumed. This may be found by weighing the burning compartment, in the case of smaller boxes by suspending it from a balance, or for larger fires by suspending the compartment from a cantilever beam to which strain gauges are fixed.

(b) Temperature in Celsius degrees inside the box at the intersection of diagonals on the plan a quarter of the height below the ceiling and a quarter of the height above the floor.

(c) Radiation from the windows one 'a' dimension centrally in front of the 'a c' face (if necessary details of calibrated radiometers can be obtained from the Joint Fire Research Organization).

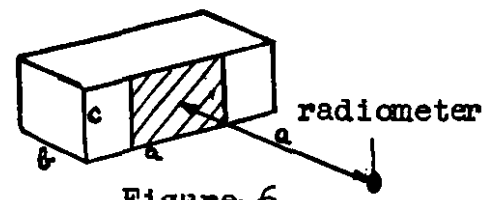


Figure 6.

(d) Radiation from the flames measured by a radiometer placed centrally 1/10 of the 'c' dimensions and in the plane of the 'a c' face as shown in Figure 7. This will give some idea of the hazard in any room above the burning compartment.

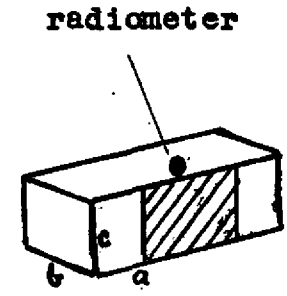


Figure 7.

The thermal properties of the box would have to be standardized and it is suggested that agreement on this be reached with participating countries. In the same way the method of ignition would also have to be standardized at a later date.

INTERCHANGE OF RESULTS OF EXPERIMENTS

It is suggested that the results of experiments be exchanged immediately they are available through the Secretary of the Working Party on Fire Research of the Conseil International du Bâtiment. To reduce the burden of correspondence and reporting to a minimum the attached form should be used, and copies should be exchanged only between countries actually participating in the work.

PUBLICATION

It is understood that each laboratory will be free to publish its own results, but that the results of other laboratories shall be regarded as being submitted 'in confidence' and that they shall not be available for publication until the permission of the originating laboratory has been obtained.

PARTICIPATION AND GENERAL REMARKS

The foregoing proposals are only to be regarded as proposals and any comments and suggestions would be appreciated.

APPENDIX 1

International experiments on fires in simple compartments

REPORT FORM

Description of Experiment

Relevant parameters to be ringed.

(1) Shape

(111) (121) (211) (221) (441)

(2) Size

½ 1 1½ metre

(3) Window opening

fully half quarter open

(4) Amount of fuel

20 30 40 Kg/m^2

(5) Dispersion of fuel

⅓ 1 3 packing

(6) Dimensions of fuel

1 2 4 cm. side

(7) Wind orientation

(i) cross, (ii) following, (iii) head wind

(8) Wind velocity

0 12 24 Km/hr

Experimental results

Time (mins)	0	2	4	6	8	10	12	14	16	18	20
Wt Kg	___	___	___	___	___	___	___	___	___	___	___
Temp. °C ceiling	___	___	___	___	___	___	___	___	___	___	___
Temp. °C floor	___	___	___	___	___	___	___	___	___	___	___
Radiation from window cal/sq.cm/sec	___	___	___	___	___	___	___	___	___	___	___
Radiation from flame cal/sq.cm/sec	___	___	___	___	___	___	___	___	___	___	___

B

SOME GENERAL QUESTIONS IN THE STUDY OF FIRES IN ROOMS

by

P. H. Thomas

SUMMARY

This paper is a series of short notes on some of the basic problems involved in the study of room fires. A description of recent work[1] at the Joint Fire Research Organization has been circulated and some of the main results are summarised here.

April 1960

SOME GENERAL QUESTIONS IN THE STUDY OF FIRES IN ROOMS

by

P.H. Thomas

Ventilation and fireload controlled fires

(1) With relatively large windows there is a rapidly moving flame zone in the fire and there is little or no part of the enclosure where the gases may be regarded as nearly stationary. Hence the pressure differences do not attain the full value corresponding to the buoyancy head. Air is therefore entrained into the flame zone by eddies and the flow is not given by the same formulae as for small windows. The fire burns more nearly as in the open and the rate of burning is generally proportional to the available surface area. If the fuel is in the form of a crib there is a region where the design of the crib is not a controlling factor. Too loosely packed a crib loses heat too readily and too tightly packed a crib may reduce the available surface for burning.

For these fires it seems that the heat from the flames falling on the fuel surface is the controlling factor and it should be possible, once the effect of heat on the decomposition of wood is understood quantitively to predict fuel burning rates.

(2) With relatively small windows the rate of burning in the period after "flashover" is, in general, proportional to the air flow through the windows.

This flow is induced by the pressure differences which arise from the difference in weight between equal heights of the outside air and the hot gases in the room. The greater the fire load the longer the fire lasts.

(3) The fire with restricted ventilation is less well understood despite certain apparent simplicities in the results. It is reasonable to assume the overall fuel/air ratio is approximately constant but in theory the air flow through the window is not the only air involved in combustion. Any flame outside the window entrains additional air and there is no immediately obvious basic reason to explain the observation that these flames are not large.

One possible factor which prevents the gross burning rate increasing in proportion to the fuel surface is that any tendency to increase this rate may tend to reduce the heat transfer to unit area of fuel and hence the rate of loss in weight per unit fuel surface. The maximum velocity head of air is proportional to the height H of the windows and the maximum velocity head of the fuel gases is proportional to $(R/A_w)^2$ where R is the gross rate of burning and Aw the windows area. If the latter were large compared with the air velocity head combustion could not occur within the enclosure and there would be insufficient heat received by the fuel. Hence considerations of mixing place an upper limit on the ratio $R/A_w\sqrt{H}$.

It is therefore possible that the observed burning behaviour $R \propto A_w\sqrt{H}$ arises from mixing considerations.

Flames

The size of flames is important in the study of models because (a) their size determines the radiation on to the fuel and hence the rate of burning and (b) the flame radiation is a hazard to nearly combustible material.

It is possible to derive theoretically a law for any one fuel:

$$\frac{H}{D} = f\left(\frac{R^2}{D^5}\right)$$

where H is flame height
D a characteristic linear dimension
R is rate of burning involved in the flame

Mean flame temperatures, gas densities and composition are assumed constant here.

The height of flames from open cribs is being studied and appears to follow this relation. Flames from cubes with one side open follow an approximate power law

$$\frac{H}{D} \propto \left(\frac{R^2}{D^5}\right)^{\frac{1}{3}}$$

where D is the cube dimension

If R is proportional to the width then for a rectangular window we should expect

$$\frac{H}{D} \propto \left(\frac{R'^2}{D^3}\right)^{\frac{1}{3}}$$

where R' is rate of burning per unit length of window, i.e. $H \propto R'^{\frac{2}{3}}$ independently of D. This law can be derived directly assuming the flame from a line source has a triangular cross section and that air is entrained into the flame with a mean velocity proportional to $\sqrt{H}$. The flame surface per unit length is proportional to H. The air flow per unit length proportional to $H^{3/2}$ and since this must, for a given fuel, be proportional to R we have the above law.

Reference

(1) THOMAS P.H. Studies of Fires in Buildings using Models. Research 1960 13 Part 1 69-77, Part 2 87-93.

PRELIMINARY EXPERIMENTS FOR THE C.I.B. PROGRAMME - ANALYSIS OF RATE OF BURNING

by

K. Kawagoe, P. H. Thomas and R. Pickard

SUMMARY

Analyses have been made of the measurements of the rate of burning obtained in a preliminary series of eight tests by eight laboratories as part of an international programme studying fully-developed fires in single compartments.

The variation between laboratories was found to be too great for different laboratories to carry out separate parts of a larger programme.

The behaviour with a fully open window was neither wholly ventilation controlled nor fire load controlled.

March 1961

PRELIMINARY EXPERIMENTS FOR THE CIB PROGRAMME

ANALYSIS OF RATE OF BURNING

by

K. Kawagoe, P. H. Thomas and R. Pickard

Introduction

Model experiments on the growth of fire in compartments are being made under the auspices of the C.I.B.(1). The first stage of this programme has been completed. Eight laboratories have performed the same eight tests,* of which the detailed results were given in the report forms completed by the participating laboratories, and circulated. This report describes the results of an analysis of the results for the rate of weight loss. A second report will deal with the results of the temperature and radiation measurements. Since a preliminary examination of data shows that there is too great a variation for the tests not to be repeated at some future date when further investigations have revealed those items which must be specified in greater detail to achieve repeatability, this analysis was confined only to the mean rate of burning. A mean rate of burning is probably the most important single statistic to be derived from the rate of burning data, because the fire load divided by this mean rate of burning is a direct measure of the duration of the fire, and this largely determines the required fire resistance. In order to exclude small experimental variations in the early stages of burning arising from the method of ignition, the time for the weight to fall from 90 per cent of its initial value to 30 per cent of its initial value was chosen as the period over which to obtain a mean rate. These times were obtained from the report forms and divided into 0.6 of the initial value to give a mean rate of burning. Some charcoal burning is unavoidably included in this range; the end point of 30 per cent is a compromise choice to give as large a time interval as possible, and to include as little of the charcoal burning as possible.

The report points out the existence of significant differences in this mean rate of burning between the various laboratories and discusses the effect of the physical variables of ventilation, spacing and fire load. The results analysed comprise those from the United Kingdom, the U. S. A., Canada, Holland, Australia and the participating laboratories in Berlin, Braunschweig, and Karlsruhe.† Table 1 shows the mean rates of burning obtained from the reports.

* ½m scale, 121 shape, 2cm for stick thickness.

† Joint Fire Research Organisation, UK; National Bureau of Standards, USA; National Research Council, Canada; Instituut TNO, Holland; Commonwealth Experimental Building Station, Australia; Bundesanstalt für Materialprüfung, Berlin; Institut für Baustoffkunde und Materialprüfung, Braunschweig; Forschungsstelle für Brandschutztechnik, Karlsruhe.

Table 1

Rate of Burning (Kg/min)

Opening	Spacing	Fire load (kg/m^2)	U.K.	U.S.A.	Canada	Berlin	Braunschweig	Karlsruhe	Holland	Australia	Mean for all laboratories
Full	1	20	0.321	0.479	0.390	0.377	0.350	0.336	0.250	0.421	0.365
		30	0.425	0.471	0.496	0.428	0.396	0.645	0.405	0.407	0.459
	3	20	0.394	0.483	0.486	0.522	0.435	0.572	0.554	0.763	0.526
		30	0.383	0.523	0.471	0.461	0.379	0.670	0.550	0.490	0.491
¼	1	20	0.130	0.280	0.244	0.179	0.269	0.238	0.260	0.205	0.226
		30	0.173	0.254	0.240	0.178	0.277	0.240	0.214	0.189	0.221
	3	20	0.283	0.292	0.261	0.234	0.339	0.273	0.273	0.217	0.291
		30	0.223	0.310	0.299	0.251	0.340	0.414	0.280	0.266	0.298

Analysis

The data for each ventilation condition were analysed separately and the results are shown in Tables 2A and 2B which summarise the analysis of variance. It will be seen that the residual errors which in both cases had 7 degrees of freedom, are different, though not significantly so. However, one cannot decide whether the error is an arithmetic or a percentage one.

Table 2-A (Full opening)

Source of variance and degrees of freedom		Sums of squares x 10^4	Mean squares x 10^4	Results of significance tests
Between S (Spacing)	1	693.8	693.8	S x W and L x W Interactions
Between W (Fire load)	1	75.0	75.0	significant at 5 per cent
Between L (Lab.)	7	1015.0	145.0	level. Spacing effect
S x W Interaction	1	344.5	344.5	significant assuming a
W x L Interaction	7	653.2	93.3	"fixed effects" model.
L x S Interaction	7	491.4	70.2	
Residual	7	143.8	20.5	
Total	31	3416.7	110.2	

Table 2-B ($\frac{1}{4}$ Opening)

Source of variance and degrees of freedom		Sums of squares x 10^4	Mean squares x 10^4	Results of significance tests
Between S (Spacing)	1	294.03	294.03	
Between W (Fire load)	1	9.03	9.03	
Between L (Lab.)	7	433.97	62.00	Spacing and laboratory
S x W Interaction	1	22.79	22.79	effects significant at 5
W x L Interaction	7	52.72	7.53	per cent level.
L x S Interaction	7	48.72	6.96	
Residual	7	83.96	11.99	
Total	31	945.22	30.49	

(Pooled residual 9.44×10^{-4} with 23 degrees of freedom).

We assume that a change of spacing, fire load or ventilation has a "fixed effect" while the variation of these effects and their interactions between laboratories is "random". On this basis the mean squares are the estimate of the quantities shown in Table 3.

TABLE 3

Source of Variance		Components of Variance*
Between S (Spacing)	1	$\sigma_e^2 + 2\sigma_{SL}^2 + 16\sigma_S^2$
Between W (Fire load)	1	$\sigma_e^2 + 2\sigma_{WL}^2 + 16\sigma_W^2$
Between L (Laboratories)	7	$\sigma_e^2 + 4\sigma_L^2$
S x W interaction	1	$\sigma_e^2 + \sigma_{LSW}^2 + 8\sigma_{SW}^2$
W x L interaction	7	$\sigma_e^2 + 2\sigma_{WL}^2$
L x S interaction	7	$\sigma_e^2 + 2\sigma_{SL}^2$
L x S x W interaction (Residual)	7	$\sigma_e^2 + \sigma_{LSW}^2$

*The variances have the usual meaning and σ_e^2 is the experimental variance. In these tests one must either assume one of the variances other than σ_e^2 is zero or obtain an estimate of σ_e^2 independently. This is now available from tests including repeats performed by Nijverheidsorganisatie voor Toegepast Natuurweternschappelijk Onderzoek, Joint Fire Research Organization and National Bureau of Standards laboratories on three woods. These tests give σ_e^2 with 8 degrees of freedom as 2.25×10^{-4} and we assume this is applicable to all laboratories. Consider Table 2A. With a 5 per cent significance level, all the variances exist except for σ_W^2 so that the effect of fire load varies from one laboratory to another without an overall effect. If σ_{LSW}^2 is assumed non-existant so that the residual of 20×10^{-4} is used for testing the other variances, we reach the same conclusion except that σ_{LS}^2 is now just below the 5 per cent level. In Table 2B the use of 2.25×10^{-4} for the variance σ_e^2 shows σ_{LSW}^2 to be significant. σ_{WL}^2 and σ_{SL}^2 although not significant are large. σ_{SW}^2, σ_L^2 and σ_S^2 are significant.

Using the residual variance of 11.99×10^{-4} one finds only σ_L^2 and σ_S^2 are significant.

We conclude that:

(1) There are significant differences between the mean levels of different laboratories.

(2) There are no overall effects of fire load as such but almost certainly in the case of the fully open window and possibly in the case of the ¼ open window, the value of the fire load affects the magnitude of the spacing effect. Despite the absence of an overall fire load effect there are significant variations in its effect between laboratories in the case of the fully open window and possibly also in the case of the ¼ open window.

(3) Increasing the spacing increases the burning rate by amounts which vary significantly between laboratories in the case of the fully open window.

(4) On the basis of the recent estimate of experimental error the way in which the level of fire load affects the magnitude of the spacing effect varies significantly between laboratories.

Table 4

Analysis of variance for separate laboratories

(Variance x 10^4)

Source of Variance	Degrees of freedom	U.K.	U.S.A.	Canada	Berlin	Braunschweig	Karlsruhe	Holland	Australia
Between V (Opening)	1	648.00	840.50	820.13	1128.12	144.50	1431.13	684.50	1770.13
Between W (Fire load)	1	8.00	0.50	21.13	0.12	0.00	378.13	18.00	78.13
Between S (Spacing)	1	60.50	18.00	28.13	105.12	50.00	253.13	338.00	325.13
V x W Interaction	1	18.00	2.00	3.13	1.13	0.50	91.13	50.00	120.13
W x S Interaction	1	60.50	12.50	10.13	10.13	18.00	6.13	12.50	45.13
S x V Interaction	1	40.50	0.50	0.13	3.13	4.50	3.13	162.00	136.13
W x V x S Interaction	1	0.50	0.00	36.09	21.12	12.50	153.13	60.50	136.13
Total	7	119.43	124.86	131.26	181.27	32.86	330.84	189.36	372.98

Table 5

Analysis of variance for each laboratory

(Variance x 10^4)

Source of Variance	Degrees of freedom	U.K.	U.S.A.	Canada	Berlin	Braunschweig	Karlsruhe	Holland	Australia
Between V	1	648.00	840.50	820.13	1128.12	144.50	1431.13	684.50	1770.13
Between S	1	60.50	18.00	28.13	105.12	50.00	253.13	338.00	325.13
W x S Interaction	1	60.50	12.50	10.13	10.13	18.00	6.13	12.50	45.13
Residual	4	16.75	0.75	15.00	6.4	4.4	156.9	72.6	117.6
Total	7	119.43	124.86	131.26	181.27	32.86	330.84	189.36	372.98

These analyses were performed with data in Table 1 rounded off to two places of decimals.

In neither Table 2A nor 2B is W (fire load) a factor compared with the variation in its effect from one laboratory to another.

In an analysis of the data for each laboratory (Table 4) one finds that the W mean square in 4 cases is not significant compared with the variance of an individual result of 2.2×10^{-4}. In one of the remaining four cases the direction of the effect differs from the other three. In two of these four cases the high value of the W mean square appears to be due to a single result, i.e. 0.763 in the Australian results and the 0.250 in the Dutch results. There is also some evidence that one or more of the results from the United Kingdom, Canada and Karlsruhe differ significantly from the value expected on the view that W is not a factor (these results are underlined in Table 1).

If each laboratory is considered in isolation (see Table 4) we find that the estimates made, say, by the Berlin and the United States data of the effect of spacing differ greatly, and the effect of changing the window opening is much less in the Braunschweig data than in the Berlin data. Table 1 shows that the relative magnitude of the rates of burning for these two laboratories are in the opposite order for the two different conditions of window opening. The fact that the difference between laboratories is not a simple one affecting the general level of the results but affecting also the magnitude of main effects and interaction suggests that the differences are not simply due to a systematic effect such as a difference in wood or in box material.

For each laboratory the effects of the three factors which are consistently significant, or nearly so, ventilation and spacing and the W S interaction have been evaluated together with the variation remaining, (see Table 5). In the case of the Dutch and the Australian results the large residual can be shown to arise from the one value in each already mentioned.

It is not possible to be so definite in the case of the Karlsruhe data for which the residual is exceptionally high.

Although in this report the term 'abnormal' result has been in connection with certain values, an inspection of the actual curves of weight against time shows that this may be more a consequence of the choice of statistic than a reflection of a real difference. For example, the Australian result giving the high rate of burning, higher than any other single value, is probably due to the fact that burning is maintained at a high value over a long period, that is down to the point of 30 per cent initial weight, while in some, if not all other cases, the burning rate tends to slow down somewhat earlier than the point at which the rate is 30 per cent of its initial value. Thus, in the Australian data the figure of 0.76 may be nearer to the maximum than the other data are to the corresponding maximum. An analysis of maximum rates of burning would possibly show other data for other countries and conditions to be somewhat 'abnormal' in the sense used here.

General discussion

The magnitude of the effects due to changing the size of the opening and the spacing will not be discussed in detail because these differ between laboratories but in approximate terms the effect of increasing the opening from a $\frac{1}{4}$ to 1 increases the rate of burning by about twice. This is less than the factor of 4 which might be expected on the grounds that burning rate is proportional to air flow and this suggests the fully open condition is intermediate between a ventilation controlled fire and a crib controlled fire which burns at a rate independent of the area of the opening. That the fully open condition is not completely controlled by the area of the surface of the wood in the crib is shown by the fact that the burning rate is not dependent on fire load to any significant extent.

The effect of spacing varies between laboratories for the fully open condition though not for the $\frac{1}{4}$ open condition. The difference between the 1 : 1 and the 1 : 3 spacing varies from an insignificant amount to about 30 per cent of the burning rates. This is large but a 1 : 4 spacing might show little change from the results for 1 : 3 spacing. In so far as spacing may have little meaning in an actual occupancy (except where combustibles are closely packed as in a store) the results of 1 : 1 spacing tests are of less immediate practical value than those for the wider spacing. However, for experimental purposes it is necessary to know the closest spacing that can be employed before the spacing between the sticks becomes a significant factor.

In a correlation of rates of burning for several fires in rooms with one window burning in a manner controlled by the window opening it has been shown[2] that the rate of burning in kg/min is approximately given by $6\ A\sqrt{H}$ where A is the window opening in square metres and H is the window height. For the $\frac{1}{4}$ open condition this gives 0.26 kg/min and this agrees closely with the value 0.25 kg/min, the mean value for all laboratories for the $\frac{1}{4}$ open condition. The fact that spacing had a significant effect even for this condition shows that the dispersion of the combustible material has some effect, even when the stick thickness is constant and the window opening is small, i.e. even in fires which can be described as ventilation controlled some features of the fuel dispersion take an effect on the burning rate.

Conclusions

1. There is too great a variation between laboratories for different laboratories to embark on separate parts of a larger programme, so that the experimental technique needs more detailed specification. A programme for this purpose has recently been completed and will be reported later.

2. The results for these eight tests suggest that the behaviour with the fully open window was neither wholly ventilation controlled nor fire load controlled.

3. With the $\frac{1}{4}$ open window the grand mean result for all laboratories agrees well with the value predicted from the assumption that the fire was ventilation controlled. However, the results show that spacing between sticks, i.e. the design of the crib itself, had some influence also.

References

1. LAWSON, D. I. International Co-operation in Modelling Fires. A suggested programme. Supplement paper 'A'

2. THOMAS, P. H. "Studies of fires in buildings using models". "Research" 1960, 13 p. 69.

PRELIMINARY EXPERIMENTS FOR THE C.I.B. PROGRAMME - ANALYSIS OF CEILING TEMPERATURES AND RADIATION FROM THE OPENING

by

K. Kawagoe, P. H. Thomas and P. G. Smith

SUMMARY

Analyses have been made of the measurements of ceiling temperature and radiation from the opening obtained in a preliminary series of eight tests performed by eight laboratories as part of an international programme of compartment fires

Due to insufficiently specified experimental conditions, there are important unexplained variations between laboratories, but the analyses do show certain changes in the experimental conditions to have significant effects.

July 1961

PRELIMINARY EXPERIMENTS FOR THE CIB PROGRAMME
ANALYSIS OF CEILING TEMPERATURES AND RADIATION FROM THE OPENING

by

K. Kawagoe, P. H. Thomas and P. G. Smith

1. Introduction

Model experiments on the growth of fire in compartments are being made under the auspices of the Conseil International du Bâtiment (CIB) (1). The first stage of this programme has been completed. Eight laboratories have performed the same eight tests, in a compartment $\frac{1}{2}$ m x $\frac{1}{2}$ m x 1 m with an opening in one end. The detailed results were given in the report forms completed by the participating laboratories and circulated between them. A first report (2) on the analysis of the rate of burning data has been issued, and this second report deals with the results of the ceiling temperatures and the radiation from the opening which were measured by each laboratory continuously throughout each test according to procedures described elsewhere (1). The following quantities are dealt with in this report: the maximum ceiling temperature, the maximum radiation from the opening and the mean radiation from the opening during the period in which the weight of fuel fell from 90 percent of its initial weight to 30 per cent. There are differences in these quantities between one laboratory and another which are in many cases significant and for which little explanation can be offered, but there are certain differences between the different test conditions which are significant, and these are discussed.

2. Results

2.1. Maximum ceiling temperatures

The maximum ceiling temperatures obtained from the reports from each laboratory are shown in Fig.1 and Table 1. These results have been analysed statistically, and the analysis of variance is shown in Table 2. To test the significance of any factor we compared the mean square for that factor with the mean square for the variation of that factor between laboratories. On this basis we find that the temperatures are higher for the fully open window condition than for the $\frac{1}{4}$ open condition, and are higher for the 1 : 1 spacing than for the 1 : 3 spacing between sticks in the wood crib. The interaction between ventilation and spacing is large but not significant at the 5 per cent level. Similarly, the interaction between ventilation, spacing and fire load is large but not significant at the 5 per cent level compared with the variation of that effect from one laboratory to another. After performing these experiments a further set of experiments in which repeat tests were made has been completed by three of the eight laboratories, and from these it is possible to obtain a true residual variance, and this is equal to 109 with nine degrees of freedom. If this result can be generalised to these earlier experiments, then a number of the interactions and variations of interactions between laboratories are significant. The meanings of these are uncertain but they suggest that there are probably important differences in technique of measuring temperatures between one laboratory and another, and these will have to be reduced in magnitude for future work of this kind by better specification of the experimental technique.

It has been shown previously (2) that the burning rate like the temperature is higher for the fully open than for the $\frac{1}{4}$ open condition and unlike the

temperature slightly higher for the 1 : 3 spacing than for the 1 : 1 spacing. Thus, the temperature differences do not correlate with the rate of burning differences qualitatively . The faster rate of burning with the fully open condition would be expected to be associated with higher temperatures in the enclosure because higher heat transfer rates are necessary in order to increase the rate of decomposition of the fuel bed, and this is in fact what is seen from these results. However, the higher rate of burning with the 1 : 3 spacing is associated with lower temperatures. But as is seen below this is not accompanied by a significant radiation difference. Fig.2 shows the maximum ceiling temperature plotted against the mean rate of burning, and clearly there is no obvious correlation. There may be some correlation if systematic differences between one laboratory and another are eliminated before such a correlation is attempted. This, however, has not yet been tried, since as will be reported later, no such correlation was found for the later series of experiments by three laboratories.

2.2. Radiation from the opening

In some cases there is an early maximum to the radiation but this may be associated with the ignition, and the results given in Table 3 for the maximum radiation refer to the maximum radiation in the middle of the burning period. The analysis of variance of these results is given in Table 4. The mean radiation in the period when the weight of the fuel falls from 90 per cent of its initial value to 30 per cent is given in Table 5, and the analysis of variance on these results in Table 6. As one might expect, there is a significant difference between the two ventilation conditions. This is largely, if not wholly, due to the radiometer "seeing" the whole window, so that with the smaller opening the total radiation is less. The spacing effect is not significant for either the mean or maximum radiation, but the fire load effect is significant with respect to its variation between laboratories in the case of the mean radiation-the higher the fire load, the higher the mean radiation. The ventilation fire load interaction is significant for both maximum and mean radiations compared with its variation between laboratories. The interaction between the spacing effect and the fire load is significant for the mean but not for the maximum radiation, and in both cases the second order interaction between ventilation spacing and fire load is significant.

The mean radiation has been plotted against the mean rate of burning in Fig.3, and a definite trend is seen in these results, higher rates of burning being associated with higher levels of radiation. In the case of the recent experiments by three laboratories in which repeat tests were done, a very close correlation is observed between radiation and rate of burning once the systematic differences between the three laboratories and the three woods used have been allowed for. This has not been attempted for these data in the same way. What has been done is that the measured mean radiation divided by the measured mean rate of burning has been evaluated and this is listed in Table 7, the analysis of variance with these ratios being given in Table 8.

This analysis has several points of interest. Firstly, because the radiation level is markedly affected by the size of the window as is the rate of burning, the ratio might well be expected to be less dependent on the size of the opening than is either the rate of burning or the radiation itself, yet the ratio does vary significantly between the two ventilation conditions. The ratio also varies significantly between the two different spacings. No interactions are significant. The results have been averaged, and assuming that only the spacing and the ventilation are real effects, Table 9 gives the expected mean ratios for all laboratories except the

Braunschweig laboratory where there was very much less difference between the radiation levels for the two window openings than for the other seven. This difference is presumed to be due to the use of a radiometer with a small acceptance angle which therefore does not show the large difference that other radiometers did.

The expected ratios for one particular set of experimental conditions for three laboratories are given in Table 10. Also given, for comparison, are ratios obtained in a later, more restricted programme by these three laboratories testing three woods with repeat tests on each, in which the set of experimental conditions chosen was : window-fully open, fire load - 20 kg m^{-2}, and spacing - 1 : 3. The procedures for the tests and the equipment used are not strictly comparable and the results are quoted for general information only.

It has been suggested that the quantity

$$\frac{\text{a measured radiation intensity}}{\text{configuration factor of radiometer with respect to opening.}} \times \frac{\text{window area}}{\text{rate of burning}}$$

is a constant characteristic of the crib and the geometry of the window and enclosure. This quantity is listed in Tables 7 & 9. The significance of the results will be discussed elsewhere.

The analysis of the results obtained on the more restricted programme has given values for the variance between repeat tests which are considerably lower than the variances in the above Tables, and if we use those as estimates of error, then a large number of the variations of effects between laboratories becomes significant, that is to say, effects such as variations between ventilation and fire load from one laboratory to another may be large compared with the repeatability of individual tests, so that it follows that, in this series of eight tests, there are a number of factors which have an important bearing on fire behaviour which either have not been specified, or have not been specified exactly enough. Thus, the eight laboratories did not use one material from which to construct the box, nor was one type of wood used throughout. At first sight this should only have produced systematic differences between laboratories, and the extent of the effect of changing from one spacing to another or from a quarter open to a fully open condition, should have been equal, or approximately equal, from one laboratory to another. This is not the case, so that it is insufficient to specify experimental conditions in the way they have been specified so far, and a more detailed specification is necessary in order to try to reduce the variability between one laboratory and another, and the way in which different laboratories assess the extent of various physical effects.

3. Conclusions

1. Owing presumably to the experimental conditions being inadequately specified there are important unexplained variations between laboratories.

2. The analyses show there are significant differences in
   (a) maximum ceiling temperatures between the two levels of ventilation and the two spacings used;
   (b) radiation from the opening between the two ventilation conditions;
   (c) mean radiation from opening between the two fire loads;
   (d) the ratio $\frac{\text{mean radiation from opening}}{\text{mean rate of burning.}}$ between the ventilation and spacing conditions.

There are also some complex physical interactions affecting the radiation from the opening and, to a lesser extent, the maximum ceiling temperatures.

3. There is little evidence of a correlation between mean rates of burning and maximum ceiling temperatures but there is a trend for the mean rates of burning to be related to the mean levels of radiation from the opening. Estimates have been made of the values of the constants of proportionality between these two quantities - averaged for all laboratories.

4. References.

(1) LAWSON, D. I. International co-operation in modelling fires -a suggested programme. Supplement paper A.

(2) KAWAGOE, K., THOMAS, P. H., and PICKARD, R. Preliminary experiments for the CIB programme. Analysis of the rate of burning. Supplement paper C.

TABLE 1.
Maximum Ceiling Temperature (°C)

Opening	Spacing	Fire load kg/m²	U.K.	U.S.A.	Canada	Berlin	Braunschweig	Karlsruhe	Holland	Australia	Mean
Full (V1)	1 (S1)	20 (F1)	995.	1025.	935.	895.	810.	817.	1020.	1010.	938.
		30 (F2)	1035.	1000.	957.	958.	812.	892.	1055.	990.	962.
	3 (S2)	20 (F1)	915.	900.	936.	880.	705.	892.	965.	865.	882.
		30 (F2)	990.	890.	906.	793.	760.	905.	960.	840.	881.
¼ (V2)	1 (S1)	20 (F1)	895.	960.	870	808.	748.	880.	1025.	905.	886
		30 (F2)	885.	925.	849.	745.	870.	818.	945.	895.	867
	3 (S2)	20 (F1)	905.	875.	835.	783.	790.	867.	950.	805.	851.
		30 (F2)	885.	910.	838.	807.	760.	817.	900.	845.	845.

TABLE 2
Maximum Ceiling Temperature
Analysis of variance

Source of variance	Degrees of freedom	Sums of squares	Mean squares
L (laboratory)	7	222,219.359	31,745.623
V (ventilation)	1	45,849.515	45,849.515
S (spacing)	1	37,781.640	37,781.640
F (fire load)	1	13.140	13.140
L x V	7	21,308.610	3,044.087
L x S	7	22,485.985	3,212.284
L x F	7	5,748.985	821.284
V x S	1	6,662.642	6,662.642
V x F	1	2,316.020	2,316.020
S x F	1	141.017	141.017
L x V x S	7	8,812.983	1,258.998
L x V x F	7	9,562.108	1,366.015
V x S x F	1	1,570.138	1,570.138
F x S x L	7	3,237.608	462.515
Residual	7	13,732.484	1,961.783
Total	63	401,442.234	6,372.099

TABLE 3

Maximum radiation from opening x 100
- cal $cm^{-2}s^{-1}$

Opening	Spacing	Fire load kg/m^2	U.K.	U.S.A.	Canada	Berlin	Braunschweig	Karlsruhe	Holland	Australia	Mean
Fully (V1)	1 (S1)	20 (F1)	42.	70.	34.	20.	20.	18.	45.	42.	36.5
		30 (F2)	45.	64.	40.	30.	28.	30.	45.	47.	41
	3 (S2)	20 (F1)	37.	43.	35.	22.	24.	32.	51.	45	36
		30 (F2)	36.	52.	35.	24.	29.	28.	45.	41.	36.5
½ (V2)	1 (S1)	20 (F1)	14.	27.	16.	9.	19.	11.	20.	19.	17
		30 (F2)	13.	21.	15.	9.	20.	11.	17.	20.	15.5
	3 (S2)	20 (F1)	15.	23.	15.	11.	21.	11.	18.	16.	16.5
		30 (F2)	14.	24.	15.	8.	25.	12.	18.	17.	17

TABLE 4
Variance of maximum radiation from opening x 10^4

Source of variance	Degrees of freedom	Sums of squares	Mean squares
L (laboratory)	7	3293.734	470.533
V (ventilation)	1	7119.140	7119.140
S (spacing)	1	23.765	23.765
F (fire load)	1	17.015	17.015
L x V	7	1223.985	174.855
L x S	7	250.860	35.837
L x F	7	58.610	8.373
V x S	1	28.892	28.892
V x F	1	31.642	31.642
S x F	1	9.767	9.767
L x V x S	7	210.733	30.105
L x V x F	7	27.983	3.998
V x S x F	1	37.513	37.513
F x S x L	7	110.358	15.765
Residual	7	42.612	6.087
Total	63	12486.609	

TABLE 5
Mean Radiation from window opening x 100
- cal $cm^{-2}s^{-1}$

Opening	Spacing	Fire load kg/mm)	U.K.	U.S.A.	Canada	Berlin	Braunschweig	Karlsruhe	Holland	Australia	Mean
Full (V1)	1 (S1)	20 (F1)	27.	47.	24.	15.	16.	12.	30.	32.	25.4
		30 (F2)	40.	50.	31.	21.	22.	21.	36.	37.	32.1
	3 (S2)	20 (F1)	33.	34.	23.	20.	21.	23.	40.	35.	28.6
		30 (F2)	35.	43.	26.	22.	28.	22.	37.	28.	30.1
$\frac{1}{4}$ (V2)	1 (S1)	20 (F1)	11.	20.	12.	7.	13.	8.	14.	13.	12.4
		30 (F2)	11.	16.	12.	7.	18.	9.	13.	12.	12.4
	3 (S2)	20 (F1)	14.	18.	12.	9.	18.	8.	16.	13.	13.5
		30 (F2)	13.	17.	13.	8.	21.	8.	15.	14.	13.6

TABLE 6
Variance of mean radiation from opening x 10^{-4}

Source of variance	Degrees of freedom	Sums of squares	Mean squares
L	7	1825.750	260.821
V	1	4192.563	4192.563
S	1	14.063	14.063
F	1	72.250	72.250
L x V	7	704.687	100.670
L x S	7	149.187	21.312
L x F	7	45.500	6.500
V x S	1	2.249	2.249
V x F	1	68.062	68.062
S x F	1	27.562	27.562
L x V x S	7	88.501	12.643
L x V x F	7	33.188	4.741
V x S x F	1	30.251	30.251
F x S x L	7	42.688	6.098
Residual	7	33.499	4.786
Total	63	7330.000	

TABLE 7

$$\frac{\text{Mean radiation from opening - cal cm}^{-2}\text{s}^{-1}}{\text{Mean rate of burning - kg min}^{-1}} \times 100$$

Opening	Spacing	Fire load kg/m^2	U.K.	U.S.A.	Canada	Berlin	Karlsruhe	Holland	Australia	Mean	Mean radiation at opening (corrected for configuration) x window area / mean rate of burning cal g^{-1}
Full	1	20	84	98	60	40	34	120	76	73	460
		30	93	106	63	48	33	90	90	75	470
	3	20	83	70	48	38	41	71	46	57	360
		30	92	81	54	48	32	67	57	62	390
¼	1	20	87	71	48	38	33	55	63	56	310
		30	65	61	52	40	35	62	65	54	300
	3	20	48	62	48	38	31	58	58	49	270
		30	57	56	44	30	20	53	54	45	250

TABLE 8

Variance of $\frac{100 \times \text{mean radiation from opening}}{\text{mean rate of burning}}$

Source of variance	Degrees of freedom	Sums of squares	Mean squares
L	6	15020	2503
V	1	3320	3320
S	1	1880	1880
F	1	0.018	0.018
L x V	6	1384	231
L x S	6	654	109
L x F	6	272	45
V x S	1	142	142
V x F	1	142	142
S x F	1	3.0	3.0
L x V x S	6	1218	203
L x V x F	6	467	78
V x S x F	1	24.4	24.4
F x S x L	6	576	96
L x V x S x F	6	314	52

TABLE 9

Expected $\frac{\text{mean radiation from opening}}{\text{mean rate of burning}}$ for all laboratories except Braunschweig

Opening	Spacing	measured $\frac{\text{radiation}}{\text{rate}}$	$\frac{\text{mean radiation at opening (corrected x window area for configuration)}}{\text{mean rate of burning}}$ -cal g^{-1}
Full	1	0.72	450
	3	0.61	380
¼	1	0.57	314
	3	0.45	248

TABLE 10

Expected $\frac{\text{mean radiation from opening}}{\text{mean rate of burning}}$ compared with ratios from later tests.

Laboratory	Expected $\frac{\text{radiation}}{\text{rate}}$	$\frac{\text{radiation}}{\text{rate}}$ from later tests
J.F.R.O.	0.81	0.61
N.B.S.	0.80	0.59
T.N.O.	0.81	0.71

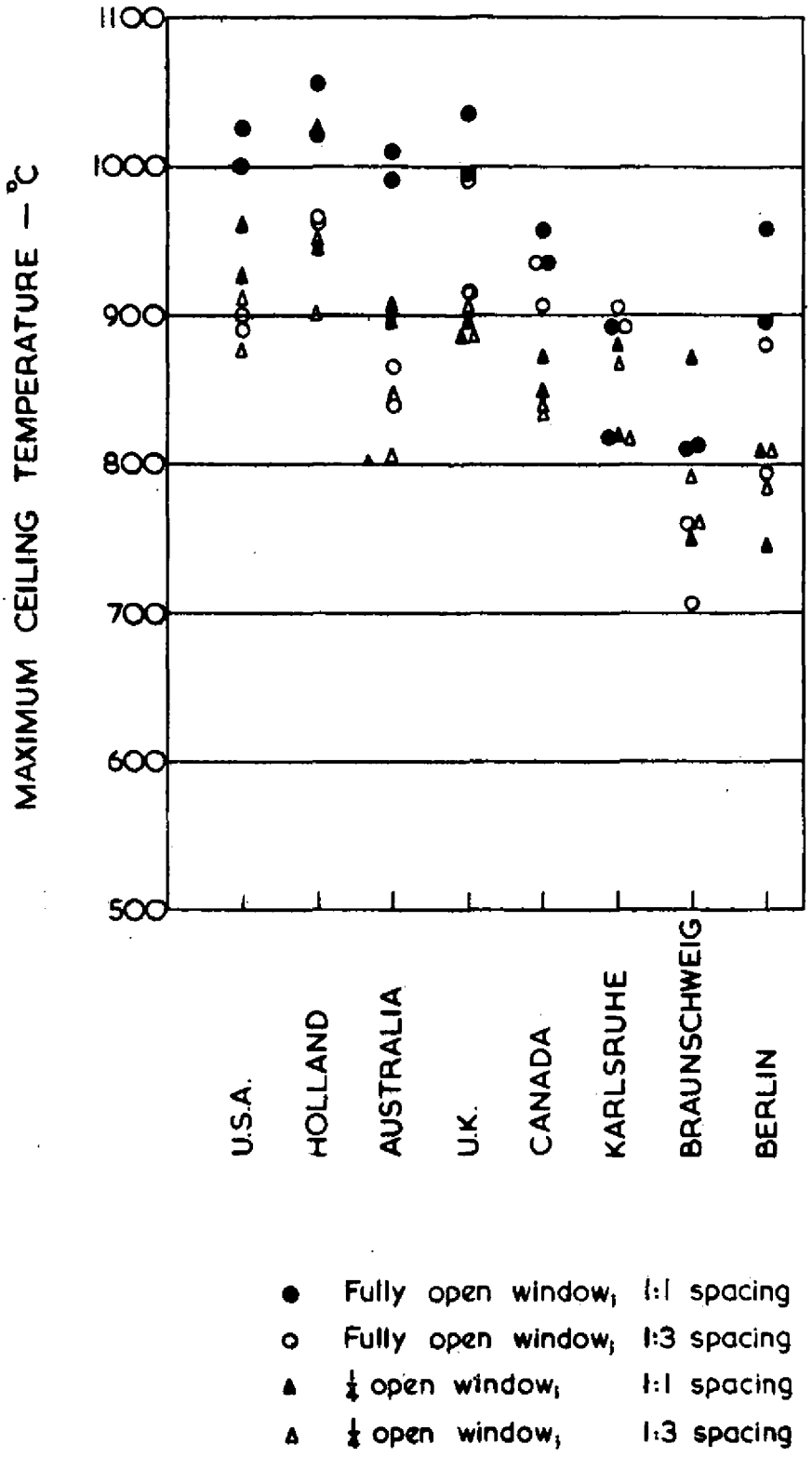
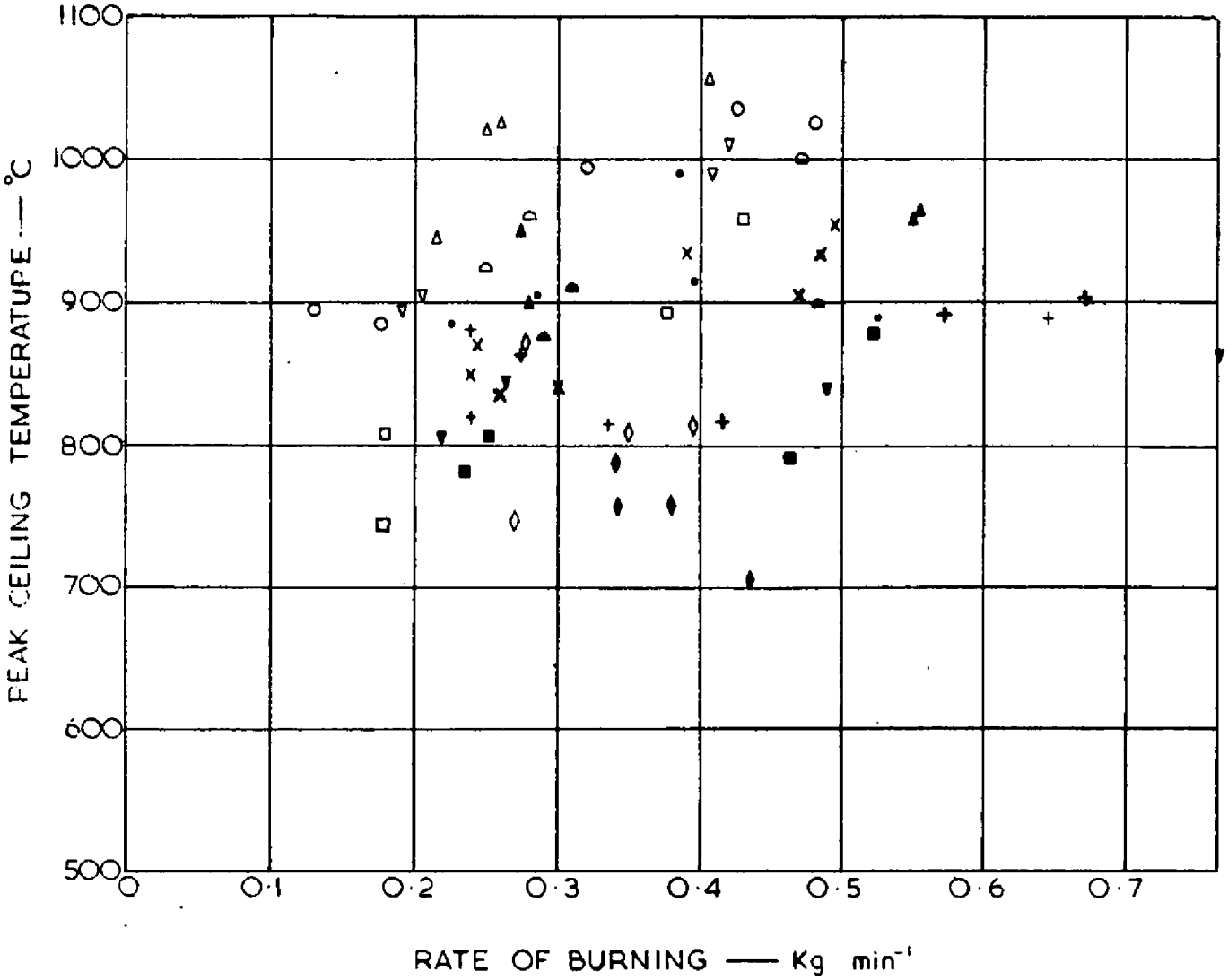
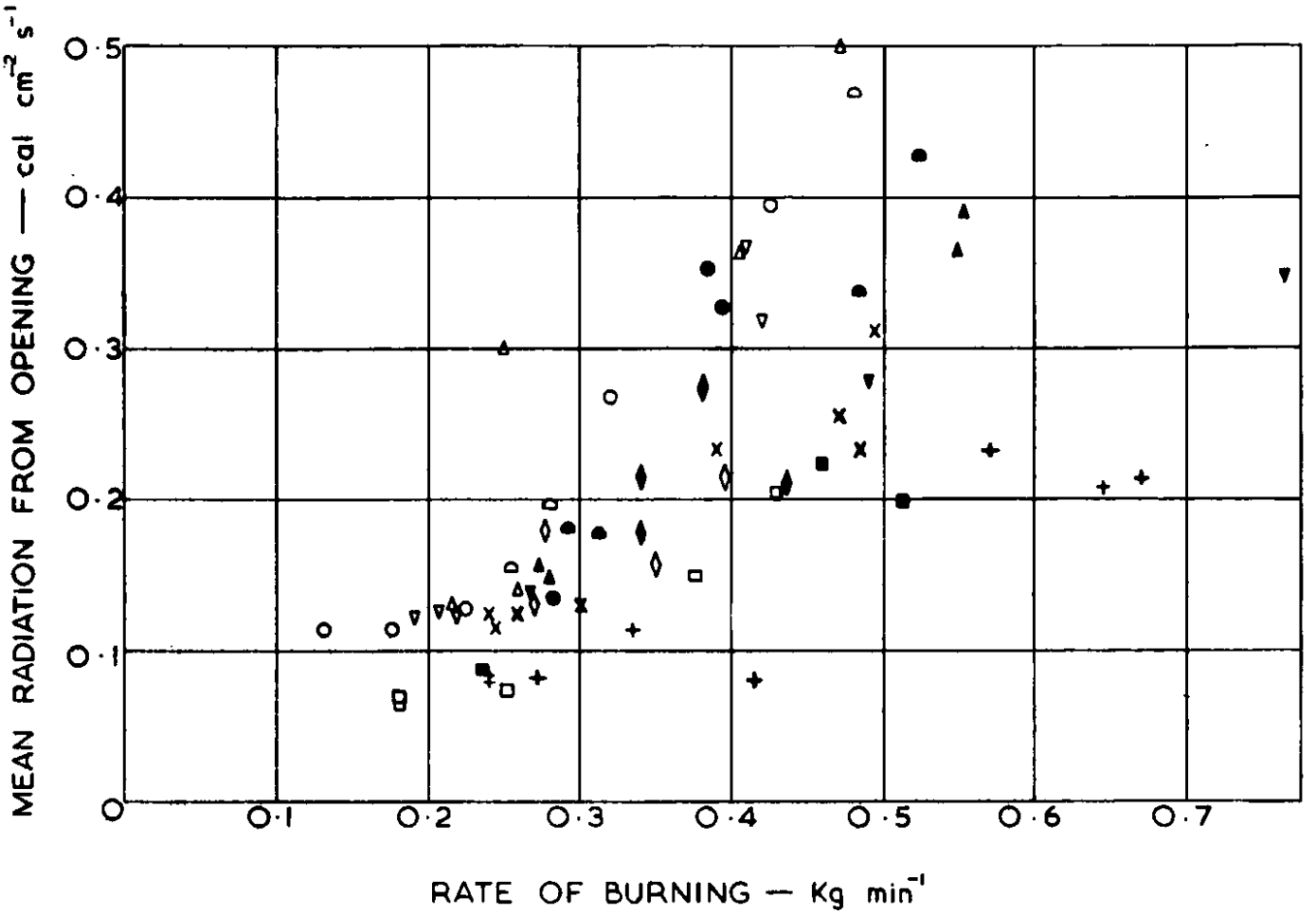


FIG. 1 MAXIMUM CEILING TEMPERATURES



LABORATORY	SPACING	
	1 : 1	1 : 3
U.K.	○	●
U.S.A.	⌓	◠
CANADA	×	✖
BERLIN	□	■
BRAUNSCHWEIG	◊	⧫
KARLSRUHE	+	+
HOLLAND	△	▲
AUSTRALIA	▽	▼

FIG. 2. TEMPERATURE AND BURNING RATE



LABORATORY	SPACING	
	1:1	1:3
U.K	○	●
U.S.A.	▫	▪
CANADA	×	×
BERLIN	□	■
BRAUNSCHWEIG	◊	♦
KARLSRUHE	+	+
HOLLAND	△	▲
AUSTRALIA	▽	▼

FIG. 3. RADIATION AND BURNING RATE

COMPARATIVE TESTS BY THREE LABORATORIES ON A FIRE IN A SMALL SCALE COMPARTMENT

by

P. H. Thomas and P. G. Smith

SUMMARY

Selected statistics from the results obtained by three laboratories for a small-scale compartment fire are analysed. The results are not entirely in agreement.

There is a high correlation between the variations in the mean radiation from the compartment opening and the mean rate of burning which is not the case for the temperature measurements.

May 1961

COMPARATIVE TESTS BY THREE LABORATORIES ON A FIRE IN A SMALL SCALE COMPARTMENT

by

P. H. Thomas and P. G. Smith

Introduction

As a result of finding rather large, and to some extent inexplicable variations between the results obtained by eight C.I.B. laboratories on the same eight tests(1)(2) it was decided by the last C.I.B. Fire Research Working Party, meeting in London, that three laboratories should perform one experiment using three different types of wood in a model of the same construction. The experiment consisted of burning 10 kg of wood in a model $\frac{1}{2}$ m x 1 m x $\frac{1}{2}$ m high with an opening ($\frac{1}{2}$ m x $\frac{1}{2}$ m) at one end of the model. The Joint Fire Research Organization (J.F.R.O), provided the material for the National Bureau of Standards (N.B.S.), and the Nijverheidsorganisatie voor Toegepast Natuurwetenschappelijk Onderzoek (T.N.O) laboratories to construct the experimental model. The National Bureau of Standards provided the glue with which to construct the wood cribs. Each laboratory performed two experiments with wood supplied by themselves and the other two laboratories. Measurements were made of the rate of burning, the radiation from the opening and the flames, and temperatures near the ceiling and the floor(1). Each day's testing was preceded by a fire in the box. This served to reduce the moisture content of the box material.

Results

From the test results the following statistics have been selected:

a) The mean rate of weight loss over the period during which the weight fell from 9 kg to 3 kg, i.e. $R_{90/30}$ and the mean rate for the shorter period when the weight fell from 8 kg to 4 kg $R_{80/40}$.

b) The mean radiation received by a radiometer $\frac{1}{2}$ m in front of the centre of the opening during the longer of the above periods; the maximum radiation and the time at which it occurred.

c) The mean radiation from the flames for the same period; the maximum radiation and the time at which it occurred.

d) The maximum "ceiling" and "floor" temperatures and the time of occurrence.

All these data are given in Table 1*.

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*Since this note was written it has been found that the values of radiation from the opening from the N.B.S. tests given in table 1 should be reduced by a factor of 0.77. This correction does not alter the majority of tables seriously, since these are based on a procedure which corrects for systematic arithmetic differences. There is a small error because the factor of 0.77 is a geometric difference, but its effect is negligible and such tables have not been corrected. Where uncorrected data are listed, this is clearly marked. In some cases, as in Tables 7, 8, 13, and 14, corrections have been made.

Analysis of results.

Mean rate of burning $R_{90/30}$.

The results are given in Table 2.

Table 2

Rate of burning $R_{90/30}$ ~ kg/min.
(The upper value is the first test in each pair.)

Wood	Laboratory J.F.R.O.	Mean	N.B.S.	Mean	T.N.O.	Mean	Mean
J.F.R.O.	0.462 0.433	0.447	0.511 0.502	0.506	- 0.454	0.454	0.469
N.B.S.	0.508 0.526	0.517	0.461 0.473	0.467	0.508 0.477	0.492	0.492
T.N.O.	0.480 0.496	0.488	0.464 0.482	0.473	0.426 0.400	0.413	0.458
Mean	0.484		0.482		0.453		0.473

A statistical analysis shows that the standard deviation σ for the 8 repeats is 0.015 kg/min. This is only 3 per cent of the grand mean value of $R_{90/30}$ which is 0.473 kg/min and implies that single values can generally be relied on. The mean rates for the J.F.R.O., N.B.S. and T.N.O. laboratories respectively are 0.484, 0.482 and 0.453*, each having a standard deviation based on the above σ of 0.006 kg/min. The difference between the largest and smallest of these three means is about 6.5 per cent*. The variation between the mean results for the three woods was also about the same; the differences are small even though significant. However, there is a highly significant interaction between the data for different laboratories and different woods. Thus there is a 20 per cent difference between the largest and smallest mean results 0.517 and 0.413. The means of each row and column represent significant, systematic differences between the data for different woods and laboratories and we can calculate values for each test, or means for each pair of tests, on the assumption that there is no inter-action, i.e. these calculated mean values correspond only to the differences between the row and column means (see Appendix I). The actual results (means for each pair) of Table 2 differ from these calculated means by amounts shown in Table 3, which is based on 0.454 for the missing value.

*This is obtained assuming the missing value was 0.454. A better estimate (see Appendix I) is 0.444 based on 0.396 for the missing value. This mean is about 8.5 per cent below the other two means.

TABLE 1

TEST RESULTS

Wood	Test No.	Time to reach 90per cent initial wt. t_{90}(min)	Time to reach 30per cent initial wt. t_{30}(min)	Rate of burning $R_{90/30}$ (kg/min)	Rate of burning $R_{80/40}$ (kg/min)	Radiation from window			Radiation from flames			Maximum temperature			
						mean 90/30 (cal $cm^{-2}s^{-1}$)	Peak at time (cal $cm^{-2}s^{-1}$)	(min)	mean 90/30 (cal $cm^{-2}s^{-1}$)	Peak at time (cal $cm^{-2}s^{-1}$)	(min)	ceiling at time (°C)	(min)	floor at time (°C)	(min)
J.F.R.O. Laboratory															
J.F.R.O.	20	2.00	15.00	0.462	0.445	0.264	0.338	20	0.180	0.230	5	874	19	962	17.5
"	21	1.70	15.55	0.433	0.407	0.261	0.330	15	0.175	0.200	16	898	18.5	1019	17
N.B.S.	26	3.00	14.80	0.508	0.500	0.315	0.442	18	0.229	0.330	7	915	18	995	19.5
"	27	2.20	13.60	0.526	0.527	0.328	0.442	17	0.273	0.368	7	915	18	980	21.5
T.N.O.	32	3.00	15.50	0.480	0.484	0.304	0.342	12	0.196	0.287	5	895	16	965	16.5
"	33	2.60	14.70	0.496	0.490	0.298	0.338	15	0.210	0.242	15	900	16	941	16.5
N.B.S. Laboratory															
J.F.R.O.	Test 2, Series 1	2.18	13.93	0.511	0.490	0.379	0.437	18	0.222	0.310	4	861	14	866	12
"	Test 2, Series 2	2.33	14.29	0.502	0.486	0.377	0.426	18	0.236	0.350	4	847	14	902	10
N.B.S.	Test 4, Series 1	2.61	15.62	0.461	0.447	0.353	0.463	18	0.227	0.310	4	879	18	981	20
"	Test 4, Series 2	2.83	15.53	0.473	0.457	0.377	0.467	16	0.221	0.273	6	863	16	943	12
T.N.O.	Test 1, Series 1	2.39	15.31	0.464	0.450	0.355	0.400	18	0.197	0.270	4	875	18	939	16
"	Test 1, Series 2	2.62	15.08	0.482	0.474	0.375	0.448	18	0.191	0.280	4	883	16	986	14
T.N.O. Laboratory															
J.F.R.O.	UK.1	3.2	-	-	-	0.281	0.350	20.0	0.272	0.580	20.0	930	18.5	970	16.5
"	UK.2	2.6	15.8	0.454	0.435	0.326	0.375	18.8	0.308	0.392	17.8	930	17.5	1015	15.8
N.B.S.	USA.1	2.6	14.4	0.508	0.503	0.344	0.445	15.6	0.353	0.520	15.8	905	16.2	1035	13.6
"	USA.2	2.3	14.9	0.477	0.455	0.339	0.445	15.8	0.353	0.530	15.1	930	16.0	1060	17.1
T.N.O.	N.1	2.7	16.8	0.426	0.413	0.289	0.340	16.5	0.296	0.360	16.8	910	16.8	975	16.0
"	N.2	2.7	17.7	0.400	0.384	0.293	0.342	18.0	0.290	0.350	20.6	925	18.0	970	16.5

For radiation from opening N.B.S. data uncorrected.

TABLE 3

Differences from $R_{90/30}$ values (means for each pair) corresponding to average differences between laboratories and woods.

Wood	Laboratory		
	J.F.R.O.	N.B.S.	T.N.O.
J.F.R.O.	- 0.033	0.028	0.004
N.B.S.	0.014	- 0.034	0.020
T.N.O.	0.019	0.006	- 0.025

The interesting feature emerges that each laboratory, while somewhat biased with respect to the others has, in addition to this bias, measured its own wood at a slightly lower rate relative to the other woods. The repeat tests for each wood do not show a significant trend in the eight pairs of results available, four show an increase from the first to second test and four show a decrease.

The same conclusions obtain in an analysis of $R_{80/40}$, and in the rate of burning over a small time interval near the maximum rate of burning.

Order of testing.

The three laboratories tested the three woods in a different order. N.B.S. included two other tests in their series but for purposes of a tentative examination of the effect of testing order these are neglected.

We construct the table showing differences between actual measured rates of burning and the values expected from the means over laboratories and woods (Table 4). For the purpose of this analysis we take the missing T.N.O. result as 0.396 (see Appendix I).

Table 3 gives, in principle, the mean of each pair of the differences in Table 4. The values do not agree exactly because the "missing" T.N.O. value was taken as 0.454 originally.

TABLE 4

Differences from $R_{90/30}$ values expected from laboratory (column) and wood (row) means.

Wood	Laboratory					
	J.F.R.O.		N.B.S.		T.N.O.	
	Differences	Order of testing	Differences	Order of testing	Differences	Order of testing
J.F.R.O	- 0.012 - 0.041	1 2	0.039 0.030	2 5	- 0.037 0.021	3 4
N.B.S.	0.002 0.020	3 4	- 0.043 - 0.031	3 6	0.042 0.012	5 6
T.N.O.	0.008 0.024	5 6	- 0.006 0.012	1 4	- 0.005 - 0.032	1 2

An analysis of variances, disregarding the wood factor, shows no significant effect of order, though in the case of the J.F.R.O. and T.N.O. laboratories the linear component of the variation with order of testing is nearly significant at the 5 per cent level. This is not enough support for the view that the interaction arises from some effect such as ageing of the box which would result in an effect of the order in which the tests were done.

Variations in ignition.

If the ignition were not reproducible we might expect the rate of growth of fire to vary between the tests - this might be correlated with the differences in mean burning rates.

An analysis has been made of times taken for the weight of fuel to fall to 90 per cent of its initial value. No significant systematic variation between laboratories or woods or interactions was found. This suggests that the method of ignition is satisfactory and does not lead to systematic error.

Analysis of radiation from opening.

The results are summarised in Table 5 for the 90/30 period.

TABLE 5
Radiation from opening (90/30) cal $cm^{-2}s^{-1}$
(Extracted from Table 1, with N.B.S. data corrected by 0.77)

Wood	Laboratory J.F.R.O.	Mean	N.B.S.	Mean	T.N.O.	Mean	Mean
J.F.R.O.	0.264 0.261	0.262	0.292 0.290	0.291	0.281 0.326	0.303	0.286
N.B.S.	0.315 0.328	0.321	0.272 0.290	0.281	0.344 0.339	0.341	0.314
T.N.O.	0.304 0.298	0.301	0.273 0.288	0.280	0.289 0.293	0.291	0.291
Mean	0.295		0.284		0.312		0.297

The N.B.S. data were obtained with an unenclosed disc radiometer. The radiometers used by J.F.R.O. and T.N.O. were enclosed to minimise convection effects. The standard deviation for all repeats was 0.0125; the standard deviation for all repeats excluding the T.N.O. tests on J.F.R.O. wood, where the variation between repeats was larger than in any other case, was 0.007.

There are in these results significant differences between laboratories and woods and there is also a significant interaction. If, as for the rate of burning data, we calculate the difference between the actual mean for any pair of repeated tests and the mean expected assuming no interaction, we obtain the following table (Table 6).

TABLE 6

Differences from opening radiation values expected from laboratory (column) and wood (row) means, (mean of each pair).

Wood	Laboratory J.F.R.O.	N.B.S.	T.N.O.
J.F.R.O.	- 0.022	0.020	0.002
N.B.S.	0.009	- 0.021	0.012
T.N.O.	0.012	0.002	- 0.015

Based on uncorrected data. Correction only affects third place of decimals to ±1.

There is the same feature as in the rate of burning data - a low value when a laboratory tests its own wood.

Table 3 has been derived on the assumption that the missing value in Table 2 was 0.454, the same as the other test of that pair, but in view of the correlation between the two sets of data and the fact that for this pair the difference between the mean radiation values was greater than in any other pair of tests, some correction is needed and we can use the correlation to establish it. The procedure is given in Appendix 1 in which it is deduced that the best value for the missing result is 0.396 ± 0.023. The correlation between the radiation and rate of burning results, after allowance has been made for systematic variations between laboratories and woods, is better than 0.1 per cent significant and the best value of the statistical line, treating rate as the independent variable, has a slope of 0.61 with a σ of 0.1 in the original units.

We have thus established a very useful proportionality between the variation in radiation from an enclosure and the variation in rate of burning in it. This result has been obtained by correction for the slight average systematic biases between different radiometers and measurements of weight loss, for the different laboratories and different woods. The results are shown graphically in Fig.1. The abscissae are the values in Table 4. The ordinates are from a Table not shown, but derived from Table 5.

If the original results are averaged over all laboratories we obtain the following data, where it is seen that the fourth column gives values similar to those deduced above.

TABLE 7

Mean radiation and rate of burning averaged over all laboratories

Wood	Mean radiation	Mean rate of burning (0.396 for missing value)	$i_o = \frac{\text{radiation}}{\text{rate of burning}}$
J.F.R.O.	0.286	0.460	0.617
N.B.S.	0.314	0.492	0.638
T.N.O.	0.291	0.458	0.636

Analysis of quantity i_o (radiation per unit rate of burning).

An alternative approach to the analysis is to estimate "i", the ratio of measured mean radiation to measured mean rate of burning, for each pair of data, the suffix "o" denoting opening. These are shown in Table 8 for the 90/30 period, the figures listed being 100 i_o in original units.

TABLE 8

Radiation per unit rate of burning.

Wood	Laboratory		
	J.F.R.O.	N.B.S.	T.N.O.
J.F.R.O.	57 60	57 58	71 72
N.B.S.	62 62	59 61	68 71
T.N.O.	63 60	59 60	68 73

Correcting for the fact that the radiation unit is cal $cm^{-2}s^{-1}$ and the weight unit is kg min^{-1}, the ratio i_o of radiation to weight loss rate is 36.5×10^{-3} cal $cm^{-2}g^{-1}$ for the J.F.R.O. laboratory data (38×10^{-3} for all three laboratories). The configuration factor of the radiometer with respect to the opening is 0.24 and there is an approximate 10 per cent reduction necessary to allow for the flame radiation received by the radiometer opposite the opening, so that with respect to the radiation level in the enclosure, the value of the ratio is approximately 0.14 cal $cm^{-2}g^{-1}$. This may be compared* with the value of approximately 400 cal/g deducible from the results obtained by Webster et al for cubical enclosures (3), with various amounts of fuel in the form of a crib. In Webster's experiments it was this quantity, based on the cube side (floor or window) area, not cal $g^{-1}cm^{-2}$ that was independent of scale, so the question arises of which area we must take to reduce our figure of 0.14 cal $g^{-1}cm^{-2}$ to a value independent of scale. The ratio of these two quantities is

$$\frac{400}{0.14} = 2900 \text{ cm}^2$$

which is nearer the window opening of 2500 cm^2 than the floor area 5000 cm^2 (for Webster's experiments these were the same). The value for these C.I.B.tests of L, where $L = \frac{\text{radiation flux within enclosure x window area}}{\text{rate of burning}}$, is 350 cal/g. Based on floor area L would be 700 cal/g. L may be expected to depend on the design of the crib. The experiments on which these figures are based are biased towards fires in which the rate of burning is no longer controlled by the air flow into the window, so one would expect the rate of burning to be controlled by the heat flux to the fuel bed. Further experiments are necessary to decide definitely whether floor or window area is more appropriate. A tentative justification for window area is that the radiating area of the flame zone is more nearly the window area than the floor (or ceiling) area.

Mean radiation from flames.

The mean levels of radiation from the flames over the 90/30 period of weight loss are shown in Table 9.

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*Since the maximum burning rates have not been evaluated for this series of C.I.B. tests, the comparison is between $\frac{\text{mean radiation from the opening}}{\text{mean burning rate}}$ for these tests and $\frac{\text{maximum radiation from opening}}{\text{maximum burning rate}}$ from Webster's results. Although the maximum values may occur at different times for the two measurements, this discrepancy is too small to affect the conclusions drawn from this comparison.

TABLE 9

Mean radiation (90/30) from flames in cal $cm^{-2}s^{-1}$
(mean of each pair - see Table 1).

Wood	Laboratory			
	J.F.R.O.	N.B.S.	T.N.O.	Mean
J.F.R.O.	0.177	0.229	0.290	0.232
N.B.S.	0.251	0.224	0.353	0.276
T.N.O.	0.203	0.194	0.293	0.230
Mean	0.210	0.216	0.312	0.246

The standard deviation for a single result based on the repeat tests is 0.014. The interaction and main effects are significant with respect to the variation between repeats. We proceed as before and from the mean value of each column and the mean for each row, we obtain expected values, i.e. values giving no interaction. The differences between the measured means and these "expected" means are given in Table 10.

TABLE 10

Differences from mean flame radiation values expected from laboratory (column) and wood (row) means.

Wood	Laboratory		
	J.F.R.O.	N.B.S.	T.N.O.
J.F.R.O.	- 0.019	0.027	- 0.008
N.B.S.	0.011	- 0.022	0.011
T.N.O.	0.009	- 0.006	- 0.003

These are highly correlated with the differences in Table 3 (see Fig.2 and Appendix 1).

Analysis of quantity i_f = flame radiation per unit rate of burning.

For the flame radiation the ratios 100 i_f are as in Table 11.

TABLE 11

Mean flame radiation per unit rate of burning.

Wood	Laboratory		
	J.F.R.O.	N.B.S.	T.N.O.
J.F.R.O.	39 41	43 47	68 68
N.B.S.	45 52	49 47	70 74
T.N.O.	41 42	43 40	70 72

The variations between laboratories and between woods are significant. Clearly the very large difference between the T.N.O. results and the others shows that the mean value evaluated is subject to considerable variation

between laboratories which presumably arises from the radiation instrumentation.

For the J.F.R.O. laboratory data $i_f = 0.43$ in original units which is equivalent to 26×10^{-3} cal $cm^{-2}g^{-1}$. Webster's result for three sizes of cube was 90 cal g^{-1} and the ratio of these two quantities is 3500 cm^2. This is not obviously in better agreement with window area (2500 cm^2) than floor area (5000 cm^2).

The two sets of data were obtained with different systems of measurement which, as we have seen comparing the results for the three laboratories, produce considerable variation. We conclude that there is a linear variation between flame radiation and rate of burning, but are not able to quote a definite value until the ambiguities in the flame radiation measurements are resolved.

Peak radiation from opening.

The peak values of radiation from the opening are given in Table 12.

TABLE 12

Peak opening radiation cal $cm^{-2}s^{-1}$.
(Extracted from Table 1 - the N.B.S. data corrected by 0.77.)

Wood	Laboratory J.F.R.O.	Mean	N.B.S.	Mean	T.N.O.	Mean	Mean	Ratio to 90/30 radiation
J.F.R.O.	0.338 0.330	0.334	0.337 0.328	0.333	0.350 0.375	0.367	0.345	1.21
N.B.S.	0.442 0.442	0.442	0.357 0.360	0.358	0.445 0.445	0.445	0.415	1.32
T.N.O.	0.342 0.338	0.340	0.308 0.345	0.327	0.340 0.342	0.341	0.336	1.15
Mean	0.372		0.339		0.384			
Ratio to 90/30 radiation	1.26		1.20		1.23			

The ratio of the row and column means to the corresponding values for mean radiation are shown next to each mean.

The arithmetic differences between peak and mean 90/30 radiation are given in Table 13.

TABLE 13

Difference between peak and mean radiation.

Wood	Laboratory J.F.R.O.	N.B.S.	T.N.O.	Mean
J.F.R.O.	0.072	0.042	0.064	0.059
N.B.S.	0.121	0.077	0.104	0.101
T.N.O.	0.039	0.046	0.050	0.045
Mean	0.077	0.055	0.072	

There are differences between the laboratories and the N.B.S. wood has a greater difference between the peak and mean radiation reflecting a real difference in the behaviour of this wood from the other two. This is clearly seen in the original radiation/time data. This may be associated with the greater ratio of mean flame radiation to burning rate than in the other two woods.

Evaluating differences between measured peak radiation and that expected from the averaging process also shows the same type of interaction as do the rates of burning data.

Radiation instrumentation

If we take the mean over the three woods for the opening radiation and the flame radiation, we can compare the radiations measured by the three laboratories. These are shown in Table 14.

TABLE 14.

Radiation averaged over woods - cal $cm^{-2}s^{-1}$

		Laboratory		
		F.J.F.R.O.	N.B.S.	T.N.O.
Radiation from opening	mean	0.295	0.284	0.312
	max.	0.372	0.339	0.384
	max/mean	1.26	1.20	1.23
Radiation from flames	mean	0.210	0.216	0.312
	max.	0.276	0.299	0.422
	max/mean	1.31	1.38	1.35
$\frac{\text{mean flame radiation}}{\text{mean opening radiation}}$		0.71	0.76	1.00

The consistency of the ratios of max/mean between laboratories is a reflection of consistent fire behaviour not of instrumentation. The T.N.O. radiometer for measuring the flame radiation appears to read high with respect to the other two (see also Table 9).

Ceiling temperatures

The peak ceiling temperatures in °C are given in Table 15.

TABLE 15

Peak ceiling temperatures - °C

Wood	Laboratory			Mean
	J.F.R.O.	N.B.S.	T.N.O.	
J.F.R.O.	874 898	861 847	930 930	890
N.B.S.	915 915	879 863	905 930	901
T.N.O.	895 900	875 883	910 925	898
Mean	900	868	922	896

An analysis of variance shows only the variation between laboratories to be significant, the standard deviation is 13.4 °C. There is no correlation of temperature differences with rate of burning differences nor with peak nor mean radiation from the opening.

Allowing for measured systematic differences between woods and laboratories gives a set of data which can be plotted against the equivalent data for peak radiation and this is shown in Fig. 3. There is no systematic correlation such as might be expected from the nature of the measurements involved.

No attempt has been made to identify peak burning rates, but since peak and mean radiation from the opening and mean burning rate are highly correlated, it follows that it is unlikely that peak burning rates and peak ceiling temperatures are closely correlated, although the means for each laboratory are in the same order as are the radiation measurements.

Floor temperatures

The results are shown in Table 16.

TABLE 16

Peak floor temperatures - °C

Wood	Laboratory			Mean
	J.F.R.O.	N.B.S.	T.N.O.	
J.F.R.O.	962 1019	866 902	970 1015	956
N.B.S.	995 980	981 943	1035 1060	999
T.N.O.	965 941	939 986	975 970	963
Mean	977	936	1004	973

An analysis of variance shows a significant laboratories x woods interaction. Following the procedure described above for ceiling temperatures one finds a similar result, namely, this interaction does not correlate with peak radiation nor mean rate of burning.

Therefore, there appears to be little significance in the temperature measurements which might have been expected on physical grounds to be correlated with radiation if not rate of burning.

Conclusions.

(1) The variation between repeat values on all measurements is, with an occasional exception, very small.

(2) There is no significant correlation between variations in temperature measurements and observations of rate of burning and radiation.

(3) There is a systematic effect that each country has underestimated the burning rate of its own wood when allowance has been made for the systematic differences between laboratories and woods. This difference is rather too large to be tolerated. No explanation has yet been confirmed. It is reflected in differences between the radiation measurements.

(4) One can deduce a value of 0.038 cal $cm^{-2}g^{-1}$ for the variation in radiation at the standard position from the opening corresponding to variation in the rate of burning. It has been suggested that, multiplied by the window area, this gives an important property of the fire.

(5) The N.B.S. wood showed a larger difference between peak and mean radiation than did the other two woods.

(6) There are noticeable differences between the radiometers used by the three laboratories.

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Appendix 1

Correlation of mean opening radiation and mean rate of burning.

In many of the examinations of data in this report we first need to eliminate systematic differences between woods and laboratories which arise from slight differences in instrumentation and woods.

By summing over all woods (rows) we get the mean result for each laboratory (column). We deduct (or add) to each of the six results in any column, a quantity (constant for each column) that makes the mean for each column equal to the grand mean. We repeat this for each wood (row) summing over all laboratories. By this means the individual results are adjusted linearly so that the three laboratory means over all woods and the three wood means over all laboratories are equal to the grand mean. This gives an "expected" value after systematic differences between laboratories and woods have been allowed for. We deduct each value from the measured value and obtain eighteen differences or nine mean differences.

This procedure can be done directly by reducing linearly all row and column totals to zero. An abbreviated description of this procedure is given for the mean flame radiation.

TABLE 17

Mean flame radiation - cal $cm^{-2}s^{-1} \times 10^{-3}$.

Wood	Laboratory J.F.R.O.	N.B.S.	T.N.O.
J.F.R.O.	180 175	222 236	272 308
N.B.S.	229 273	227 221	353 353
T.N.O.	196 210	197 191	296 290
Mean	210	216	312

Deduct 210, 216, 312 from each result in the three columns respectively, and obtain Table 18.

TABLE 18

Second stage in evaluating differences between "expected" values of mean flame radiation and measured values.

Wood	Laboratory J.F.R.O.	N.B.S.	T.N.O.	Totals	Mean
J.F.R.O.	- 30 - 35	6 20	- 40 - 4	- 83	- 14
N.B.S.	19 63	11 5	41 41	180	30
T.N.O.	- 14 0	- 19 - 25	- 16 - 22	- 96	- 16
Totals	3	- 2	0	1	

Add 14 to each result in the top row, deduct 30 in the middle row, and add 16 in the bottom row, and hence obtain Table 19.

TABLE 19

Differences between "expected" values of mean flame radiation and measured values based on wood and laboratory means.

Wood	Laboratory			Totals
	J.F.R.O.	N.B.S.	T.N.O.	
J.F.R.O.	- 16 - 21	20 34	- 26 10	1
N.B.S.	- 11 33	- 19 - 25	11 11	0
T.N.O.	2 16	- 3 - 9	0 - 6	0
Totals	3	- 2	0	

The residual row and column totals can be partitioned but to simplify the arithmetic the resulting fractions have been neglected.

The results in Table 10 are the arithmetic means of these pairs and are appropriate to the means of the original pairs of results. Tables 3 and 6 are other examples where only the nine mean differences are given. The sum of the squares of the numbers in Table 19 is a direct measure of the interaction variance (laboratories x woods) for the original data.

In the case of the rate of burning, there is a missing value which is denoted by a symbol "y", say. The results in the table (not given) corresponding to Table 19 are linear functions of y. The results in the corresponding table for the opening radiation (not given, though Table 6 gives the mean for each pair of results) were then correlated directly with this data - the correlation and regression coefficients being a function of y. This correlation coefficient was evaluated * as

$$r = \frac{7730 - 394\alpha}{\sqrt{5866}\sqrt{12753 - 1220\alpha + 234\alpha^2}}$$

$$\text{where } \alpha = \frac{1000y - 400}{18}$$

r is a maximum when $\alpha_m = -0.20$ i.e. when $y = 0.396$.

Using the binomial theorem for small α we obtain

$$r = 0.895\ (1 - 0.0030\alpha - 0.008\alpha^2)$$

This approximate form gives the value of α_m as - 0.19. Clearly, over a wide range of α, r is highly significant. The degrees of freedom in this correlation are 11. In a table of 18 results in which the row and column totals are fixed, there are 12 degrees of freedom and deducting one for the missing value gives 11 as the degrees of freedom.

* Based on uncorrected N.B.S. radiation data. The 0.77 correction is so nearly a simple linear difference and hence a systematic one, that little change would be necessary.

The expression for the regression coefficient of radiation on rate of burning is

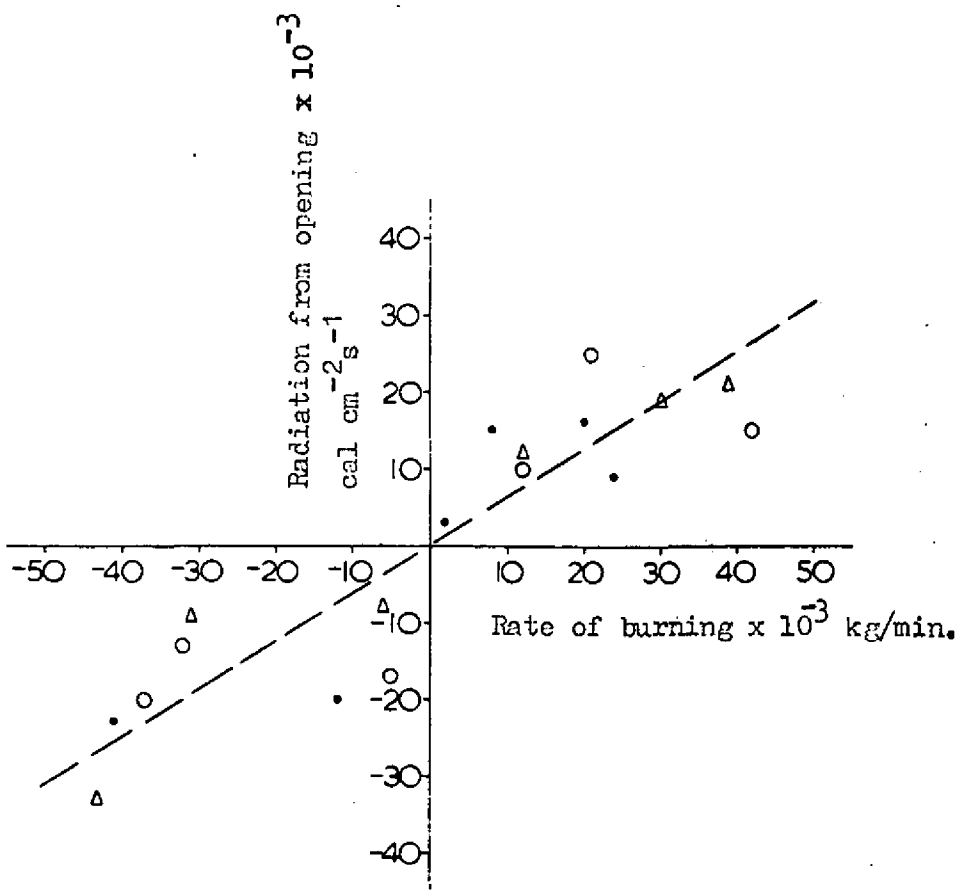
$$b = \frac{7730}{12753} \left(1 + 0.041 \alpha - 0.014 \alpha^2 \right).$$

Neglecting α the value of σ^2 is $\frac{5866 (1 - r^2)}{11} \times 10^{-6} = 104 \times 10^{-6}$.
The confidence limits for one observation are $\pm t\sigma$, or $\pm$ 0.023 at the 95 per cent level, so that the likely range of y is 0.373 (α = - 1.5) to 0.419 (α = 1). Neglecting α, b = 0.61. With α = + 1, b = 0.63 and with α = - 1.5, b = 0.55.

The confidence limits of the slope b obtained by treating α as zero are $\pm t \sigma_{slope} = \pm$ 0.2.

A best line drawn on a graph without a definite choice as to which is the dependent variable will tend to be at a slope larger than 0.61 viz 0.76.

In correlating other quantities such as mean flame radiation with rate of burning, the missing value was taken as 0.396 kg/min. For mean flame radiation the correlation coefficient was 0.850 and the regression of radiation on rate 0.575, the 95 per cent confidence limits being $\pm$ 0.24. The ratios obtained for each wood taken separately were 0.50 for the J.F.R.O. and T.N.O. woods (both were spruce) and 0.56 for the N.B.S. wood.



Line having same slope as $\frac{\text{grand mean radiation}}{\text{grand mean rate}} = 0{\cdot}63$

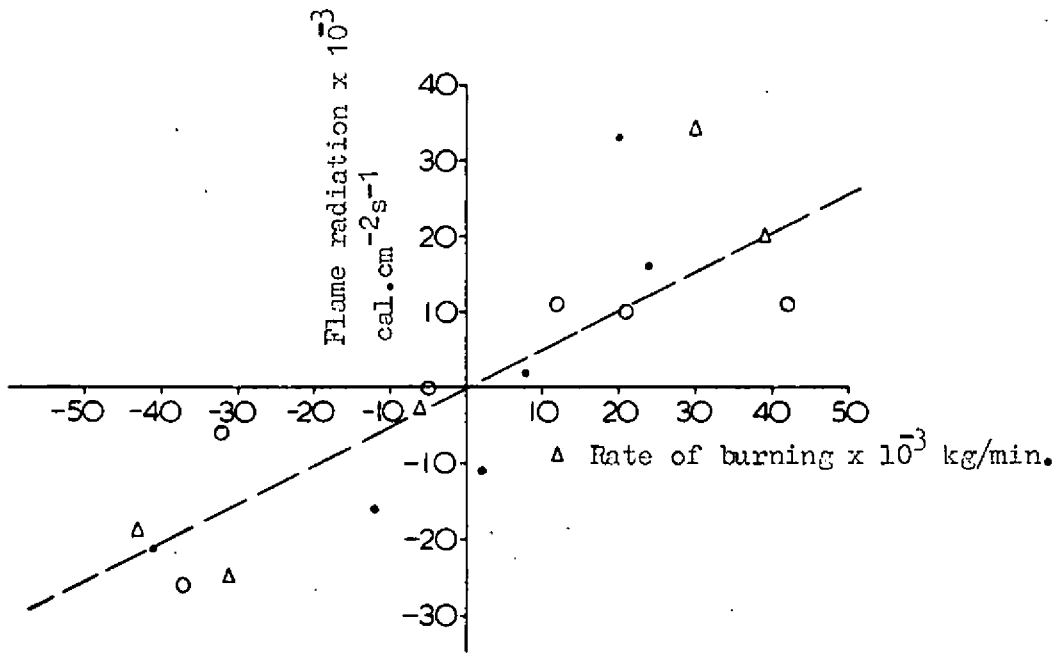
(Best regression through points is 0·61)

• — J.F.R.O. data

Δ — N.B.S. data

o — T.N.O. data

FIG. 1. RADIATION FROM OPENING AND RATE OF BURNING (90/30 PERIOD)



$$\frac{\text{grand mean flame radiation}}{\text{grand mean rate}} = 0{\cdot}52$$

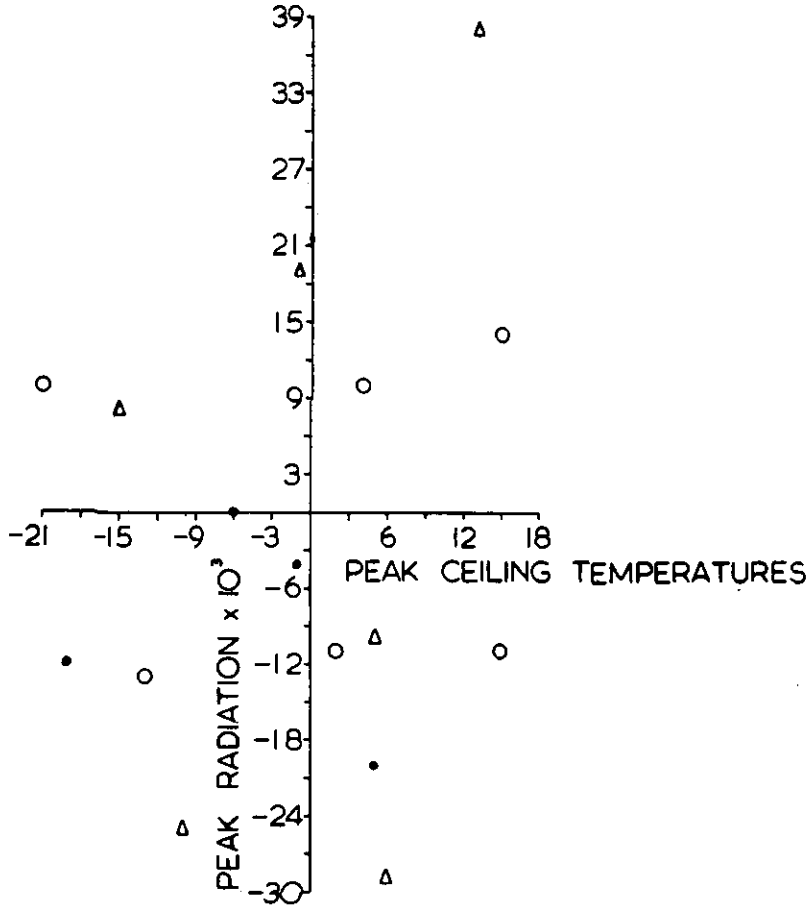
'Best' line through points has slope of 0·575

• — J.F.R.O. data

Δ — N.B.S. data

o — T.N.O. data

FIG. 2. FLAME RADIATION AND RATE OF BURNING (90/30 PERIOD)



• — J.F.R.O. data

Δ — N.B.S. data

o — T.N.O. data

FIG. 3. NO CORRELATION BETWEEN TEMPERATURE AND RADIATION

PROPOSALS FOR NEXT STAGE OF C.I.B. PROGRAMME ON FIRES IN COMPARTMENTS

by

P. H. Thomas, Mrs. Jane Hather and P. G. Smith

SUMMARY

A design for the main programme is proposed in which there is some replication of certain tests ("Series 1") between laboratories to permit laboratory biases to be measured and if necessary allowed for. This is necessary since it has not been found practicable to reduce variation sufficiently by close specification of experimental conditions.

The design is also shown in a tabular form.

September 1961

PROPOSALS FOR NEXT STAGE OF C..I. B. PROGRAMME ON FIRES IN COMPARTMENTS

by

P. H. Thomas, Mrs. J. Mather and P. G. Smith

1. At the last meeting of the C.I.B. Working Party proposals were made for allocating various parts of the next phase of the joint programme between the various participating laboratories.

2. These proposals were conditional on the results of the preliminary tests being satisfactory. In view of the actual results obtained in the two preliminary series of tests:-

(i) the eight tests by eight laboratories [1] [2]

(ii) the restricted programme by three laboratories [3]

some changes are desirable in the programme originally proposed.

3. In that programme there were some tests which were done by two laboratories i.e., Experimental Group (2) (Australia) and Experimental Group (4) (Germany) were both to perform experiments on ½m and 1m scale on shape (211) with a stick spacing of (2.1). There were similar links between other pairs of laboratories, but there were no tests common to all laboratories. In view of the unexplained discrepancies found in the preliminary tests we suggest that the number of these sets of common tests between one laboratory and the others should be increased, even at the expense of some of the simplicity of the scheme as a whole, if the scheme is not to be postponed until these difficulties are resolved. In this revised scheme some tests are repeated by each laboratory to provide a measure of experimental variation.

Experiments allocated to Germany 1 were carried out by B.A.M., Berlin, and those allocated to Germany 2 and 3 by F.F.B., Karlsruhe.

4. The scheme is given in Table 1. Series 1 consists of eight tests each repeated, making sixteen. On this series of repeats is based the estimate of experimental variation and also, because of the links between the tests of one laboratory and another, it is this series which enables a common standard between laboratories to be found. The majority of tests are on the 1m scale but sufficient tests on ½ in and 1½ in scale are planned to find scale effects.

5. The conditions for this scheme are more restricted than before.

It is now almost essential that nine laboratories participate, but any additional participants could of course undertake other tests in part of the original programme not included in this phase of the work. It is highly desirable that at least the tests of the first series conducted in any one laboratory be done in a randomised order. This slightly increases the complications of the experimental procedure but should improve the reliability of the resulting information considerably. Details are given in Table 2.

6. To minimise the risk of avoidable errors in instrumentation, choice of equipment etc, it is desirable that all laboratories first of all perform a small number of tests nominally identical with those which the National Bureau of Standards, Nijverheidsorganisatie Voor Toegepast Natuurweternschappelijk Onderzoek and the Joint Fire Research Organization have already done. This would consist of a ½ m model of shape (121) burning 10 kg of wood (20 kg/m^2) of 2 cm sticks spaced (1.3.) The box material should be as near to the following specification as possible: weight 90 lb cu. ft (1.5 gm/cc), thermal conductivity 8.5 x 10^{-4}c.g.s. and the wood a spruce of density 27 lbs/cu.ft (0.43 gm/cc) and these should be the materials chosen for the subsequent tests.

TABLE 1

Laboratory and Series	Shape	Scale	Fireload	Ventilation	Stick spacing combinations	Repeats	No. of tests	Total
Holland 1	211	1	20.40	$\frac{1}{4}$.1	(2.1)	2		
	121	1	20.40	$\frac{1}{4}$.1	(2.1)	2	16	
2	121	1	20.30.40	$\frac{1}{4}$.1	(2.$\frac{1}{3}$) (4.1) (1.3) (2.3)	1		
	121	1	30	$\frac{1}{4}$.1	(2.1)	1	26	
	121	$\frac{1}{2}$	20	$\frac{1}{4}$.$\frac{1}{2}$.1	(2.$\frac{1}{3}$) (2.1) (4.1) (1.3) (2.3)	1	15	57
Australia 1	121	1	20.40	$\frac{1}{4}$.1	(2.1)	2		
	221	1	20.40	$\frac{1}{4}$.1	(2.1)	2	16	
2	221	1	20.30.40	$\frac{1}{4}$.1	(2.$\frac{1}{3}$) (4.1)	1		
	221	1	30	$\frac{1}{4}$.1	(2.1)	1	14	
	221	$\frac{1}{2}$	20	$\frac{1}{4}$.$\frac{1}{2}$.1	(2.$\frac{1}{3}$) (2.1) (4.1)	1	9	39
Japan 1	221	1	20.40	$\frac{1}{4}$.1	(2.1)	2		
	211	1	20.40	$\frac{1}{4}$.1	(2.1)	2	16	
2	211	1	20.30.40	$\frac{1}{4}$.1	(2.$\frac{1}{3}$) (4.1)	1		
	211	1	30	$\frac{1}{4}$.1	(2.1)	1	14	
	211	$\frac{1}{2}$	20	$\frac{1}{4}$.$\frac{1}{2}$.1	(2.$\frac{1}{3}$) (2.1) (4.1)	1	9	39
Germany (1)† 1	211	1	20.40	$\frac{1}{4}$.1	(2.1)	2		
	221	1	20.40	$\frac{1}{4}$.1	(2.1)	2	16	
2	221	1	20.30.40	$\frac{1}{4}$.1	(1.3) (2.3)	1		
	221	1	30	$\frac{1}{4}$.1	(2.1)	1	14	
	221	$\frac{1}{2}$	20	$\frac{1}{4}$.$\frac{1}{2}$.1	(1.3) (2.1) (2.3)	1	9	39
France 1	121	1	20.40	$\frac{1}{4}$.1	(2.1)	2		
	211	1	20.40	$\frac{1}{4}$.1	(2.1)	2	16	
2	211	1	20.30.40	$\frac{1}{4}$.1	(1.3) (2.3)	1		
	211	1	30	$\frac{1}{4}$.1	(2.1)	1	14	
	211	$\frac{1}{2}$	20	$\frac{1}{4}$.$\frac{1}{2}$.1	(1.3) (2.1) (2.3)	1	9	39

† Experiments allocated to Germany (1) were carried out by B.A.M., Berlin, and those allocated to Germany (2) and (3) by Forschungsstelle für Brandschutztechnik, Karlsruhe.

TABLE 1 (Cont'd)

Laboratory and Series	Shape	Scale	Fireload	Ventilation	Stick spacing combinations	Repeats	No. of tests	Total
Germany (2)† 1	221	1	20.40	$\frac{1}{4}$.1	(2.1)	2		
	121	1	20.40	$\frac{1}{4}$.1	(2.1)	2	16	
2	221	1	20.40	$\frac{1}{2}$	(2.1)	1	2	
	121	1	20.40	$\frac{1}{2}$	(2.1)	1	2	
	211	1	20.40	$\frac{1}{4}$.$\frac{1}{2}$.1	(2.1)	1	6	
	221	1	30	$\frac{1}{4}$.$\frac{1}{2}$.1	(2.1)	1	3	
	121	1	30	$\frac{1}{4}$.$\frac{1}{2}$.1	(2.1)	1	3	
	211	1	30	$\frac{1}{4}$.$\frac{1}{2}$.1	(2.1)	1	3	35
* 1	221	1	20.40	$\frac{1}{4}$.1	(2.1)	2		
	121	1	20.40	$\frac{1}{4}$.1	(2.1)	2	16	
2	121	$1\frac{1}{2}$	20.30.40	$\frac{1}{4}$.1	(2.$\frac{1}{3}$) (2.1) (4.1) (1.3) (2.3)	1	30	46
U.S.A. 1	211	1	20.40	$\frac{1}{4}$.1	(2.1)	2		
	221	1	20.40	$\frac{1}{4}$.1	(2.1)	2	16	
2	221	$1\frac{1}{2}$	20.30.40	$\frac{1}{4}$.1	(2.$\frac{1}{3}$) (2.1) (4.1) (1.3) (2.3)	1	30	46
Germany (3)† 1	121	1	20.40	$\frac{1}{4}$.1	(2.1)	2		
	211	1	20.40	$\frac{1}{4}$.1	(2.1)	2	16	
2	211	$1\frac{1}{2}$	20.30.40	$\frac{1}{4}$.1	(2.$\frac{1}{3}$) (2.1) (4.1) (1.3) (2.3)	1	30	46
J.F.R.O.	111 121 211 221	$\frac{1}{2}$	30	$\frac{1}{4}$.$\frac{1}{2}$.1	(2.1)	Two wind speeds in three directions		72
	441	$1\frac{1}{2}$.$\frac{1}{2}$	20.30.40	$\frac{1}{4}$.$\frac{1}{2}$.1	(2.1)	Still air		18

* These experiments were allocated to a laboratory which was eventually not able to participate.

TABLE 2

Order of testing for Series 1

The number or letter given to a test is defined by the following table:-

Test	1	2	3	4	5	6	7	8	9	0	X	Y
Shape	221	121	211	221	121	211	221	121	211	221	121	211
Fireload	20	20	20	40	40	40	20	20	20	40	40	40
Ventilation	½	½	½	½	½	½	1	1	1	1	1	1

Laboratory	Order of tests	
	First Set	Second Set
Holland	8 6 9 3 X Y 5 2	2 Y 8 5 9 X 6 3
Australia	7 X 1 0 8 5 2 4	0 8 4 5 1 X 2 7
Japan	0 4 1 9 3 Y 6 7	3 4 7 9 1 Y 6 0
Germany (1)	9 7 Y 6 1 3 4 0	7 4 1 3 6 Y 9 0
France	3 Y X 2 8 5 9 6	5 9 2 X 8 Y 3 6
Germany (2)	2 0 4 1 5 7 X 8	4 2 7 1 8 X 0 5
*	X 0 8 4 1 2 7 5	0 8 1 5 4 2 X 7
U.S.A.	5 6 X 3 Y 9 2 8	5 Y 2 3 6 9 8 X
Germany (3)	1 7 4 0 6 3 Y 9	Y 1 0 9 6 3 7 4

* Experiments allocated, but not carried out.

If this one test is repeated two or three times (3-4 tests in all) it will be possible to compare the results directly with those of the 18 tests by three laboratories using 3 woods (two of which were spruce) and this would provide a reference standard for

(a) the particular construction of box material and wood,

(b) the radiometers and weighing apparatus.

Combination of box material and wood giving results not substantially different from the best available results could then be employed in the tests proper.

7. In reporting results it is suggested that each laboratory evaluate certain statistics prior to correlating their detailed results. This would save considerable labour for any laboratory wishing to analyse data. If, subsequently, other statistics are thought to be important then the original records can, of course, be used.

The statistics suggested are R80/55, R55/30, I_o80/55, I_o80/55, I_o55/30, I_f80/55, I_f55/30, θ_b80/55, θ_b55/30, θ_c80/55, θ_c55/30 and t_{80}. R is rate of weight loss in kg/min. I is intensity of radiation cal $cm^{-2}s^{-1}$ and θ is temperature, t_{80} is time from ignition to time when weight is 80 per cent of its initial value. 80/55 denotes mean value between the times when the initial weight has fallen from 80 per cent of its initial value to 55 per cent of its initial value and 55/30 denotes a similar mean between 55 per cent and 30 per cent initial weight. The suffix 0 denotes opening, f denotes flame, b floor and c ceiling.

Excluding the initial 20 per cent and the last 30 per cent loss excludes the early growth period when the rate of burning varies most with time and the time when the residual charcoal burns. A comparison between an 80/55 value and a 55/30 value is a measure of variation in the approximately steady period and each period covers a quarter of the total initial weight. t_{80} gives a measure of the repeatability and variation of the early growth period. Taking corresponding measures for I and θ allow correlations to be investigated between these quantities and the corresponding R^3

8. In the main series (para. 5) (though not in the preliminary tests, para. 6) the method of ignition* should be changed to the following. The ignition sticks should be one third the length of the model $L/3$, where L is the model dimension measured perpendicular to the window, still containing 1cc of kerosine per cm of igniting stick so that the total amount of kerosine is just over one third at present specified. This shorter stick should be under the crib nearest to the window, i.e. the front third. This is adequate to ignite the fire and, by employing less kerosine, interferes less with the subsequent burning.

---

* Ignition is at present by sticks of fibre insulation board size $5/6\,L \times \frac{1}{2} \times \frac{3}{8}$ in ($5/6\,L \times 1.27 \times 0.95$cm) where L is the box dimension perpendicular to the plane of the window with 1 c.c. per cm. of stick of kerosine added to each length. One of these sticks is laid in each space between the sticks of the lowest row of the crib resting on the base of the compartment and a flame is quickly applied to the near ends of all the sticks. For stick spacing combination ($2\frac{1}{3}$) ignition to be by fibre insulating board length $L/3$ of smaller section 1.27 x 0.63 cm ($\frac{1}{4}$" x $\frac{1}{2}$") and 0.5cc kerosine per cm of stick.

References.

1. KAWAGOE, K., THOMAS, P. H. and PICKARD, R. Preliminary experiments for the CIB programme - Analysis of rate of burning. Supplement paper C

2. KAWAGOE, K., THOMAS, P. H., and SMITH, P. G. Preliminary experiments for the CIB programme - Analysis of ceiling temperature and Radiation from the opening, Supplement paper D

3. THOMAS, P. H. and SMITH, P. G. Comparative tests by three laboratories on a fire in a small scale compartment. Supplement paper E.

SCALE		COMPARTMENT SHAPE																		
		121						211						221						441
	Ventilation	¼ & 1			½			¼ & 1			½			¼ & 1			½			¼, ½ & 1
	Stick spacing / Fire load kg/m²	2.1	2.⅓ 4.1	1.3 2.3	2.1	2.⅓ 4.1	1.3 2.3	2.1	2.⅓ 4.1	1.3 2.3	2.1	2.⅓ 4.1	1.3 2.3	2.1	2.⅓ 4.1	1.3 2.3	2.1	2.⅓ 4.1	1.3 2.3	2.1
½	20	N	N	N	N	N	N	F J	J	F	F J	J	F	A G1	A	G1	A G1	A	G1	B
	30 & 40																			B
1	20 & 40	A F G2 G3 N *	N	N	G2			F G1 G2 G3 N J U	J	F	G2			A G1 G2 * J U	A	G1	G2			
	30	N G2	N	N	G2			F J G2	J	F	G2			A G1 G2	A	G1	G2			
1½	20, 30 & 40	*	*	*				G3	G3	G3				U	U	U				B

A Australia
B United Kingdom
F France
G_1 Germany 1 (Berlin)
G_2 Germany 2) (Karlsruhe)
G_3 Germany 3)

N Netherlands
J Japan
U U.S.A.

All 1m scale, 20 & 40 kg/m² fire load, (2.1) stick spacing. ¼, and 1 opening experiments repeated except by Japan and by Germany (2) for 211 compartment shape.
Circles indicate the results which have been circulated between the laboratories. (June 1964)

G

SOME OBSERVATIONS ON THE EFFECT OF WIND ON COMPARTMENT FIRES

by

P. H. Thomas, P. G. Smith, A. J. M. Heselden and D. L. Simms

SUMMARY

Some of the results of experiments in the C.I.B. programme with fires in small-scale compartments exposed to wind are analysed.

The rate of burning was not more than 100 per cent higher for a wind of 8 m/s than for still air; the direction of the wind was unimportant except for the 111 shape where the effect was substantial.

The data also enable some comparisons to be made between different shapes.

March 1964

SOME OBSERVATIONS ON THE EFFECT OF WIND ON COMPARTMENT FIRES

by

P. H. Thomas, P. G. Smith, A. J. M. Heselden and D. L. Simms

The results of the tests undertaken by the Fire Research Station as part of the C.I.B. programme have already been circulated. A complete analysis of the data has yet to be made but in this short note attention is drawn to some of the more obvious results.

The rate of burning

A statistical analysis has been made of the rate of burning data measured as the burning rate per unit floor area. For a first analysis no distinction was made between the burning in the early part of the fire and in the later part, so that the statistic used was $R_{80/30}/A_{fl}$,

where A_{fl} denotes the floor area.

The analysis showed:-

(a) The rate of burning per unit floor area was less than 10 per cent higher for the larger compartments (211) and (221) than for the corresponding small compartments, and the effect is not statistically significant. The shapes (111) (121) (211) and (221) can therefore be considered in pairs, e.g. (211) is similar to two (111) compartments side by side with the adjoining walls removed, and (221) can be compared to two (121) compartments.

(b) The change in shape from (111) to (121) and similarly from (211) to (221) produced a significant change in the burning rate. The absolute rate of burning $R_{80/30}$ increased by about 50 per cent. This is less than the increase in floor area so that the rate of burning per unit floor area $R_{80/30}/A_{fl}$ decreased as the length of the room, perpendicular to the window, increased in relation to the height.

(c) The increase in wind speed from 15 ft/s to 25 ft/s which, for the purposes of this report, can be regarded as nominally equivalent to 5 m/s and 8 m/s, produced only an approximately 20 per cent increase in the burning rate.

(d) The change in wind direction produced no significant effect, except for the (111) shape, where the effect was substantial.

(e) An increase in window size increased the burning rate.

The best values of the burning rate per unit floor area, averaged from the experimental results to allow for only those factors found significant, are shown in Table 1. An inspection of the values of $R_{80/55}$ shows that those results follow a very similar pattern.

The values shown in Table 1 have been recalculated in Table 2 as rates of burning per unit window area. As for still air, this is highest for the smallest window. The results for still air and small windows can be calculated from the formula

$$R/A_w = 6\sqrt{H_w}\ \text{kg m}^{-2}\text{min}^{-1}$$

where A_w and H_w are the area and height of the window in m^2 and m respectively.

Since H equals $\frac{1}{2}$ m this equation gives the rate of burning per unit window area as 4.2 kg $m^{-2}min^{-1}$. A comparison with the results for $\frac{1}{4}$ opening in Table 2 suggests that the effect of wind on the burning rate is not large.

Comparable values of $R_{80/30}$ for still air have already been reported from the United States and Australia. These results are shown in Table 3, from which the effect of these relatively high wind speeds is seen to be less than 100 per cent increase.

Analysis of $I_{80/30}$

A provisional analysis was undertaken on the effective mean radiation intensity corrected for the geometric shape factor, i.e. the results were normalised to a mean radiation level in the plane of the window. The values lie in the range 1.2 to 3.5 cal $cm^{-2}s^{-1}$, but the effects of wind direction, compartment shape and window size are interdependent and a more detailed analysis is required before the effects of each can properly be discussed.

Discussion and Conclusion

A number of other experiments of a similar kind but not yet reported have been conducted in which baffles were constructed at the sides of the compartment and a horizontal ground plate placed on a level with the compartment floor and projecting in front of it. Additional experiments were made in which the crib was shielded from the direct path of the wind. The difference between the rates of burning in still air and in a wind was found to be no more than the effect of these other variations in the experimental conditions but the deflection of the flames is greatly influenced by the presence or absence of baffles.

In order to obtain a realistic arrangement for experiments on the effect of a wind the influence of these and similar factors which were not included in the original C.I.B. programme needs to be explored, particularly when studying the radiation from the fire and the deflection of the flames.

The change in the rate of burning in a wind is significant but is probably less important than the effect of wind on the risk of fire spread to other buildings or parts of the same building.

TABLE 1

Summary of best values of $R_{80/30}$ per unit floor area for effects found to be significant

$R_{80/30}/A_{fl}$ kg $m^{-2}min^{-1}$

Compartment Shape	Wind velocity											
	5 m s^{-1}						8 m s^{-1}					
	Wind angle						Wind angle					
	0°			60°			0°			60°		
	Window opening			Window opening			Window opening			Window opening		
	$\frac{1}{4}$	$\frac{1}{2}$	1	$\frac{1}{4}$	$\frac{1}{2}$	1	$\frac{1}{4}$	$\frac{1}{2}$	1	$\frac{1}{4}$	$\frac{1}{2}$	1
111	1.32	1.68	2.24	0.48	0.84	1.44	1.52	1.88	2.44	0.68	1.04	1.64
121	0.52	0.92	1.48	0.52	0.92	1.48	0.72	1.12	1.68	0.72	1.12	1.68
211	1.00	1.40	1.96	1.00	1.40	1.96	1.20	1.60	2.16	1.20	1.60	2.16
221	0.60	0.96	1.52	0.60	0.96	1.52	0.80	1.16	1.72	0.80	1.16	1.72

σ for single value is 0.24 kg $m^{-2}min^{-1}$

Mean Values $R_{80/30}/A_{fl}$ kg $m^{-2}min^{-1}$

Compartment shape	111 121 211 221	1.44 1.08 1.56 1.12
Window opening	$\frac{1}{4}$ $\frac{1}{2}$ 1	0.88 1.24 1.80
Wind velocity	5 m s^{-1} 8 m s^{-1}	1.20 1.40
Wind angle	0° 60°	1.40 1.20
Grand mean		1.32

TABLE 2

$$\frac{\text{Best values of } R_{80/30}}{\text{Area of opening } (A_w)} \quad \text{kg m}^{-2}\ \text{min}^{-1}$$

Compartment Shape	Wind velocity											
	5 m s^{-1}						8 m s^{-1}					
	Wind angle						Wind angle					
	0°			60°			0°			60°		
	Window opening			Window opening			Window opening			Window opening		
	$\frac{1}{4}$	$\frac{1}{2}$	1	$\frac{1}{4}$	$\frac{1}{2}$	1	$\frac{1}{4}$	$\frac{1}{2}$	1	$\frac{1}{4}$	$\frac{1}{2}$	1
111	5.3	3.3	2.2	1.9	1.7	1.4	6.0	3.7	2.4	2.8	2.1	1.6
121	4.3	3.6	2.9	4.3	3.6	2.9	5.9	4.4	3.3	5.9	4.4	3.3
211	4.0	2.8	2.0	4.0	2.8	2.0	4.9	3.2	2.2	4.9	3.2	2.2
221	4.8	3.9	3.1	4.8	3.9	3.1	6.4	4.7	3.5	6.4	4.7	3.5

TABLE 3

Values of $R_{80/30}$ kg min^{-1}

Compartment Shape	Window opening	$R_{80/30}$		
		Single values still air	Best values	
			5 m s^{-1}	8 m s^{-1}
121	$\frac{1}{4}$	0.36*	0.27	0.37
	1	0.40*	0.73	0.84
211	$\frac{1}{4}$	0.70	0.51	0.61
	1	0.63	0.97	1.08
221	$\frac{1}{4}$	0.58* 0.75	0.60	0.80
	$\frac{1}{2}$	0.68*	0.96	1.17
	1	0.74* 1.13	1.53	1.74

*Australian results. Other still air data from U.S. results.

EFFECT OF WIND ON FIRES IN MODEL COMPARTMENTS

by

P. G. Smith

SUMMARY

Experiments are described in which wind was blown into model compartments containing fires. Several positions of the compartment in the building facade were simulated and the fuel was either exposed directly to the wind or was shielded from it. The effect of these factors on the rate of burning and the intensity of radiation at the compartment opening was measured and compared with the effect due to changing the wind speed.

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EFFECT OF WIND ON FIRES IN MODEL COMPARTMENTS

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P. G. Smith

Introduction

The series of experiments* assigned to the Joint Fire Research Organization in the Conseil International du Bâtiment models programme(1) was intended to provide information on the effect of wind speed and orientation for comparison with a large number of experiments in still air. However, the effect of wind on fully developed fires in compartments is likely to depend not only on the speed of the wind and its orientation but also on the height of the compartment above the ground, the position of the compartment in the building facade, and on whether the fuel is directly exposed to the wind. Changes in the experimental arrangement e.g. the provision of deflector plates adjoining the window of a compartment, may produce variations in fire behaviour comparable with those due to wind speed and orientation. Therefore the sensitivity of the experimental arrangement used in the C.I.B. programme was measured by carrying out some additional experiments which are described in this note.

Some of the effects of wind e.g. in deflecting flames, depend on the ratio of the horizontal momentum force of the wind to the vertical buoyancy force of a flame (Froude Number) which is of the form V^2/gH, neglecting density variations in the flame due to variation of temperature with scale, where V is the wind velocity, H a characteristic height and g the acceleration due to gravity. Thus for a constant wind velocity the momentum force has relatively more importance for smaller values of H. Because, however, other effects of a wind e.g. on the burning of directly exposed glowing wood, will be dependent on the geometry of the fuel and the fuel bed rather than the compartment i.e. will be, to some extent, independent of compartment scale, it is not possible to scale up these results quantitatively. It is expected, nevertheless, that the effects of wind found in these experiments are greater than would be found for actual buildings.

Description of experiments

To simulate a ground floor compartment, asbestos wood sheets were mounted horizontally, level with the floor of the compartment, to form a "ground plate" (Fig. 1). Adjacent walls were similarly represented by asbestos wood sheets, or "baffles", mounted vertically in the plane of the window opening near both sides and the ceiling of the compartment (Fig. 2).

The cribs used in all the groups of experiments described in this note were constructed with a stick-spacing combination of 2.1 (i.e. 2 cm sticks, spaced 4 cm between stick centres) to produce fire loads of 30 kg/m^2. The species of wood was Pinus sylvestris. A poly-vinyl-acetate emulsion glue was used to join the sticks together.

In some experiments the crib was placed on the compartment floor and a shield placed in the window opening to prevent wind being blown directly onto the crib as shown in Fig. 1. In other experiments the crib was placed just below the compartment floor where it was similarly shielded (Fig. 2). The cribs were ignited from ten 17 cm x 1 cm x 1.3 cm strips of fibre insulating board, each strip soaked in 17 ml of paraffin, placed under the cribs.

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*These experiments will be reported elsewhere, although the results of some of them have been included in this note.

TABLE 1

GROUPS OF EXPERIMENTS

Group	No. of experiments	Compartment			Position of crib	Ground plate and baffles	Wind	
		Shape	Scale	Lining Material			Speed (m/s)	Direction
1	8	111	$\frac{1}{2}$ m	Asbestos wood 1 cm thick	On compartment floor; shielded and unshielded	With and without ground plate and baffles	5	0° and 5°
2	12 (including 4 from Group 1)	111	$\frac{1}{2}$ m	Asbestos wood 1 cm thick	As group 1 and below compartment	With and without ground plate; with and without baffles	5	0°
3	8 (including 1 from Group 2)	111	$\frac{1}{2}$ m	Asbestos wood 1 cm thick	On compartment floor; unshielded	With plain and aluminised ground plates; without baffles	0, 5 and 8	0°
4	32	121	$\frac{1}{2}$ m	Asbestos millboard 1 cm thick	On compartment floor; unshielded	With and without blackened ground plate; with and without side baffles	5 and 8	0° and 60°

In all experiments the rate of burning and the intensity of radiation from the compartment opening were measured. The gold-disc radiometer[2] was shielded to prevent radiation from flames above or to the side of the compartment being received. The experiments fall into four groups as shown in Table 1.

Group 1. It was expected that the experiments at these two angles would show if there was instability in the burning of the cribs when the wind was blown directly into the compartment.

Group 3. The ground plate was covered with aluminium foil in an attempt to discover if the effect of the ground plate on the rate of burning was due to heating of the ground plate.

Group 4. This group includes the twelve experiments carried out by the Joint Fire Research Organization in a 121, $\frac{1}{2}$ m asbestos millboard compartment as part of the C.I.B. programme[1]. These experiments were done with the window $\frac{1}{4}$, $\frac{1}{2}$ and fully open with winds of velocities 5 and 8 m/s blown directly into the compartment and at 60° to this direction. Another similar series of 12 experiments was carried out with a ground plate painted black on its upper surface, and finally a set of 8 experiments for similar wind conditions was done with baffles at the sides of the compartment with the window fully open and both with and without ground plate. In addition to weight and radiation measurements, the temperatures near the floor and ceiling of the compartment were recorded.

Although the experiments in each group were not arranged to be carried out in a completely random order, in most instances the sequence of experiments did not follow any systematic plan.

Results and discussion

Group 1.

The rates of burning $R_{80/30}$*, $R_{80/55}$ and $R_{55/30}$ are given in Table 2.

Table 2 - Rate of burning (kg/min)

Wind Speed 5 m/s		Without ground plate or vertical baffles		With ground plate and vertical baffles	
		0°	5°	0°	5°
$R_{80/30}$	Crib unshielded	0.46	0.41	0.51	0.50
	Crib shielded	0.28	0.36	0.35	0.33
$R_{80/55}$	Crib unshielded	0.46	0.51	0.58	0.56
	Crib shielded	0.31	0.36	0.37	0.38
$R_{55/30}$	Crib unshielded	0.46	0.34	0.45	0.45
	Crib shielded	0.26	0.36	0.32	0.30

The rate of burning $R_{80/30}$ with the crib unshielded was about 40 per cent higher than with crib shielded compared with a 50 per cent increase in area of window opening, and was about 12 per cent higher with a ground plate and vertical baffles than without. There was no change in burning rate due to the change in angle from 0° to 5°. The other rates of burning show similar effects.

*$R_{80/30}$ is the mean rate of burning during the period when the weight of the crib was falling from 80 per cent to 30 per cent of its initial value; $R_{80/55}$ and $R_{55/30}$ are similarly defined.

The radiation intensity (I_o) measured by the radiometer at a point in front of the compartment, divided by the configuration factor ($\emptyset$) of the compartment opening with respect to the radiometer, allowing for the shielding, is given in Table 3 for the 80/30, 80/55 and 55/30 periods.

Table 3 - Equivalent intensity of radiation in the plane of the opening (cal $cm^{-2}s^{-1}$)

Wind speed 5 m/s		Without ground plate or vertical baffles		With ground plate and vertical baffles	
		0°	5°	0°	5°
$\frac{I_o\ 80/30}{\emptyset}$	Crib unshielded Crib shielded	1.66 0.90	1.66 1.02	1.86 1.07	1.63 1.51
$\frac{I_o\ 80/55}{\emptyset}$	Crib unshielded Crib shielded	1.71 0.71	1.93 0.90	1.73 0.73	1.40 1.35
$\frac{I_o\ 55/30}{\emptyset}$	Crib unshielded Crib shielded	1.61 1.06	1.53 1.10	1.96 1.35	1.87 1.62

This ratio would be the mean intensity in the plane of the opening except that radiation reflected and/or re-radiated from the ground plate may also be received by the radiometer.

The mean equivalent intensity of radiation in the plane of the opening over the 80/30 period was on the average about 50 per cent higher with the crib unshielded than with the crib shielded. A similar comparison for the 80/55 period shows that the greatest increase for a pair of experiments was 140 per cent whilst the smallest increase was less than 4 per cent. The presence of baffles and ground plate increased the equivalent intensity of radiation at the opening by nearly 30 per cent in the 55/30 period but had very little effect in the earlier part of the burning. There was no consistent effect of angle.

Group 2.

The rates of burning $R_{80/30}$, $R_{80/55}$ and $R_{55/30}$ are given in Table 4.

Table 4 - Rate of burning (kg/min.)

Wind speed 5 m/s		Without ground plate		With ground plate		Mean
		Without vertical baffles	With vertical baffles	Without vertical baffles	With vertical baffles	
$R_{80/30}$	Crib unshielded Crib shielded Crib below compartment	0.46 0.28 0.38	0.55 0.30 0.41	0.49 0.29 0.45	0.51 0.35 0.50	0.50 0.31 0.44
$R_{80/55}$	Crib unshielded Crib shielded Crib below compartment	0.46 0.31 0.38	0.49 0.26 0.38	0.54 0.33 0.51	0.58 0.37 0.50	0.52 0.32 0.44
$R_{55/30}$	Crib unshielded Crib shielded Crib below compartment	0.46 0.26 0.38	0.63 0.35 0.46	0.45 0.26 0.41	0.45 0.32 0.49	0.50 0.30 0.44

Shielding the crib produced the lowest rate of burning ($R_{80/30}$). This was increased by 43 per cent when the crib was below the compartment and by 65 per cent when the crib was unshielded.

An analysis of variance showed that the presence of a ground plate significantly increased $R_{80/55}$ whereas the presence of baffles significantly increased $R_{55/30}$. The interaction between ground plate and crib position on $R_{80/30}$ may just be significant.

By taking the data in pairs the ratios listed in Table 5 were formed; each ratio being based on four tests.

Table 5 - Effect of ground plate and vertical baffles

Wind speed 5 m/s		Ratios of rates of burning			
		With ground plate / Without ground plate		With vertical baffles / Without vertical baffles	
			Mean		Mean
$R_{80/30}$	Crib unshielded	0.99	1.09	1.12	1.11
	Crib shielded	1.10		1.14	
	Crib below compartment	1.20		1.10	
$R_{80/55}$	Crib unshielded	1.18	1.24	1.07	1.02
	Crib shielded	1.23		0.99	
	Crib below compartment	1.33		0.99	
$R_{55/30}$	Crib unshielded	0.83	0.94	1.19	1.22
	Crib shielded	0.95		1.29	
	Crib below compartment	1.07		1.20	

This shows that adding the ground plate increased the rate of burning in the 80/55 period, and that this increase was greatest when the crib was below the compartment. Introducing baffles increased $R_{55/30}$ particularly when the crib was shielded. $R_{80/30}$ was increased some 10 per cent by the addition of either ground plate or baffles.

The values of radiation at the compartment opening for the three periods considered are given in Table 6.

Table 6 - Equivalent intensity of radiation (cal $cm^{-2}s^{-1}$)

Wind speed 5 m/s		Without ground plate		With ground plate		Mean
		Without vertical baffles	With vertical baffles	Without vertical baffles	With vertical baffles	
$\frac{I_{o\ 80/30}}{\phi}$	Crib unshielded	1.66	1.58	1.38	1.86	1.62
	Crib shielded	0.90	0.98	1.20	1.07	1.04
	Crib below compartment	0.77	0.85	0.66	0.77	0.76
$\frac{I_{o\ 80/55}}{\phi}$	Crib unshielded	1.71	1.53	1.23	1.73	1.55
	Crib shielded	0.71	0.79	1.18	0.73	0.86
	Crib below compartment	0.71	0.76	0.61	0.69	0.69
$\frac{I_{o\ 55/30}}{\phi}$	Crib unshielded	1.61	1.69	1.54	1.96	1.70
	Crib shielded	1.06	1.25	1.22	1.35	1.22
	Crib below compartment	0.85	0.97	0.70	0.85	0.84

The mean radiation at the opening over the 80/30 period was on the average nearly 60 per cent higher with the crib unshielded than with the crib shielded. This was similar to the change in the rate of burning. However with the crib below the compartment floor the radiation fell to less than 50 per cent of the value with the crib unshielded compared with a corresponding decrease of less than 15 per cent in the rate of burning.

Table 7 - Effect of ground plate and vertical baffles on intensity of radiation at opening

Wind speed 5 m/s		Ratio of intensities of radiation at opening: With ground plate / without ground plate	Mean	With vertical baffles / without vertical baffles	Mean
$\frac{I_o\ 80/30}{\emptyset}$	Crib unshielded	1.00	1.03	1.13	1.08
	Crib shielded	1.21		0.98	
	Crib below compartment	0.88		1.14	
$\frac{I_o\ 80/55}{\emptyset}$	Crib unshielded	0.91	1.00	1.11	1.02
	Crib shielded	1.28		0.80	
	Crib below compartment	0.89		1.11	
$\frac{I_o\ 55/30}{\emptyset}$	Crib unshielded	1.06	1.03	1.16	1.16
	Crib shielded	1.11		1.14	
	Crib below compartment	0.85		1.17	

Table 7 shows that the presence of the ground plate increased the radiation at the opening when the crib was shielded, reduced it when the crib was below the compartment, and had little effect when the crib was unshielded. The greatest effect of the vertical baffles was a decrease of 20 per cent in the radiation at the opening over the 80/55 period with the crib shielded although this was due to the radiation obtained in one experiment over this period being about 50 per cent higher than comparable values. In general the vertical baffles increased the radiation at the opening.

Group 3

Table 8 - Effect of wind and type of ground plate on rate of burning

	Type of ground plate	Rate of burning (kg/min): No wind	Wind 5 m/s	Wind 8 m/s	Mean	Ratio of rates of burning: vel. = 5 / vel. = 0	vel. = 8 / vel. = 0
$R_{80/30}$	Plain	0.44	0.54, 0.49	0.63	0.53	1.29	1.71
	Aluminised	0.42	0.59	0.88, 0.80	0.62		
$R_{80/55}$	Plain	0.38	0.63, 0.54	0.67	0.55	1.45	1.63
	Aluminised	0.52	0.71	0.83, 0.76	0.68		
$R_{55/30}$	Plain	0.53	0.48, 0.45	0.60	0.53	1.10	1.67
	Aluminised	0.36	0.51	0.93, 0.84	0.58		

Table 8 shows that the rate of burning $R_{80/55}$ was higher in a wind of velocity 5 m/s than in still air. $R_{55/30}$ was much less increased, whereas an 8 m/s wind increased both $R_{80/55}$ and $R_{55/30}$ almost equally above the still air values.

The rate of burning is higher with the aluminised ground plate in a wind. The relatively fewer experiments in still air suggest the effect may be different in the early and later stages of burning. The ground plate affects the flow pattern of the air incident on the fire by causing a boundary layer to develop and also, by being heated by the fire, it tends to preheat the air entering the compartment. However, the way the resulting behaviour of the fire is affected by these changes is not yet fully understood.

Table 9 - Effect of wind and type of ground plate on equivalent intensity of radiation at opening

	Type of ground plate	Equivalent intensity of radiation at opening (cal $cm^{-2}s^{-1}$)				Ratio of intensities of radiation	
		No wind	Wind 5 m/s	Wind 8 m/s	Mean	vel. = 5 / vel. = 0	vel. = 8 / vel. = 0
$\frac{I_{o\ 80/30}}{\emptyset}$	Plain Aluminised	1.54 1.79	1.51, 1.38 1.91	1.26 2.12, 1.58	1.42 1.85	1.01	0.93
$\frac{I_{o\ 80/55}}{\emptyset}$	Plain Aluminised	1.48 1.81	1.29, 1.23 1.70	0.99 2.16, 1.43	1.24 1.77	0.90	0.85
$\frac{I_{o\ 55/30}}{\emptyset}$	Plain Aluminised	1.59 1.78	1.63, 1.54 2.07	1.54 2.06, 1.69	1.57 1.90	1.09	1.01

Table 9 shows that the effect of wind on the intensity of radiation at the opening is less than that on the rate of burning, and that there is a tendency for the radiation to decrease with increasing wind velocity. Aluminising the ground plate had most effect on the radiation during the 80/55 period - the same period during which the rate of burning was most affected by the presence of the ground plate (Table 5). However, the increase in radiation of over 40 per cent was greater than the increase in rate of burning; possibly because the radiometer received radiation reflected by the aluminium.

Group 4

The burning rate values obtained are given in Table 10.

Table 10 - Effect of wind velocity, angle, ground plate and side baffles on burning rate (kg/min)

Rate of burning	Side baffles	Window opening	Without ground plate				With ground plate			
			Wind 5 m/s		Wind 8 m/s		Wind 5 m/s		Wind 8 m/s	
			0°	60°	0°	60°	0°	60°	0°	60°
$R_{80/30}$	Without	$\frac{1}{4}$	0.34	0.35	0.36	0.32	0.32	0.34	0.38	0.28
	"	$\frac{1}{2}$	0.39	0.52	0.56	0.60	0.36	0.52	0.38	0.52
	"	1	0.72	0.71	0.76	0.78	0.69	0.82	0.73	0.72
	With	1	0.53	0.78	0.81	0.74	0.73	0.65	0.91	0.74
$R_{80/55}$	Without	$\frac{1}{4}$	0.38	0.35	0.37	0.38	0.36	0.35	0.43	0.29
	"	$\frac{1}{2}$	0.46	0.66	0.66	0.64	0.37	0.56	0.43	0.59
	"	1	0.75	0.87	0.91	0.92	0.77	0.88	0.99	0.87
	With	1	0.62	0.90	0.97	0.87	0.81	0.77	1.09	0.95
$R_{55/30}$	Without	$\frac{1}{4}$	0.31	0.35	0.35	0.28	0.29	0.33	0.34	0.27
	"	$\frac{1}{2}$	0.34	0.43	0.49	0.56	0.36	0.48	0.33	0.46
	"	1	0.70	0.59	0.66	0.68	0.62	0.76	0.58	0.62
	With	1	0.46	0.68	0.69	0.65	0.67	0.57	0.78	0.61

Table 11 - Greatest effects of factors on rate of burning

Rate of burning	Window opening							
	$\frac{1}{4}$		$\frac{1}{2}$		1		1	
	Without baffles		Without baffles		Without baffles		With baffles	
	Factors	Rate of burning ratio	Factors	Rate of burning ratio	Factors	Rate of burning ratio	Factors	Rate of burning ratio
$R_{80/30}$	$\frac{A_oB_1 + A_1B_o}{A_oB_o + A_1B_1}$	1.14*	$\frac{B_1}{B_o}$	1.28	$\frac{A_oC_1 + A_1C_o}{A_oC_o + A_1C_1}$	1.06	$\frac{A_1}{A_o}$	1.19*
	$\frac{B_o}{B_1}$	1.09	$\frac{C_o}{C_1}$	1.16			$\frac{B_oC_1 + B_1C_o}{B_oC_o + B_1C_1}$	1.16*
			$\frac{A_1}{A_o}$	1.15				
			$\frac{A_oC_1 + A_1C_o}{A_oC_o + A_1C_1}$	1.13				
$R_{80/55}$	$\frac{B_o}{B_1}$	1.12	$\frac{B_1}{B_o}$	1.28*	$\frac{A_1}{A_o}$	1.13**	$\frac{A_1}{A_o}$	1.25*
			$\frac{C_o}{C_1}$	1.24	$\frac{A_oB_1 + A_1B_o}{A_oB_o + A_1B_1}$	1.10*	$\frac{A_oB_1 + A_1B_o}{A_oB_o + A_1B_1}$	1.15
			$\frac{A_1}{A_o}$	1.13			$\frac{C_1}{C_o}$	1.08
			$\frac{A_oC_1 + A_1C_o}{A_oC_o + A_1C_1}$	1.12				
$R_{55/30}$	$\frac{A_oB_1 + A_1B_o}{A_oB_o + A_1B_1}$	1.19***	$\frac{B_1}{B_o}$	1.27**	$\frac{B_oC_o + B_1C_1}{B_oC_1 + B_1C_o}$	1.11	$\frac{B_oC_1 + B_1C_o}{B_oC_o + B_1C_1}$	1.19*
	$\frac{C_o}{C_1}$	1.05***	$\frac{A_oC_1 + A_1C_o}{A_oC_o + A_1C_1}$	1.21**	$\frac{A_oC_1 + A_1C_o}{A_oC_o + A_1C_1}$	1.09	$\frac{A_1}{A_o}$	1.15
			$\frac{A_1}{A_o}$	1.14**			$\frac{A_oB_1 + A_1B_o}{A_oB_o + A_1B_1}$	1.14
			$\frac{C_o}{C_1}$	1.12*				

*Significant at .05 level **Significant at .01 level ***Significant at .001 level

A_o Wind speed = 5 m/s A_1 Wind speed = 8 m/s B_o Orientation of wind = 0° B_1 Orientation of wind = 60°

C_o Without ground plate C_1 With ground plate

With the window fully open the rate of burning was hardly altered by the addition of side baffles. Increasing the wind speed from 5 to 8 m/s caused an increase in the burning rate, largest at 0° with side baffles when the rate of burning at the higher wind velocity was up to 50 per cent above that at the lower velocity. A statistical analysis of the complete set of results in this group is too complicated to interpret easily due to significant interactions between the window opening factor and the other factors. Consequently each level of window opening has been considered separately (Table 11). (For the fully open window condition the experiments with and without baffles have also been separately considered). This table gives ratios of the two levels of all main effects and terms forming interactions which are statistically significant or which have ratios greater than about 1.1.

Unfortunately the fire behaviour is very complex and, in most instances, it is difficult to decide which physical factors caused these effects. The second order interaction sum of squares, taken as the error sum of squares since there was no replication, had only one degree of freedom. Therefore an estimate of the error mean square was formed by pooling the second order interaction sum of squares with certain other sums of squares using the criterion recommended by Paull[3]. Consequently some caution must be used in making use of the significance levels obtained.

Table 11 shows that the greatest effect of changing the levels of any factors was for the window ½ open for a change in wind orientation. The rate of burning without a ground plate was higher than with a ground plate which was the reverse of the effect with the 111 compartment (Tables 2 and 4). The effect of orientation of the wind was reversed between window ¼ open and ½ open. There was a change in the rate of burning of up to 21 per cent between combinations of any two factors at two levels.

The burning rate for a fully open window was about twice that for a ¼ open window.

Table 12 - Effect of wind velocity, orientation, window opening, ground plate and side baffles on radiation from the opening (cal $cm^{-2}s^{-1}$)

Intensity of radiation at opening	Side baffles	Window opening	Without ground plate				With ground plate			
			Wind 5 m/s		Wind 8 m/s		Wind 5 m/s		Wind 8 m/s	
			0°	60°	0°	60°	0°	60°	0°	60°
I_o 80/30 / Ø	Without	¼	2.39	1.26	1.78	1.74	2.20	1.28	1.80	1.09
	"	½	1.87	2.36	3.03	2.30	1.74	1.77	1.73	2.08
	"	1	1.98	2.08	2.29	1.98	2.05	2.32	2.13	2.32
	With	1	1.88	1.89	2.22	1.87	2.34	2.05	2.33	1.91
I_o 80/55 / Ø	Without	¼	2.32	1.05	1.49	1.43	2.13	1.12	1.72	0.97
	"	½	1.90	1.99	3.11	1.87	1.71	1.41	1.86	1.65
	"	1	1.80	1.96	2.39	1.66	1.76	2.01	2.08	1.85
	With	1	1.67	1.87	2.24	1.68	2.10	1.73	2.28	1.77
I_o 55/30 / Ø	Without	¼	2.44	1.47	2.05	1.94	2.26	1.43	1.86	1.20
	"	½	1.84	2.61	2.98	2.67	1.77	2.13	1.62	2.42
	"	1	2.12	2.17	2.22	2.24	2.30	2.56	2.17	2.62
	With	1	2.02	1.90	2.20	2.15	2.58	2.29	2.38	1.99

The overall effect of side baffles on the equivalent intensity of radiation at the opening was small (Table 12) and was similar to that on the rate of burning. The intensities with and without side baffles differed by more than 20 per cent in one experiment and this was not one in which the rate of burning was much affected by the presence or absence of side baffles. There was no consistent effect on the radiation due to the change in wind speed. However with the window ¼ open and the wind at 0° the radiation was between 20 and 50 per cent higher at the lower

wind speed. The reverse effect occurred for the experiments with other window openings with the compartment at 0° but only when no ground plate was used. The difference obtained was up to over 60 per cent. Changing the wind direction also produced inconsistent effects. The effect was greatest with the window $\frac{1}{4}$ open when the radiation for 0° was on the average some 50 per cent higher than for 60°. A similar change of about 10 to 20 per cent was obtained with side baffles. The reverse effect was found in the 55/30 period with the window $\frac{1}{2}$ and fully open without side baffles. Inconsistencies were again present in the effect of the ground plate. The greatest effect was with the window $\frac{1}{2}$ open when the radiation without ground plate averaged between 20 and 25 per cent higher than that with ground plate. The effect at a window opening of $\frac{1}{4}$ was similar but smaller - between 5 and 15 per cent higher. There was a tendency for the reverse effect to occur with the window fully open both with and without side baffles, although the mean change was less than about 10 per cent.

Conclusions

Experiments in which wind was blown into compartments containing burning wood cribs have shown that the presence of ground plates and vertical baffles, representing the ground in front of a ground floor compartment and walls of adjacent compartments, can have a greater effect on the rate of burning and the intensity of radiation at the window opening than a change of nearly 2:1 in the wind speed under certain circumstances. Insufficient comparable still air experiments to those in a wind have been carried out in this series to enable accurate estimates to be made of the effect of wind. The results of two still air experiments given in this note show that the presence of winds of up to 8 m/s did not change the rate of burning by more than 70 per cent, and this change is expected to be reduced for the same wind speed with full size compartments. It is expected that more comparisons with still air experiments will be possible when the results from the present C.I.B. programme[1] have been analysed.

It is clear that the experimental arrangement is of major importance, and that it is of doubtful value to study all these results in detail. If the detailed behaviour of a fire in a wind is to be investigated some effort must be made to study the separate effects of wind in isolation using a different experimental procedure to this - the object of which was to survey the possible effects of some of the more obviously variable experimental features.

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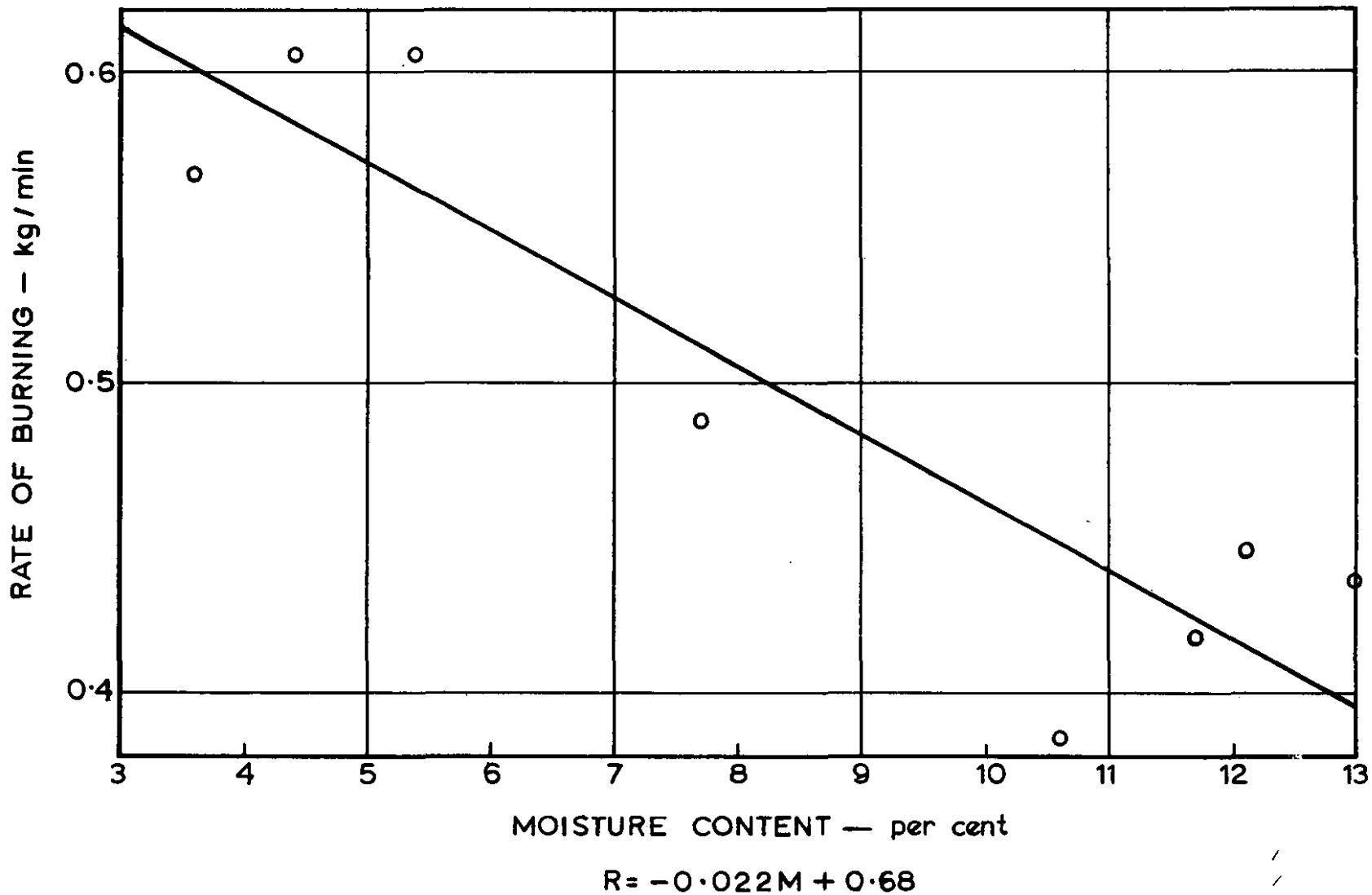

FIG.1. EFFECT OF MOISTURE CONTENT ON RATE OF BURNING OF INITIAL KILOGRAM OF FUEL

FACTORS AFFECTING THE RATE OF BURNING OF WOOD IN ASBESTOS-LINED COMPARTMENTS

by

P. G. Smith

SUMMARY

Following the discovery of an unexplained variation between the experimental results from three laboratories in the C.I.B. modelling programme, further experiments have shown that the rate of burning can be affected by the moisture content and/or the temperature of the compartment lining at the start of each experiment, and also possibly by the age of the crib. These effects may account for part of the variation in the C.I.B. experiments but there is insufficient information on the earlier experimental procedure to show whether these effects were present.

October 1965.

FACTORS AFFECTING THE RATE OF BURNING OF WOOD IN ASBESTOS-LINED COMPARTMENTS

by

P. G. Smith

INTRODUCTION

An international programme on modelling fires in compartments is being carried out under the auspices of the Conseil International du Bâtiment. In a preliminary investigation, eight laboratories carried out the same eight tests[1][2]. The repeatability of the tests carried out in each laboratory was satisfactory, but the variation in the measured rates of burning between the results of the tests from the different laboratories was greater than could be accepted. A restricted programme[3] was therefore arranged in which only the National Bureau of Standards laboratory, Washington D.C., the Nijverheids-organisatie voor Toegepast Natuurwetenschappelijk Onderzoek at Delft, Holland, and the Fire Research Station, Boreham Wood (J.F.R.O.) took part, in order to find what further experimental details needed to be specified. In particular, sufficient wood for the tests was exchanged instead of just specifying the density of the wood, and the compartment materials were supplied to each laboratory by the J.F.R.O. Each laboratory carried out the same experiment using the three woods supplied by the three laboratories. Even in this restricted programme an unexplained variation was found over and above the normal variation present between repeated tests at the same laboratory and the systematic variations between one laboratory and another. Each laboratory had underestimated the burning rate $\{R_{90/30}\}$ of its own wood by 5 - 7 per cent, and had overestimated $R_{90/30}$ for wood, received from other laboratories by 1 - 6 per cent, after allowance had been made for the systematic differences between laboratories and woods.

Since no complete explanation for this variation, which was significantly correlated with similar variations in the intensity of radiation, could be suggested, it was decided to carry out a series of experiments at the Joint Fire Research Organization during which differences in laboratory conditions would be noted. Although it was unlikely that the results of these experiments would explain the variation found, it was thought that they might show if any laboratory conditions needed to be more closely controlled in future experiments.

Variation in laboratory conditions

Only one type of wood (Pinus sylvestris) was used, conditioned at a temperature of 20°C (68°F) and a relative humidity of about 60 per cent to a moisture content of approximately 11 per cent. An experiment, identical to that carried out previously , was performed three times on the same day each week for eight weeks. The following variables were noted:

the temperature, relative humidity, and wind conditions inside and outside the laboratory, at the beginning and end of each experiment;

the temperature inside the compartment immediately before each experiment;

the time of day each experiment was started;

the number of sticks in each crib;

the mean moisture content* of each crib; and any other observed variations in laboratory conditions which it was thought might influence the burning rate of the crib, for example, whether the main doors of the laboratory were opened during an experiment.

The main variables are recorded in Table I.

The experimental procedure was identical to that adopted earlier except that no temperature measurements were made inside the compartment whilst the crib was burning. Continuous records were taken during each experiment of the weight of the crib and of the radiation from the compartment opening and from the flames above the compartment. From these measurements, the mean rates of burning over the periods during which the weights fell from 90 per cent to 30 per cent and from 90 per cent to 60 per cent of their initial values have been calculated. These rates $\left(R_{90/30}\right)$ and $\left(R_{90/60}\right)$ are given in Table II. The mean intensities of radiation from the opening and from the flames over the 90/30 period have been calculated by taking the averages of the intensity measurements at two minute intervals, and are also given in Table II.

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*The moisture content was obtained with an instrument which basically measured the electrical resistance between pins pushed into the wood. Errors of several per cent of moisture are possible with this type of instrument.

Table I

Laboratory, crib and experimental variables

Test No.	Age of crib (days)	Time between experiments (min.)	Conditions inside laboratory: Temperature (°C) At start of experiment	Temperature (°C) At end of experiment	Relative Humidity (%) At start of experiment	Relative Humidity (%) At end of experiment	Conditions outside laboratory: Temperature (°C)	Relative humidity (%)	Wind Speed (f/s)	Wind Direction	No. of short sticks in crib	Mean* density of crib (g/cm³)	Approx. moisture content of crib (%)	Temperature inside compartment (°C)
44	18	70	15.6	18.0	80	73	14	84	light	variable	55	0.448	11	24.0
45	19	160	16.4	18.2	71	69	16	76	6.3	S	55	0.448	10	18.0
46	19	85	17.0	18.4	76	69	16.6	76	6.9	S	57	0.441	10	19.0
47	20	53	16.8	17.5	79	72.5	15.3	85	10.3	S	59	0.434	10	24.2
48	20	170	18.0	20.0	79	70	18.0	77.5	~20	S	55	0.448	-	20.0
49	20	87	20.1	20.1	66	66	18.5	73.5	~15	S	58	0.438	11	21.5
50	34	55	15.6	16.0	66	62	13.0	84	~5	N	62	0.425	10	21.0
51	34	160	15.5	16.5	49	46	14.5	55	~8	N-E	62	0.425	10	17.5
52	35	90	15.6	16.5	49	46	13.0	59	6.7	N-W	60	0.431	10	17.4
53	32	45	15.2	15.5	56	49	12.0	68	~13	S-SW	59	0.434	10	27.0
54	35	160	17.5	17.0	48	47	14.5	52	~13	S	60	0.431	10	17.7
55	28	90	17.0	15.0	47	61	13.5	55	8.7	S-W	59	0.434	10	18.8
56	45	79	11.2	12.0	66	63	7.5	87	~6	S	57	0.441	9-11	12.8
57	44	130	13.0	15.0	64	56	10.4	77	~6	W-S	60	0.431	9-10	14.5
58	45	98	13.0	13.0	59	59	10.0	71	~6	W-S	57	0.441	9	14.9
59	27	70	12.7	12.2	74	78	9.5	94	9.2	S-SW	62	0.425	9	16.0
60	27	120	12.4	13.4	79	70	10.9	83	~9	S	60	0.431	9	13.5
61	27	120	12.2	12.4	84	84	10.3	95	~7	S	59	0.434	9	13.5
62	24	60	11.5	12.4	72	68	9.0	88	~31	E	59	0.434	9	16.5
63	18	150	11.0	12.3	72	68	9.3	82	~32	E	58	0.438	9	12.0
64	18	97	10.5	11.7	77	72	8.2	91	~28	E	60	0.431	9	12.5
65	>81	65	10.2	11.5	65	57	7.2	81	5.8	N	58	0.438	9	14.3
66	>81	160	12.2	12.0	57	57	8.0	75	~3.3	variable	56	0.444	9	13.0
67	>81	90	11.0	11.0	61	61	6.2	80	~3.3	variable	55	0.448	9	12.7

*The density was calculated from the assumption that all sticks were of the nominal size.

Table II

Experimental results

Test No.	Rate of burning (kg/min)		Mean Radiation from opening (90/30) cal $cm^{-2}s^{-1}$	Mean Radiation from flames (90/30) cal $cm^{-2}s^{-1}$
	$R_{90/30}$	$R_{90/60}$		
44	0.49	0.47	0.29	0.21
45	0.48	0.46	0.29	0.21
46	0.53	0.49	0.29	0.21
47	0.50	0.45	0.28	0.21
48	0.44	0.41	0.27	0.19
49	0.45	0.43	0.26	0.19
50	0.50	0.47	0.28	0.21
51	0.46	0.43	0.29	0.21
52	0.52	0.51	0.29	0.23
53	0.46	0.45	0.29	0.21
54	0.48	0.45	0.29	0.21
55	0.50	0.49	0.31	0.22
56	0.48	0.44	0.31	0.22
57	0.49	0.45	0.31	0.22
58	0.53	0.50	0.32	0.22
59	0.52	0.50	0.30	0.22
60	0.47	0.46	0.29	0.20
61	0.49	0.45	0.30	0.21
62	0.47	0.47	0.29	0.21
63	0.46	0.42	0.28	0.20
64	0.46	0.45	0.30	0.21
65	0.51	0.51	0.36	0.22
66	0.51	0.47	0.31	0.24
67	0.55	0.55	0.33	0.24

Discussion of results

The results of these experiments have standard deviations (σ) of 0.028 kg/min for the rate of burning $\{R_{90/30}\}$, 0.033 kg/min for $R_{90/60}$, 0.020 cal $cm^{-2}s^{-1}$ for the radiation from the opening, and 0.012 cal $cm^{-2}s^{-1}$ for the radiation from the flames.

The comparable values of σ for the repeat experiments carried out by the three laboratories[3] were 0.015 kg/min*, 0.025 kg/min, 0.013 cal $cm^{-2}s^{-1}$ and 0.014 cal $cm^{-2}s^{-1}$ respectively.

Analysis of results

Several preliminary regression analyses were carried out to find whether there were any correlations between the rate of burning and the laboratory variables. The correlation coefficients obtained for these variables taken separately are given in Table III.

The only laboratory condition that was significantly correlated with $R_{90/30}$ was the age of the crib; that is, the length of time it had been conditioned before being burnt. The variation of $R_{90/30}$ with the age of the crib is shown in Fig. 1. The ages of the cribs used in test Nos. 65, 66 and 67 are uncertain but are between 80 and 110 days old. The correlation coefficient is only slightly altered by this variation in age, whereas if these tests are omitted, the coefficient is no longer significant.

The two variables that were most nearly significant were the time since the end of the previous test, and the temperature in the laboratory at the start of the test. This time might be a measure of the amount of moisture taken up by the compartment material and also of the temperature of the compartment if this had not cooled sufficiently since the earlier test. The multiple correlation of rate of burning $\{R_{90/60}\}$ on this time, the laboratory temperature, and the age of the cribs was therefore calculated.

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*Based on 8 degrees of freedom.

Table III

Correlation coefficients

Variables: Independent	Variables: Dependent	Correlation coefficient	Significance level of correlation coefficient (per cent)
$R_{90/30}$	Age of crib*	0.523	1
$R_{90/30}$	Age of crib‡	0.508	2
$R_{90/30}$	Age of crib**	0.328	-
$R_{90/30}$	Time since end of previous test$^{\theta}$	-0.31	-
$R_{90/30}$	Temperature in lab. at start of test	-0.256	-
$R_{90/30}$	Temperature of compartment at start of test	-0.219	-
$R_{90/30}$	Humidity inside lab. at start of test	0.175	-
$R_{90/30}$	Density of wood in crib	0.124	-
$R_{90/30}$	Humidity outside lab. at start of test	0.0165	-
Radiation from opening 90/30 / $R_{90/30}$	Age of crib‡	0.4	5
Radiation from flames 90/30 / $R_{90/30}$	Age of crib‡	0.257	-

* Cribs used for tests 65-67 taken as 80 days old
‡ " " " " " " 110 days old
** Omitting tests no.65-67.
θ It was assumed that the duration of each experiment was 25 minutes.

The earlier part of the fire was chosen since it was expected that this would be more affected by differences in these variables. This analysis showed that the age of the crib and the time between tests were both correlated with $R_{90/60}$ at the 1 per cent level, but that the temperature in the laboratory was not correlated. The regression equation (omitting the temperature in the laboratory) was

$$R_{90/60} = 0.482 + 0.000973A - 0.000489\ t \qquad \text{..... (1)}$$

where $R_{90/60}$ is the rate of burning in kg/min,

A is the age of the crib in days,

and t is the time between tests in hours.

The standard deviation of the residual variance about the regression line was 0.022 kg/min compared with 0.025 kg/min for the 3 laboratories experiments. From equation (1) estimates were made of $R_{90/60}$ and these are shown plotted against the measured rates of burning in Fig. 2.

In the multiple regression of $R_{90/60}$ on A and t omitting the results for the three oldest cribs, A is not significant and t is significant at the 5 per cent level, so it is very largely these three results which are causing factor A to be significant in equation 1.

The rate of burning of a crib would be expected to depend, at least partly, on the radiation to the crib from the enclosing compartment and from the flame. The lower the thermal conductivity of the compartment walls the higher the inner surface temperature and therefore the higher the wall radiation. Flame radiation to the crib might also be increased since a higher wall temperature would mean a lower radiation transfer from the flame to the wall and therefore a higher flame temperature. Hence the rate of burning might be expected to vary inversely with the thermal conductivity of the walls. Increases in burning rate and temperature with increasing thermal insulation of the walls have been reported by Simms et al[4] and Yokoi[5].

If the moisture content of the compartment lining increases with t, then its thermal conductivity would increase with t, since the thermal conductivity of asbestos wood increases with moisture content. Therefore, $R_{90/60}$ would be expected to vary inversely with t as equation (1) shows. In addition, at higher moisture contents (and hence higher values of t) more heat would be required to evaporate the moisture, thus tending to reduce the rate of burning.

If only a short time elapses between tests the temperature of the compartment would be relatively high thus reducing heat transmission through the walls. This would be expected to cause a higher rate of burning, which is again in agreement with equation (1).

Additional experiments have been carried out at the J.F.R.O. to provide more detailed information on the effects attributed to the age of crib and the time between experiments.

Effect of moisture content

Since it is unlikely that the wood itself could change markedly over a period of up to about sixteen weeks, 'ageing' might be due to variations in moisture content; the moisture content of wood conditioned to equilibrium at constant humidity is known to vary in a way depending on whether the wood was initially wetter or drier than after conditioning(6).

Appendix I discusses the moisture content attained by conditioned wood. Experiments, in which cribs of different moisture contents were burned, are described elsewhere(7). The range of moisture contents was much wider than is possible between samples of wood conditioned in the same atmosphere. An analysis of these results showed that the relationship between $R_{90/60}$ and moisture content was not statistically significant, although that between the rate of burning during the loss of the first of the ten kilograms of wood i.e. $R_{100/90}$ and moisture content was highly significant. It has not been possible, therefore, to show conclusively whether the effect due to the age of the cribs can be attributed to differences in their moisture contents.

Effect of time between experiments

As stated earlier, varying the time between experiments could affect the amount of moisture taken up by the compartment and also its temperature. No direct measurements were made, in the series of 24 experiments, of the temperature of the compartment material but this was estimated from the difference in air temperature inside and outside the compartment. The correlation between this estimate and rate of burning was not significant. This may be due to different cooling conditions changing the relation between compartment and air temperature.

An experiment was carried out to measure the variation with time of the moisture taken up by the compartment and the temperature of its linings.

A 28 S.W.G.*chromel/alumel thermocouple was welded to a 28 S.W.G.* copper disc 2.5 cm. in diameter, the other side of the disc being covered with asbestos paper. This disc was then attached with a silicate cement to the centre of the outer surface of one side of the compartment so that the thermocouple was in contact with the asbestos wood.

* 0.4mm.

A crib, similar to those previously used, was burnt in the compartment. Measurements were frequently taken of the total weight of compartment and crib and of the temperature of one side of the compartment over a period of three hours from the start of the experiment. It can be shown that the buoyancy force due to the burning crib was equivalent to less than 0.02 per cent of the weight of the compartment lining, so this force is neglected.

Results

The temperature rise above ambient of the outside of the compartment is shown plotted against time in Fig. 3. The moisture content of the compartment was obtained by assuming that the lowest weight measured corresponded to a moisture content of zero. Since this minimum weight occurred after the crib had been completely burned, the weight of ash was small and constant and no allowance for it was necessary. The moisture content expressed as a percentage of the dry weight of the compartment is shown plotted against time in Fig. 4.

Discussion

Figs. 3 and 4 show that there is a considerable variation in both the temperature rise of the compartment lining and its moisture content over the range of time between experiments (45 - 170 min, which is equivalent to a range of time subsequent to ignition of 70 - 195 min) for this series of 24 experiments.

Regression analyses of $R_{90/60}$ on the age of the crib and the time between experiments or related variables have been carried out. The coefficients of the dependent variables with the levels of significance and values for the standard deviation obtained from these analyses are given in Table IV. This shows that replacing the term for the time between experiments (t) by either the temperature (θ) or the moisture content (M) of the compartment lining (obtained from Figs 3 and 4) left only the term for the age of the crib significant. However, when t was replaced by θ and M then all three terms were highly significant, although the coefficient of θ was negative which is contrary to what would be expected from physical arguments. This indicates that it is not possible to separate the effect of changes in θ on $R_{90/60}$ from the effect of changes in M. This is to be expected since both θ and M are related to t, and therefore θ is related to M.

Table IV

Regression analyses of $R_{90/60}$ on the age of the crib and the time between the experiments or related variables

Dependent variables											
A		t		θ		M		M^2			
coefficient	significance level (per cent)	coefficient	significance level (per cent)	coefficient	significance level (per cent)	coefficient	significance level (per cent)	coefficient	significance level (per cent)	constant term	residual standard deviation (kg/min.)
.00097	1	-.00049	1							.482	.022
.00091	1			.00038	not significant					.431	.029
.00092	1					-.093	10			.49	.027
.00089	0.2			-.0042	1	-.33	0.2			.652	.023
.00087	1					1.54	1	-1.49	1	.054	.022

The final regression analysis carried out contained both the linear and the quadratic components of M. This showed that both these components were significant, the coefficient of the linear component and also the overall term for M being positive; the residual standard deviation was as low as that for the regression of $R_{90/60}$ on A and t. Fig. 5 shows the values of $R_{90/60}$ obtained from this analysis plotted against the measured values. However, this analysis does not provide evidence to show whether or not the moisture content of the compartment lining was the major factor accounting for the effect on the rate of burning of varying the time between experiments.

Conclusions

It has been found that the variation in the rate of burning of wood cribs in a 121, $\frac{1}{2}$ m scale, asbestos wood compartment can be related to the moisture content of the compartment and/or the temperature of the compartment lining and possibly also to the age of the crib. It has not been possible to show, by a separate experiment, that the rate of burning $\left(R_{90/60}\right)$ is affected significantly by the moisture content of the crib although this seems to be the only factor which could account for an age of crib effect.

It is possible that the variations in the rate of burning obtained in the earlier C.I.B. experiments[3] could have been caused by changes in these factors but insufficient data is available to substantiate this supposition. However, in the part of the programme carried out by the J.F.R.O. several experiments were done on the same day. It is certain that the time between these experiments varied and, in view of the above conclusions, that insufficient time was allowed for the compartment to cool down or to reach an equilibrium moisture content with the atmosphere.

If these variations are to be eliminated in future experiments the condition of the compartment at the start of each experiment will have to be standardised and the moisture contents of the cribs will possibly have to be more closely controlled.

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Appendix I

Moisture content of conditioned wood

Continuous recording of the relative humidity in the room used for conditioning the wood cribs has shown that the relative humidity is unlikely to have gone outside the range 55 to 65 per cent R.H. which corresponds to a range in moisture content in the wood of 2 per cent[8]. The actual* variation in moisture content should be less than this, however, since the main fluctuations in relative humidity would take place over a very short period compared to that required to produce a change in the equilibrium moisture content of wood. There was no indication of long term drifts in the relative humidity of the conditioning atmosphere. Variations in moisture content of conditioned wood due to hysteresis[4] caused by some wood being wetter immediately before conditioning is started than is finally required, and the remainder being drier, would not account for a change in moisture content greater than 2 per cent, provided no wood was heated to a temperature greater than 50°C.

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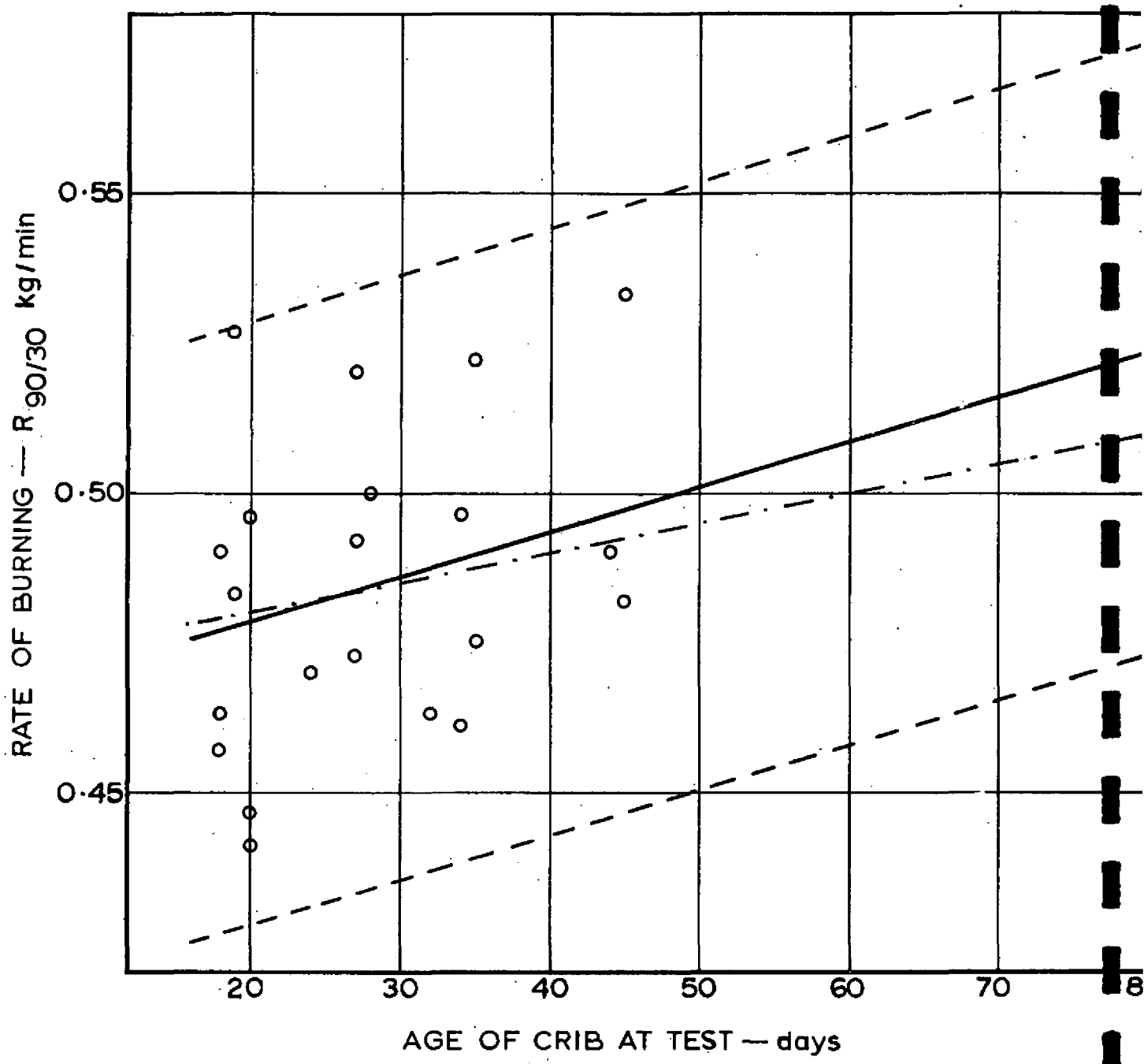
*A sample of the wood used in the cribs was kept in the conditioning room for 9 months and was weighed frequently. During the first 15 days there was a steady decrease in weight but after this there was no regular change in weight. If it is assumed that the mean moisture content after 15 days is 11 per cent, then the initial value is calculated to be 13.5 per cent and the maximum variation after 15 days from 10.5 to 11.7 per cent.



— — — — — 95% confidence limit. Age of oldest cribs = 80 days

——————— Age of oldest cribs = 80 days

·—·—·— Age of oldest cribs = 110 days

FIG.1. AGE OF CRIB

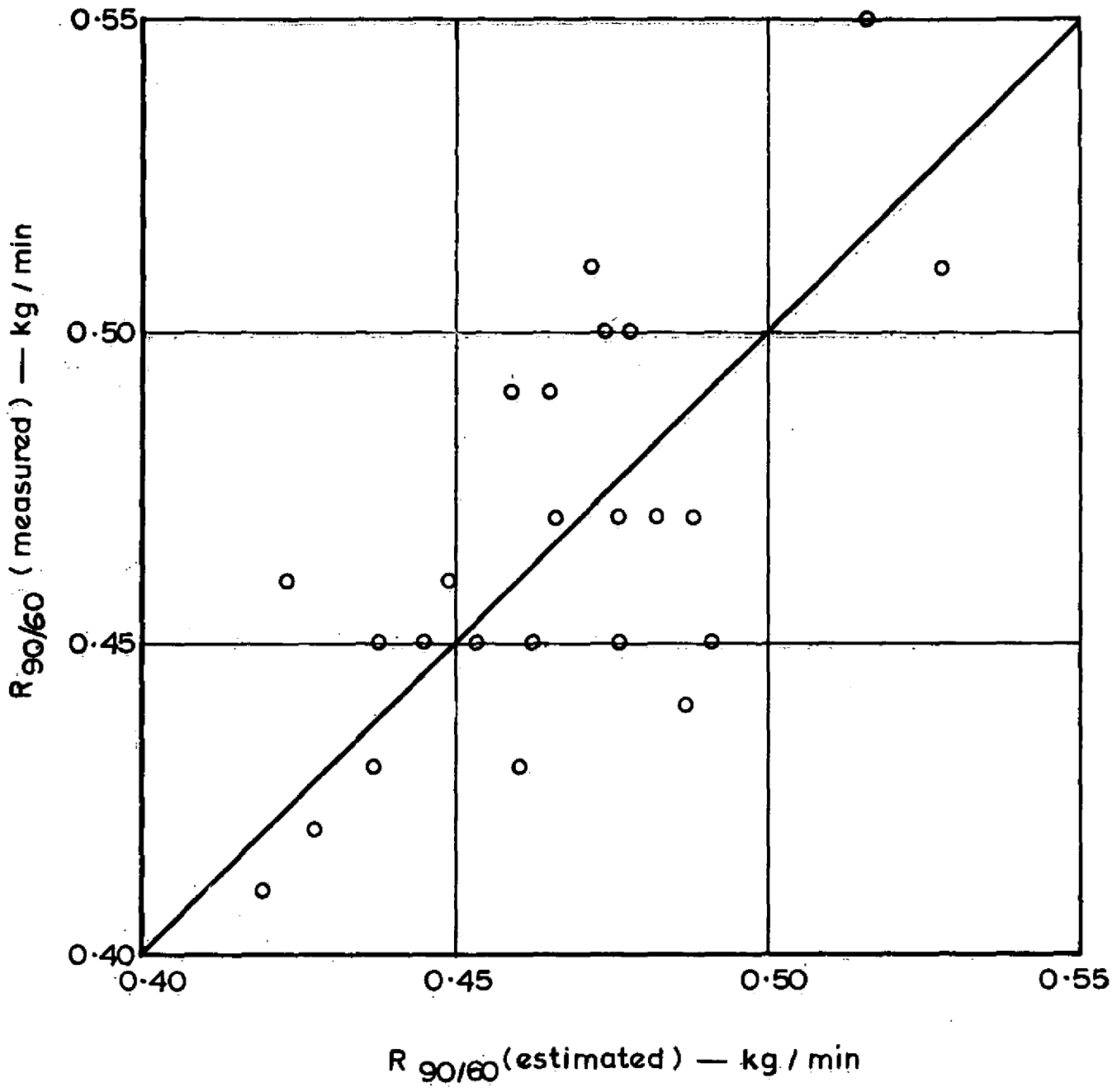


FIG.2. CORRELATION USING AGE OF CRIB AND TIME BETWEEN EXPERIMENTS

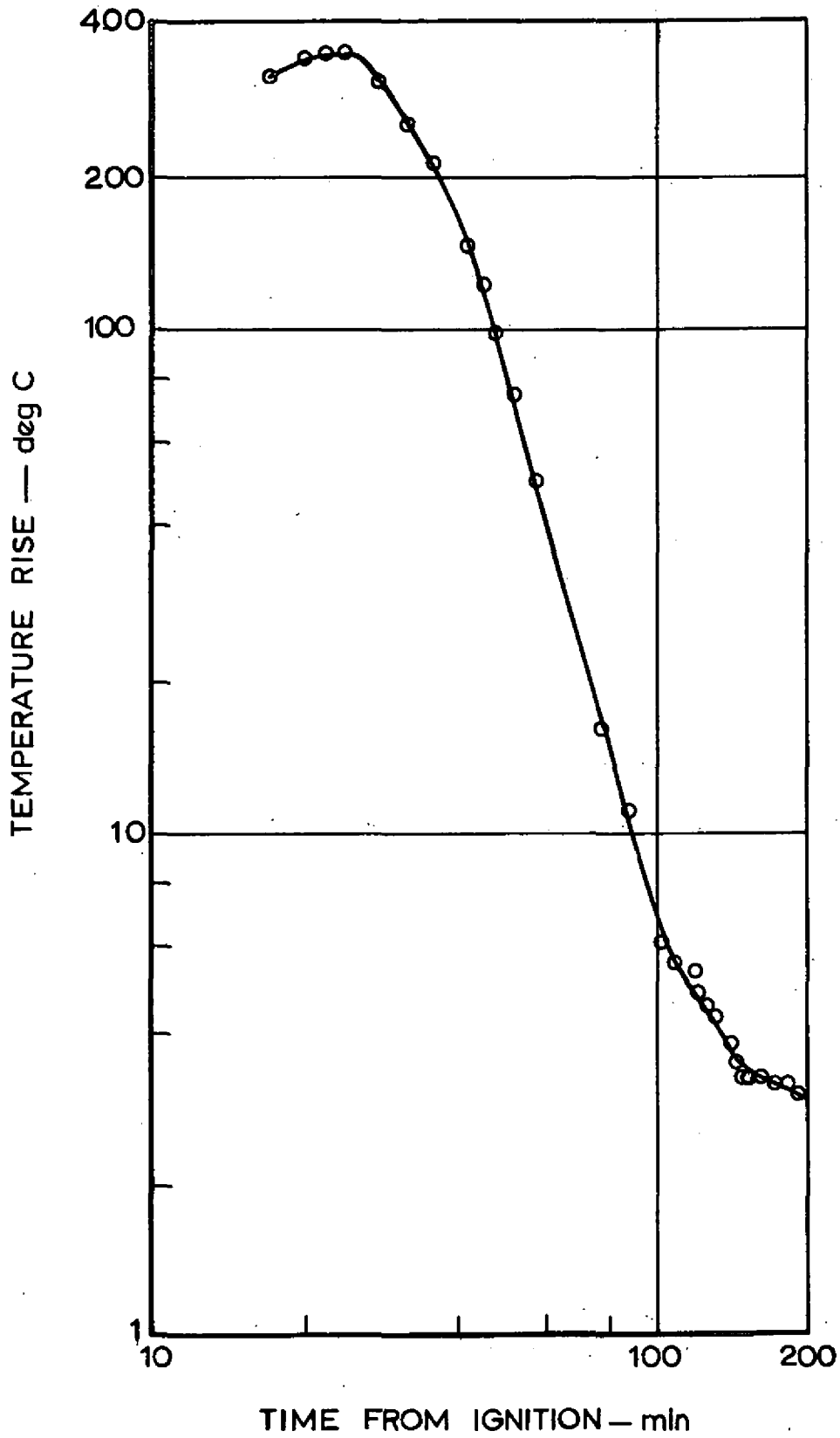


FIG.3. TEMPERATURE OF OUTSIDE OF COMPARTMENT

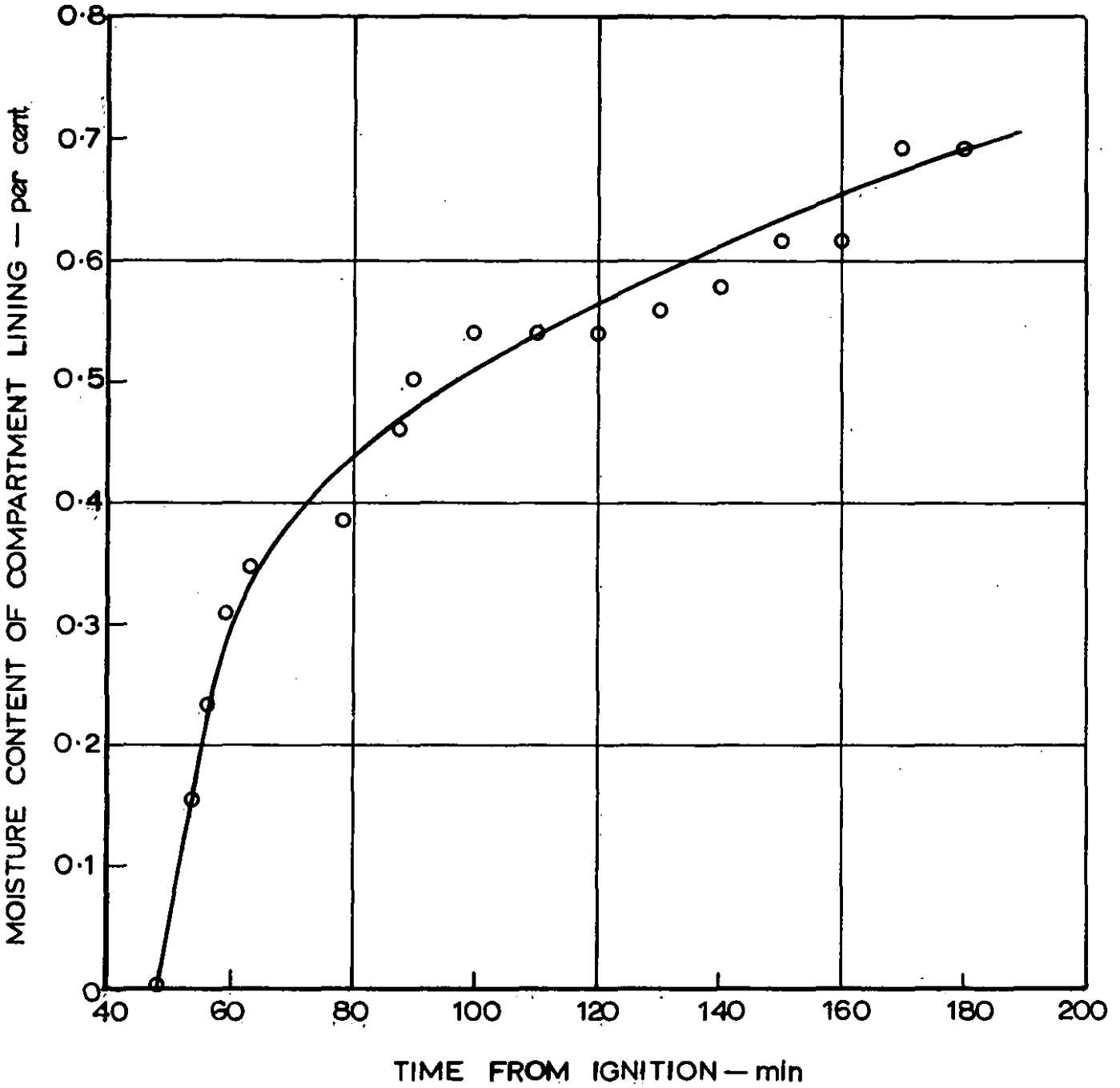


FIG.4. MOISTURE REGAIN OF COMPARTMENT LINING

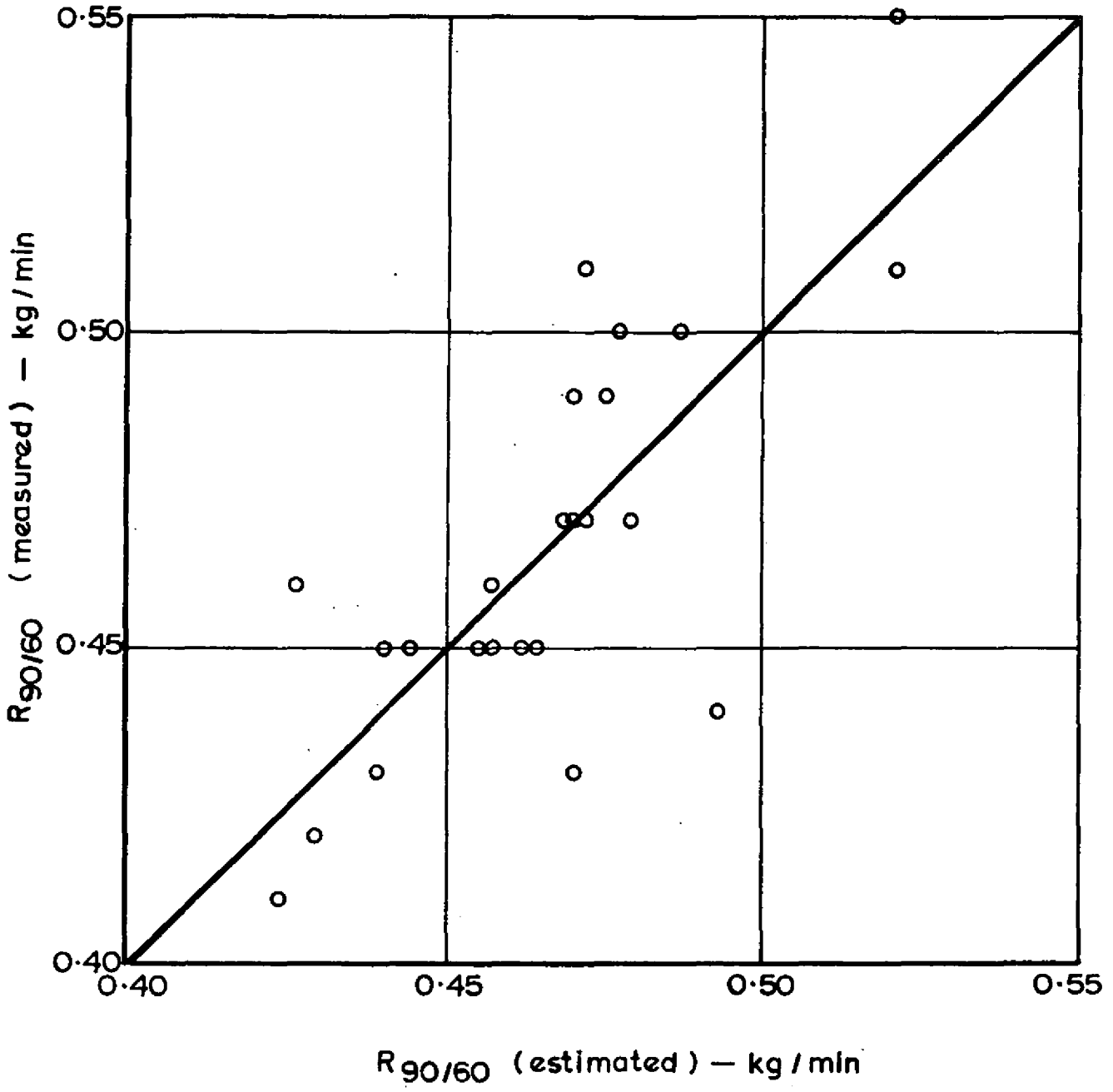


FIG.5. CORRELATION USING AGE OF CRIB AND LINEAR AND QUADRATIC COMPONENTS OF MOISTURE CONTENT OF COMPARTMENT LINING

THE INFLUENCE OF MOISTURE CONTENT OF WOOD FUEL ON FIRES IN A MODEL COMPARTMENT

by

P. G. Smith and A. J. M. Heselden

SUMMARY

Wood cribs containing moisture contents of 3.6 to 13 per cent have been burned in a compartment $\frac{1}{2}$ m x 1 m x $\frac{1}{2}$ m. A very close empirical relationship has been found between the rate of burning during the first kilogram loss in weight and the moisture content of the wood. At slightly later times this relationship ceased to exist, and a possible explanation for this is discussed.

November 1965

THE INFLUENCE OF MOISTURE CONTENT OF WOOD FUEL ON FIRES IN A MODEL COMPARTMENT

by

P. G. Smith & A.J.M. Heselden

Introduction

Following unexplained differences between the results[1] obtained by several laboratories participating in the C.I.B. programme on the growth of fire in model compartments, a series of 24 experiments[2] was carried out by the Joint Fire Research Organization to discover any factors which could account for these differences. One factor which possibly affected the rate of burning of a crib in a compartment was the length of time the crib had been conditioned before being burned. Apart from chemical changes in the wood, which were likely to be very small because of the comparatively short conditioning period (a few weeks), the most probable cause of this effect was thought to be differences in the moisture contents of the cribs. Accordingly a few experiments, which are described in this note, were carried out with cribs having a range of moisture content.

Experimental method

The experiments were carried out in accordance with the procedure given earlier[3]. The values for the compartment and crib parameters were: shape of compartment - 121; height of compartment - $\frac{1}{2}$ m; window fully open; amount of fuel - 20 kg/m^2; dispersion of fuel - 1:3 spacing; and dimension of fuel - 2 cm side. These were also the values used in the series of 24 experiments[2].

The cribs were dried in an oven at 75°C* for at least 72 hours, and two were then placed in each of three sealed containers into which different salt solutions were put so that atmospheres of different relative humidities were obtained. Another two dried cribs were conditioned in a room in which the atmosphere was controlled at 20°C and 60 per cent relative humidity. The final values of moisture contents were 3.6, 4.4, 5.4, 7.7, 10.6, 11.7, 12.1 and 13.0 per cent of the dry weights. The experimental procedure was identical to that adopted earlier[2], except that the weight of each crib was not adjusted to a predetermined value. The experiments were carried out in a random order.

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*Normally wood is dried at 100°C but no oven large enough was available. The rate of loss in weight after 72 hours was small so that the remaining moisture content was low.

Table 1

Experimental data (Rates of burning, radiation measurements, etc.)

Test number	Moisture content of crib (M) per cent	Initial weight of crib (kg)	Calculated initial weight of crib with zero moisture content (kg)	Rate of burning (kg/min) $R_{90/60}$	Rate of burning (kg/min) $R_{60/30}$	Radiation from opening* (cal $cm^{-2}s^{-1}$) $I_{o\ 90/60}$	Radiation from opening* (cal $cm^{-2}s^{-1}$) $I_{o\ 60/30}$	Radiation from flames (cal $cm^{-2}s^{-1}$) $I_{f\ 90/60}$	Radiation from flames (cal $cm^{-2}s^{-1}$) $I_{f\ 60/30}$	Time to lose 1 kg of initial weight t_1 (min)	Mean rate of burning during period 0 to t_1 (kg/min)	Time to lose 2 kg of initial weight t_2 (min)	Rate of burning during period t_1 to t_2 (kg/min)	$\frac{I_{o\ 90/60}}{R_{90/60}}$
82	3.6	9.1	8.8	0.544	0.613	0.331	0.337	0.334	0.299	1.80	0.566	3.55	0.572	0.608
76	4.4	9.35	8.95	0.623	0.549	0.334	0.355	0.470	0.377	1.65	0.606	3.20	0.646	0.536
78	5.4	9.7	9.2	0.510	0.520	0.308	0.340	0.374	0.343	1.65	0.606	3.55	0.527	0.604
77	7.7	9.65	8.95	0.567	0.567	0.322	0.334	0.422	0.343	2.05	0.488	3.65	0.625	0.567
79	10.6	10.2	9.2	0.453	0.478	0.315	0.329	0.270	0.226	2.60	0.385	4.50	0.527	0.695
80	11.7	10.25	9.2	0.505	0.633	0.321	0.329	0.293	0.273	2.40	0.417	4.20	0.556	0.636
75	12.1	10.1	9.0	0.525	0.612	0.337	0.334	0.340	0.284	2.25	0.445	3.85	0.625	0.642
81	13.0	10.05	8.9	0.499	0.542	0.323	0.335	0.283	0.270	2.30	0.435	4.10	0.556	0.647

*Radiation received at radiometer.

Table 2

Experimental data (Ceiling temperatures, etc.)

Test number	Moisture content per cent	Peak ceiling temperature °C	Time (min) for ceiling temperature to change from:-							Time (min) for I_o to attain $\frac{1}{2} I_o$ 90/60	Time (min) for I_f to attain $\frac{1}{2} I_f$ 90/60
			0-200	0-400	0-600	0-Peak	200-400	400-600	600-Peak		
82	3.6	780	0.5	1.0	4.9	14.1	0.5	3.9	9.2	0.84	0.52
76	4.4	810	0.25	1.1	5.1	14.0	0.85	4.0	8.9	0.84	0.71
78	5.4	790	0.5	1.4	5.8	14.9	0.9	4.4	9.1	1.04	0.65
77	7.7	800	0.5	1.4	6.5	14.0	0.9	5.1	7.5	1.25	1.05
79	10.6	790	0.6	1.9	9.6	15.9	1.3	7.7	6.3	1.71	0.92
80	11.7	750	0.6	2.1	7.9	15.8	1.5	5.8	7.9	1.70	0.88
75	12.1	790	0.4	1.9	7.4	15.9	1.5	5.5	8.5	1.43	1.03
81	13.0	760	0.7	1.7	8.6	17.1	1.0	6.9	8.5	1.71	1.00

Results

Table 1 gives measurements of the moisture contents and initial weights of the cribs together with the values obtained for rates of burning, and intensities of radiation from the opening and from the flames. Although all the cribs contained the same number of sticks of the same nominal thickness there were slight differences in their dry weights presumably mainly due to variations in the thickness of the sticks. The mean rate of burning during the period in which the crib lost the first kg of its initial weight is given in Table 1 together with the corresponding rate of burning for the period in which the second kg was burnt.

Table 2 gives measurements of the peak ceiling temperatures, the times for the ceiling temperature to rise between certain values, and the times for both I_o and I_f to attain one half their 90/60 values.

Table 3

Regression coefficients

Dependent variable	Independent variable(s)	Regression coefficient (b)	Significance level of b (per cent)
$R_{1st\ kg}$	M	-0.022	0.1
$R_{2nd\ kg}$	M	-0.0024	Not significant
$R_{90/60}$	M	-0.0083	10
$R_{60/30}$	M	-0.0001	Not significant
$I_{o\ 90/60}$	M	-0.0001	Not significant
$I_{o\ 90/60}$	$R_{90/60}$	0.11	13
$R_{90/60}$	$I_{o\ 90/60}$	3.1	13
$I_{o\ 90/60}/R_{90/60}$	M	0.0091	5
$R_{90/60}$	$I_{o\ 90/60}$ and M $I_{o\ 90/60}$	3.1 for I_o -0.024 for M I_o	Both at 7
$I_{f\ 90/60}$	$R_{90/60}$	0.69	1
$I_{f\ 90/60}$	M	-0.0125	10
$I_{f\ 60/30}$	M	-0.00092	Not significant

Table 3 gives the regression coefficients and significance levels from calculations of the regression of some of the rate of burning and radiation measurements on moisture content (M), $R_{90/60}$ and $I_{o\ 90/60}$.

Rate of burning

The mean rate of burning during the time in which the first kg of wood was burnt ($R_{1st\ kg}$) was found to be highly correlated with the moisture content of the wood fuel (M). Fig. 1 shows the regression line for this correlation which has the equation

$$R_{1st\ kg} = -0.022M + 0.68 \qquad \text{..... (1)}$$

The 95 per cent confidence limits for the regression coefficient are $\pm$ 0.008.

However the rate of weight loss during the time in which the weight of fuel fell from 1 to 2 kg below the initial weight ($R_{2nd\ kg}$) was not significantly correlated directly with moisture content and neither were the rates of burning $R_{90/60}$ and $R_{60/30}$.

It is unlikely that the moisture in all the cribs could have been evaporated in the time taken for the 1st kg to be lost; indeed some cribs contained more than 1 kg of moisture. Furthermore it was noted in these experiments that the fire took several minutes to spread from front to back of the crib. Thus the evolution of moisture is likely to have been spread over an extended period of the fire.

Consequently it might be expected that the moisture content should control the rate of burning $R_{2nd\ kg}$, $R_{90/60}$ and possibly even $R_{60/30}$ to some lesser but still significant extent compared with $R_{1st\ kg}$. The absence of these direct correlations might be because it has been assumed that the measured rate of weight loss equalled the rate of burning of the fuel. Any moisture in the fuel must be evaporated when the fuel is burned, and this will increase the rate of weight loss during the period of evaporation. It is possible that at the higher moisture contents the actual burning rate of the fuel was lower, but that this was masked by an increase in the rate of evaporation of moisture so that the measured rate of weight loss was nearly constant.

Intensity of radiation from the opening (I_o)

$I_{o\ 90/60}$ is not correlated with moisture content although a correlation would be expected if in fact the cribs containing higher moisture contents gave a lower rate of heat release (owing to a smaller rate of evolution of combustible volatiles) as was suggested earlier.

$I_{o\ 90/60}$ is not correlated with $R_{90/60}$ although a relation between these variables was found in a series of tests by three laboratories using three woods[1], when systematic differences between laboratories and woods were allowed for.

However, the significance level of the regression coefficient of $I_{o\ 90/60}/R_{90/60}$ on M was higher than that of $R_{90/60}$ on M or $R_{90/60}$ on $I_{o\ 90/60}$. This suggested that it might be useful to calculate the multiple regression of $R_{90/60}$ on M $I_{o\ 90/60}$ and $I_{o\ 90/60}$. This gives

$$R_{90/60} = 3.1\ I_{o\ 90/60} - 0.024\ M\ I_{o\ 90/60} - 0.40 \qquad \text{..... (2)}$$

The residual deviations of the experimental values of $R_{90/60}$ from the values predicted from equation (2) are uncorrelated with M.

From the experimental data the values of $I_{o\ 90/60}/R_{90/60}$ (Table 1) are very close to the value of 0.61 (in the original units) for the ratio $I_{o\ 90/30}/R_{90/30}$ obtained from the results of three laboratories[1], after allowing for systematic differences between laboratories. From equation (2) an approximate value of 240 cal/g is derived in the Appendix for the heat required to produce 1 gm of volatiles from wood fuel.

Although $I_{o\ 90/60}$ is not directly correlated with $R_{90/60}$, the ratio of the two depends on moisture, in a relation of the form:-

$$\frac{I_{o\ 90/60}}{R_{90/60}} = 0.0091\ M + 0.54 \qquad \text{.....(3)}$$

derived directly from the regression of the ratio on M. The approximate relation derived from equation (2) inserting a mean $I_{o\ 90/60}$ of 0.3 cal $cm^{-2}s^{-1}$ is:-

$$\frac{I_{o\ 90/60}}{R_{90/60}} = 0.007\ M + 0.5$$

The time taken for radiation from the opening to attain $\frac{1}{2} I_{o\ 90/60}$ (Table 2) is correlated with moisture content at the 0.1 per cent level.

Intensity of radiation from the flames (I_f).

The values for I_f (Table 1) vary considerably between experiments and are significantly correlated with rate of burning over the 90/60 period but not with moisture content of the crib over either the 90/60 or 60/30 periods.

The time taken for the intensity of radiation from the flames to attain $\frac{1}{2} I_{f\ 90/60}$ (Table 2) is correlated with moisture content at the 2 per cent level.

Although no shield was used with the I_o radiometer to cut off flame radiation, the variations in I_o were not due to variations in the flame radiation because I_o is not correlated with I_f.

Temperatures

Although the peak ceiling temperatures (Table 2) are not significantly correlated with moisture content, the times taken to reach particular temperatures are highly correlated.

The correlations are significant between the 0.1 and 1 per cent levels not only for the time for the ceiling temperature to reach 400°C, 600°C and its peak, but also for the time for the temperature to change from 200 - 400°C and 400 - 600°C. Times for changes 0-200°C and 600°C-peak are not significant. 600°C was attained in 5-10 minutes and the peak temperature in 14-17 minutes, so that even after the period in which the 1st kg of weight loss occurred (up to 2½ min) the rate of temperature rise was less with the cribs with a higher moisture content, and this is in accordance with the lower heat release rate that would be expected from the wetter cribs if the rate of decomposition of dry wood were lower.

Similar, although less statistically significant, correlations were obtained from measurements of the temperature of the outside of the compartment. The floor temperatures were too inconsistent to show any general trend.

Conclusions

In these experiments decreasing the moisture content of the crib increases the rate of loss of weight in the earliest part of the fire, but has no statistically significant effect on $R_{90/60}$ or $R_{60/30}$. This may be because as wood moisture content increases a lower rate of decomposition of wood is accompanied by an increase in the rate at which moisture is driven off.

The moisture content has no statistically significant effect on $I_{o\ 90/60}$, $I_{f\ 90/60}$ and $I_{f\ 60/30}$, but is correlated with $\frac{I_{o\ 90/60}}{R_{90/60}}$.

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(2) SMITH, P. G. Factors affecting the rate of burning of wood in asbestos lined compartments. Supplement paper I

(3) LAWSON, D. I. International co-operation in modelling fires. A suggested programme. Supplement paper A.

APPENDIX

Let R_M = rate of burning (kg/min) of wood assumed constant during the test containing a percentage moisture content of M

R_D = rate of burning of dry wood (kg/min)

H_D = heat required (cal) to produce a loss in weight of dry wood of 1 gm

H_M = heat required (cal) to produce a loss in weight of 1 gm of wood containing a percentage moisture content of M.

H_W = difference in enthalpy between water vapour emerging from the fuel bed and adsorbed water in the fuel at initial fuel temperature (cal/g).

I = radiant intensity incident on crib (cal $cm^{-2}s^{-1}$), assumed to be directly related to I_o.

A = effective surface area of crib (cm^2).

Then if the burning rate is assumed to be proportional to the radiant heat received by the crib:-

$$AI = \frac{1000}{60}\left\{R_M H_M\right\} = \frac{1000}{60}\left\{R_D H_D\right\}^*$$

Then
$$\frac{R_M}{R_D} = \frac{H_D}{H_M} = \frac{H_D}{H_D\left(1 - \frac{M}{100}\right) + H_W \frac{M}{100}}$$

assuming that moisture is liberated at a constant rate throughout a test.

$$\frac{R_D}{R_M} = 1 - \frac{M}{100} + \frac{H_W}{H_D}\frac{M}{100} \qquad \text{..... (4)}$$

Equation (2) gives $R_D = 3.1\ I_{o\ 90/60} - 0.40$ ..... (5)

and $R_M = 3.1\ I_{o\ 90/60} - 0.024\ M\ I_{o\ 90/60} - 0.40$ ..... (6)

Dividing (5) by (6) gives, for $I_o \simeq 0.3$ cal $cm^{-2}s^{-1}$,

$$\frac{R_D}{R_M} = \frac{1}{1 - 0.0136\,M} \qquad \text{..... (7)}$$

Equating (4) and (7)

$$\frac{H_W}{H_D} = \frac{100}{M - 0.0136\,M^2} - \frac{100}{M} + 1 = \frac{2.36 - 0.0136M}{1 - 0.0136\,M}$$

---

*Table 3 shows that I_o does not depend on moisture content.

$$\text{For } M = 3.6, H_D = \frac{H_W}{2.43}$$

$$\text{For } M = 13, H_D = \frac{H_W}{2.65}$$

If it is assumed that the water vapour emerges from the wood at 100°C, H_W can be taken as about 620 cal/g neglecting any heat of wetting.

The $H_D \simeq 240$ cal/g.

The regression coefficients in equation (2) are best estimates and calculations similar to that carried out above but with the 95 per cent confidence limits for the regression coefficients gave values of H_D of 150 and 800 cal/g, so that H_D can be said to lie probably within these limits. These are of the same order as the value of 350 cal/g obtained by Thomas and Smith[1] from correlations of burning rate and radiation intensity in previous experiments.

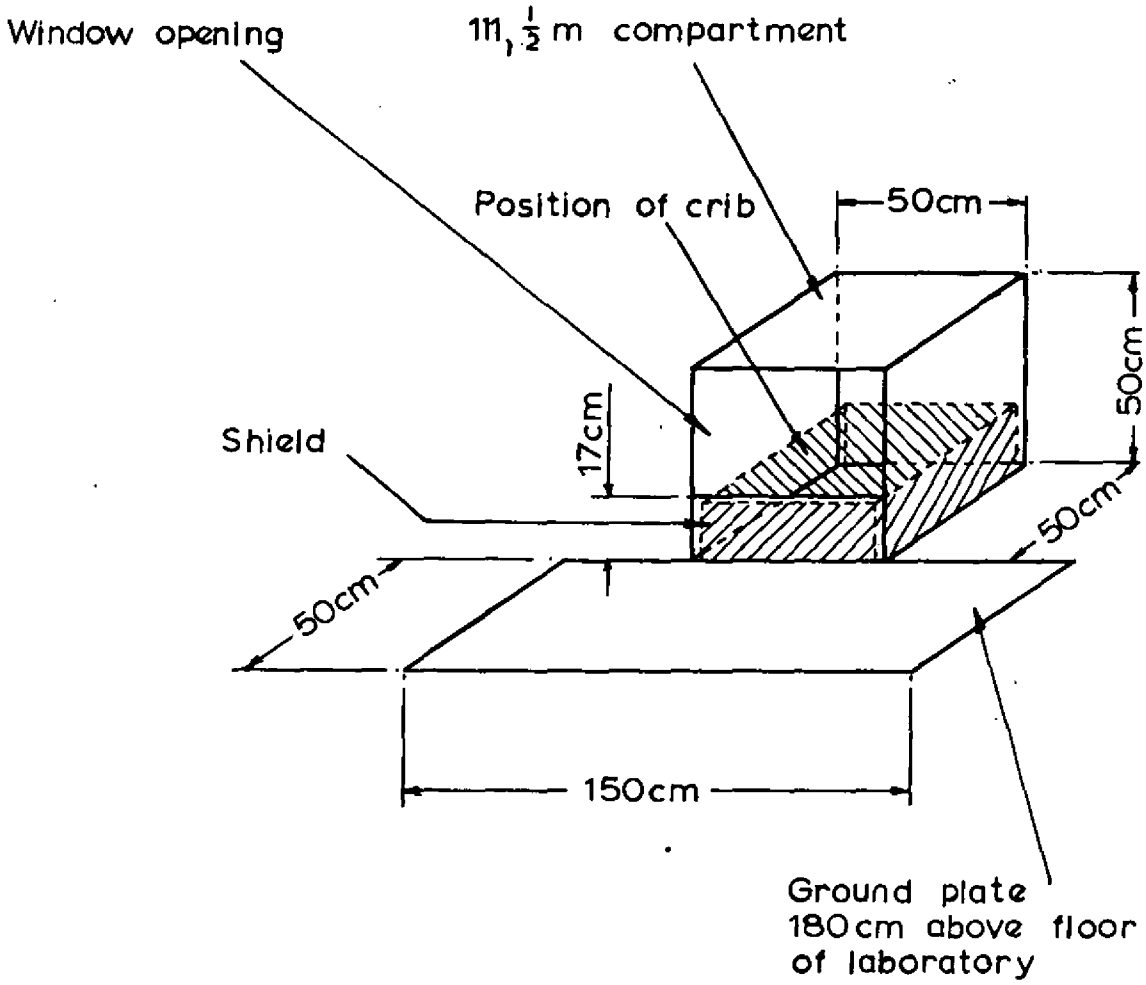

FIG.1. 111, ½ m COMPARTMENT AND GROUND PLATE

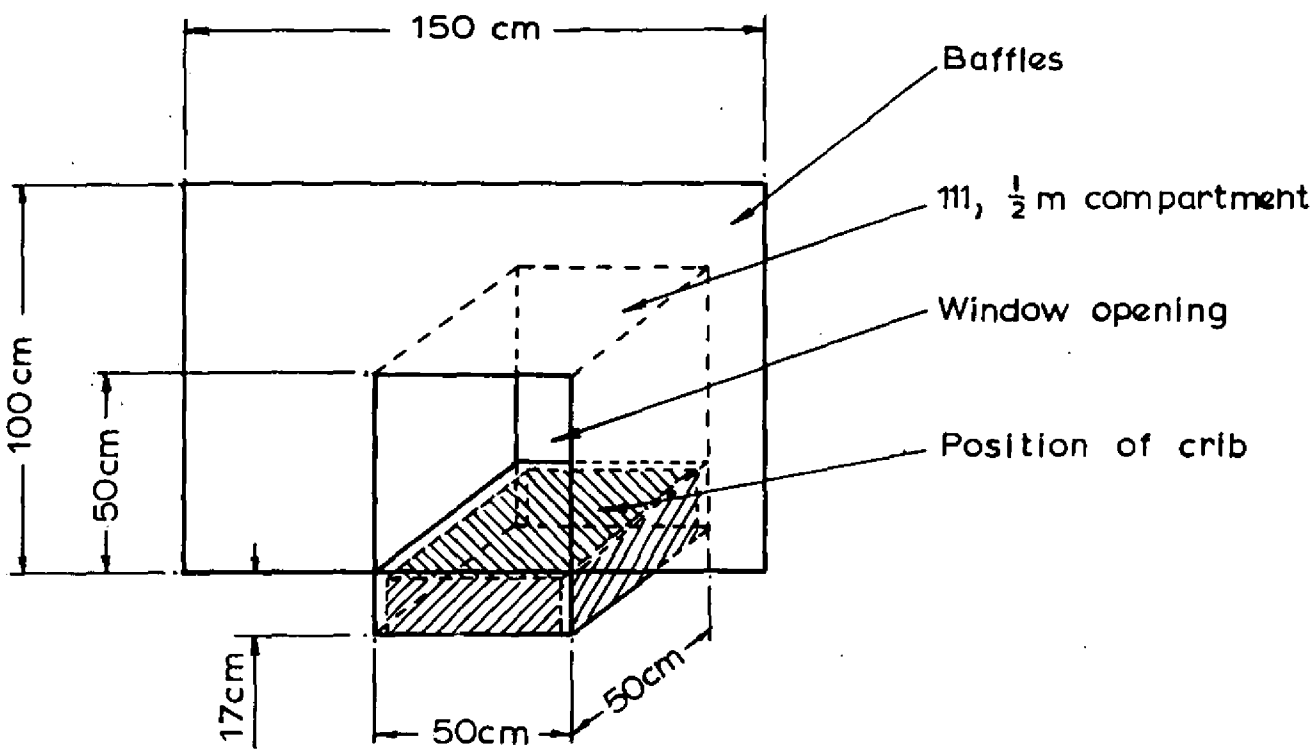

FIG.2. 111, ½ m COMPARTMENT WITH BAFFLES

COMPARTMENT MATERIALS USED IN THE C.I.B. PROGRAMME

by

G. K. Bedford

SUMMARY

This note describes the different materials which have been used as compartment linings in the C.I.B. International Co-operation Programme studying fully-developed fires, and gives details of their composition and thermal properties.

April 1966

COMPARTMENT MATERIALS USED IN THE C.I.B. PROGRAMME

by

G. K. BEDFORD

1. Introduction

The C.I.B. International Co-operation Programme studying the growth of fully-developed fires comprises some 500 experimental fires in asbestos-lined compartments, carried out by 10 laboratories. The influence of a number of factors is being explored, notably compartment size, shape and ventilation, and fuel quantity and dispersion. Since the laboratories could not all use precisely the same compartment material it was thought advisable to collect into one report data on all the materials used, their thickness and any known thermal properties which might influence the growth of fire. This is particularly important in those few cases where laboratories have had to change the material during a series of experiments; in some cases it is clear that the fire behaviour was affected by the change.

In the model experiments conducted by C. T. Webster and others on the growth of fire,(1),(2),(3) a material manufactured in the United Kingdom and marketed under the name "Turnall" Asbestos Insulation Board, was used as the lining for the compartments. This material which is commonly referred to as "Asbestos wood" was known for its durability at high temperatures and its hardness which enabled it to be accurately cut to size. It was used in some of the first experiments in the C.I.B. programme,(4),(5),(6) but when employed in large sheets, was found to crack severely and, following the experience of the T.N.O. laboratory, other boards, in most cases softer, had to be used for most of the programme. Table 1 lists the C.I.B. meetings at which the modelling programme was discussed together with decisions arrived at, and the experimental work carried out between meetings.

2. Classification of Asbestos-based boards

These are manufactured to conform generally to one of three categories, depending largely on the content of asbestos fibres.

1) Asbestos Cement is the most brittle of all asbestos-based sheets, and consists of an inert composition of clean asbestos fibres bonded together by an inorganic cement, the cement being the main constituent of the material.

In the United Kingdom the asbestos conforms to British Standard Specification 690/1963, the inorganic cement conforming to British Standard Specification 12/1958.

Because it is very brittle and liable to spall when heated this material could not be used as a compartment lining for fire tests.

2) Asbestos Insulating Board and Wall Boards have been used in the C.I.B. modelling programme, and like asbestos cement consist of asbestos fibres bonded together with an inorganic cement, an approved medium being china clay. Unlike asbestos cement sheet their main constituent is asbestos fibres. They conform in the United Kingdom to British Standard Specification 3536/1962.

3) Asbestos Millboard is very similar to Asbestos Insulating Board and Wall Board, since the asbestos fibres make up the greater proportion of the material. The content of asbestos fibres is much higher however, and never accounts for less than 97 per cent of the finished millboard. In the United Kingdom millboard may conform to a Ministry of Defence Specification[7]. The board is very soft, it can stand very little handling and is therefore difficult to work with and fix. It is however, a suitable material for use as a lining for compartments containing fires, though it does need to be extensively supported.

Table 2 gives the density, thermal conductivity and commercially available thickness of the categories of asbestos-based sheets. Details of proprietary boards used in the programme are given in the Appendix.

3. Materials used in C.I.B. programme

The C.I.B. modelling programme consists of three main sections:-

a) Initial tests in 121 ½ m compartments conducted by the T.N.O., J.F.R.O., and N.B.S. laboratories[5] and the preliminary tests conducted by some other laboratories prior to starting Series I experiments

b) Series I experiments conducted by nine laboratories[8]

c) Series II experiments conducted by ten laboratories[8]

Tables 3 to 9 show the types of asbestos board used in the programme and their properties.

During the Series I experiments the C.E.B.S. found that asbestos wood was unsuitable for large compartment fires. "Asbestolux" was tried as an alternative but proved to be no more satisfactory. An asbestos millboard compartment was then constructed and used to complete the remaining tests in both Series I and II. Difficulties with other materials were also experienced by the B.A.M. (Germany(I)).

Tables 5, 6, 7 and 8 show the different types of asbestos boards used in both Series I and Series II experiments conducted by the C.E.B.S. and B.A.M. and the actual tests in which the boards were used. The N.B.S. used "Superbestos" for their compartments and since it cracked severely during the initial tests repairs were effected by spraying a thin layer of fire-resisting plaster over the board. Large fissures were also made good with this plaster whose thermal conductivity was the same as that of the "Superbestos".

The 1½ m 441 experiments by the J.F.R.O. proved to be so severe that it was necessary to use a composite construction for the walls and ceiling, consisting of a 6 mm thickness of "Fibrefrax Locon Felt" (see Appendix), manufactured by Carborundum Co.LLtd., treated with a rigidiser and cemented with silicate adhesive to a suporting exterior layer of 6mm thick asbestos wood. The floor was formed of two 1cm layers of asbestos millboard.

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7. U.K. Ministry of Defence Specification, Asbestos Millboards No.D.E.F./92 31st July, 1957.
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APPENDIX

DESCRIPTIONS OF PROPRIETARY MATERIALS USED

"Asbestolux"

Is a low density asbestos board of British manufacture consiting of amosite asbestos fibres and silica. A silica/lime bond between the asbestos fibres is obtained by the addition of hydrated lime during the manufacturing process.

"Superbestos"

Is a low density asbestos board of Canadian manufacture very similar to Asbestolux.

"Pearlite Board"

Is a low density asbestos board of Japanese manufacture consisting of Pearlite, asbestos fibres and cement in the ratio 5 : 7 : 8 by weight.

"Pical"

Is a low density asbestos board of French manufacture consisting of approximately 70 per cent of asbestos fibre and 30 per cent of perlite, sand and cement binder.

"Fibrefrax Locon Felt"

Is made by the Carborundum Co. (New York) and consists of ceramic alumina-silica fibres with up to 3% of a non-flamming organic binder added to increase the handling strength. Melting point of the fibres is above 1760°C and they will withstand continuous use at 1260°C. There is no water of combination. To improve further the ease of handling, the felt was treated with a rigidiser.

TABLE 1

C.I.B. meetings and Modelling Programme Decisions

C.I.B. meeting	Venue	Date	Decisions in future programme	Work carried out between meetings
3rd	Brussels and The Hague	September 1958	Draft programme to be produced	
				8 laboratories carried out experiments in 121 $\frac{1}{2}$ m. Model Compartment (material not specified)
4th	London	May 1960	3 laboratories to carry out experiments using asbestos wood as supplied by J.F.R.O., with wood from several countries. Experimental procedure more closely specified.	
				3 laboratories carried out experiments as decided.
5th	Rome	October 1961	10 laboratories each to carry out parts of a large programme (4 shapes, 3 scales). The T.N.O. design of box would be adopted if it proved satisfactory.	
				Some of the 10 laboratories completed their experiments. A few laboratories used different compartment materials to those used by T.N.O.
6th	Berlin	April 1964	Data to be analysed and more experiments completed before any extension of the programme.	
				Most laboratories circulated complete results to the other participating laboratories.

TABLE 2

Categories of asbestos-based sheets

Material	Range of thickness cm	Range of Density g/cm^3	Range of Thermal Conductivity $cal\ cm^{-1} s^{-1} deg\ C^{-1} \times 10^4$
Asbestos cement board	0.5 - 1.25	1.36 1.5 2.0	5 - 7 7 - 10 10 - 15
Asbestos wall board	-	0.9 - 1.45	< 8.6
Asbestos insulating board	0.62 - 1.25	0.5 - 0.9	< 3.4
Asbestos millboard	0.5 - 1.5	0.75 - 1.25	2.5 - 4

TABLE 3

Asbestos boards used in Preliminary Tests[6],[9] (121, ½ m)

Material	Manufacturer or supplier	Laboratory	Approximate average thickness cm	Density g/cm^3	Thermal Conductivity at room temperature $cal\ cm^{-1} s^{-1} deg\ C^{-1} \times 10^4$
"Turnall" Asbestos Insulation Board (Asbestos Wood)	Turner's Asbestos Cement Co. Ltd.	C.E.B.S. (Australia) N.B.S. (U.S.A.) T.N.O. (Netherlands) J.F.R.O. (United Kingdom)	1.0	1.25	7
"Pical"	Sté. du Fibrociment et des Revêtements ELO à TRIEL (Seine-et-Oise)	C.S.T.B. (France)	1.6	0.64 (D)	1.9 (D)
Asbestos Millboard[f]	German	B.A.M. (Germany (1)) *F.B.K. (Germany (2)) *F.B.K. (Germany (3))	1.0	1.0	4

*F.B.K. = Forschungsstelle für Brandschutztechnik, Karlsruhe

[f] AP60 DIN 3752 (60 per cent asbestos, 40 per cent mineral fibre)

(D) = Dry material

TABLE 4

Asbestos boards used in Series I Experiments

Material	Manufacturer or supplier	Laboratory	Approximate average thickness cm	Density g/cm^3	Thermal Conductivity at room temperature cal $cm^{-1} s^{-1} deg\ C^{-1} x10^4$
Asbestos Millboard	Turner's Asbestos Cement Co. Ltd. and Bell's Asbestos & Engineering Co. Ltd.	J.F.R.O. (United Kingdom)	1.0	1.1	3.4
	Australian	C.E.B.S. (Australia)	1.2	1.06	2.8 (D)
	Dutch	T.N.O. (Netherlands)	1.0	1.1	3.9 (M)
Asbestos Millboard/	German	B.A.M (Germany (1))	1.0	1.0 and 1.1	4
Asbestos Millboard*	German	F.B.K. (Germany (2))	1.0	1.1	4
		F.B.K. (Germany (3))	1.0	1.1	4

/Two kinds of asbestos millboard used. See Table 7.

*AP60 DIN 3752 (60 per cent asbestos, 40 per cent mineral fibre)

(D) = Dry material

(M) = Material containing equilibrium moisture content at room temperature

TABLE 4 (Cont'd.)

Asbestos boards used in Series I Experiments

Material	Manufacturer or supplier	Laboratory	Approximate average thickness cm	Density g/cm^3	Thermal Conductivity at room temperature cal $cm^{-1}s^{-1}deg\ C^{-1} \times 10^4$
Reinforced Sprayed Asbestos Fibres	German	(Germany (1))	1.5	0.3	-
"Turnall" Asbestos Insulation Board (Asbestos Wood)	Turner's Asbestos Cement Co. Ltd.	C.E.B.S. (Australia)	1.0	1.25	7
Asbestolux	James Hardie and Co. Pty. Ltd.	C.E.B.S. (Australia)	0.95	0.82 (M)	2.8 (D)
Pearlite Board	Asano-Slate Co. (Japan)	**B.R.I. (Japan)	1.2	0.66	2.8
Superbestos	Turner Newall (Canada) Ltd.	N.B.S. (U.S.A.)	0.95	0.67	2.9 (D)
Pical	See Table 3	C.S.T.B. (France)	1.6	0.69 (D)	1.9 (D)

**B.R.I. = Building Research Institute, Tokyo, Japan.

(D) = Dry material

(M) = Material containing equilibrium moisture content at room temperature

TABLE 5

Asbestos Board distribution in C.E.B.S. Series I Experiments

Scale m	Fire load density kg/m^2	Window opening	121 shape		221 shape	
			2.1 crib		2.1 crib	
			Material	Test No.	Material	Test No.
1	20	1/4	ALX ALX	7 15	AWB AMB	3 13
		1	AWB ALX	5 10	AWB AMB	1 16
	40	1/4	AWB ALX	6 14	ALX AMB	8 11
		1	AWB ALX	2 12	AWB AMB	4 9

ALX = 1 cm thick "Asbestolux"

AWB = 1 cm thick Asbestos Wood Board

AMB = 1.25 cm thick Asbestos Millboard.

TABLE 6

Asbestos Board Distribution in B.A.M. (Germany(I))
Series I Experiments

Scale m	Fire load density kg/m^2	Window opening	121 shape		221 shape	
			2.1 crib		2.1 crib	
			Material	Test No.	Material	Test No.
1	20	1/4	AMB 60 AMB 60	6 1	AMB 97 SAF	10 15
		1	AMB 60 AMB 60	4 2	AMB 60 SAF	9 12
	40	1/4	AMB 60 AMB 60	5 8	AMB 97 SAF	11 16
		1	AMB 60 AMB 60	3 7	SAF SAF	13 14

Key: AMB 60 = Asbestos Millboard AP60 (DIN 3752) containing 60 per cent asbestos fibres, 40 per cent mineral fibres (Density 1.1 g/cm^3).

AMB 97 = Asbestos Millboard AP97 (DIN 3752) containing 97 per cent asbestos fibres, 3 per cent mineral fibres (Density 1.0 g/cm^3).

SAF = Sprayed Asbestos fibres reinforced with expanded metal.

TABLE 7

Asbestos Boards used in Series II Experiments

Laboratory	Boards used
C.E.B.S. (Australia)	See Table 9
B.A.M. (Germany (1))	See Table 10
F.B.K. (Germany (2)) (Germany (3))	Asbestos Millboard AP60, (as in Series I)
T.N.O. (Holland)	Asbestos Millboard, (as in Series I)
B.R.I. (Japan)	Pearlite Board, (as in Series I)
N.B.S. (U.S.A.)	Superbestos, (as in Series I)
C.S.T.B. (France)	Pical, (as in Series I)
J.F.R.O. (U.K.)	Asbestos Millboard for the ½ m 441 fires (Table 4). Composite construction for the 1½ m 441 fires (section 3).

TABLE 8

Asbestos Board Distribution in C.E.B.S. Series II Experiments

Scale m	Fire load density kg/m^2	Window opening	221 shape					
			2.1/3 crib		2.1 crib		4.1 crib	
			Material	Test No.	Material	Test No.	Material	Test No.
1/2	20	1/4	AWB	31	AWB	32	AWB	33
		1/2	AWB	34	AWB	35	AWB	36
		1	AWB	37	AWB	38	AWB	39
1	20	1/4	AMB	17			AMB	19
		1/2						
		1	AMB	18			AMB	20
	30	1/4	AMB	21	AMB	29	AMB	23
		1/2						
		1	AMB	22	AMB	30	AMB	24
	40	1/4	AMB	25			AMB	27
		1/2						
		1	AMB	26			AMB	28

Key: As for Table 6.

TABLE 9

Asbestos Board Distribution in B.A.M. (Germany (1))
Series II experiments

Scale m	Fire load density kg/m^2	Window opening	211 shape					
			1.3 crib		2.1 crib		2.3 crib	
			Material	Test No.	Material	Test No.	Material	Test No.
1/2	20	1/4	AMB 60	34	AMB 60	36	AMB 60	35
		1/2	AMB 60	39	AMB 60	38	AMB 60	37
		1	AMB 60	33	AMB 60	32	AMB 60	31
1	20	1/4	AMB 60	28			AMB 60	21
		1	AMB 60	25			SAF	17
	30	1/4	AMB 60	29	AMB 60	24	AMB 60	22
		1	AMB 60	26	AMB 60	19	SAF	18
	40	1/4	AMB 60	30			AMB 60	23
		1	AMB 60	27			AMB 60	20

Key: As for Table 7.

ANALYSIS OF THE EXPERIMENTS

PART 1. VARIATION BETWEEN LABORATORIES

by

R. Baldwin, A. J. M. Heselden and P. H. Thomas

SUMMARY

There are significant variations between the results of laboratories participating in Series I for the rates of burning and intensity of radiation from the flames above the window. This variation is found to be due to one laboratory only, and although it is fairly large for the rates of burning, there is some evidence that the greater part of the variation is due to differences between compartment materials.

October 1965

ANALYSIS OF THE EXPERIMENTS

PART I VARIATION BETWEEN THE LABORATORIES.

by

R. BALDWIN, A.J.M. HESELDEN and P. H. THOMAS.

Introduction

This report describes an analysis of Series 1 of the experiments on the modelling of fires in compartments carried out by different countries under the auspices of the Conseil International du Bâtiment[1]. Previous preliminary experiments aimed at standardization of technique and experimental method showed unexplained differences in the rates of burning measured by different laboratories under similar experimental conditions[2,3,4]. Series 1 of the programme, has been designed with the object of measuring and where necessary allowing for these differences[5]. The application of the laboratory biases to these data and the results of future experiments as a means of standardizing the results so that real physical effects may be investigated is discussed below. The present report is divided into three parts:-

1. The presentation of the results of the experiments.
2. The search for significant differences between laboratories.
3. The estimation of the bias to be associated with each laboratory and a discussion of its application.

Design of the experiments

Each laboratory carried out a series of experiments on fires in model compartments in which the fire load ventilation and compartment shape were varied in order to measure their effect on the rate of growth, intensity and duration of fires. The design of the series was such that an estimate of the variation between laboratories, and also of replications in any one laboratory, could be obtained with the minimum number of experiments. This was achieved by considering three different compartment shapes, but only two of these were studied by each laboratory, as shown in Table 1; this scheme forms a balanced incomplete block design, in which each compartment shape is studied by four different laboratories giving an estimate of variation between laboratories. A definition of the notation used is given in Appendix I. The original series included nine laboratories, but two of these have not completed the experiments allotted to them. Since the remaining data no longer formed a balanced incomplete block design, making analysis very difficult, if not impossible,

Table 1

Compartment shape studied by the participating laboratories

	Laboratory					
	L1	L2	L3	L4	L5	L6
211	-	X	X	-	X	X
121	X	-	X	X	-	X
221	X	X	-	X	X	-

Participating laboratories

L1	Commonwealth Experimental Building Station	Australia
L2	Bundesanstalt für Materialprüfung	Germany (Berlin)
L3	Brandveiligheids Instituut T.N.O.	Netherlands
L4	Forschungsstelle für Brandschutztechnik	Germany (Karlsruhe)
L5	National Bureau of Standards	U.S.A.
L6	Forschungsstelle für Brandschutztechnik	Germany (Karlsruhe)

The two shapes studied by each laboratory are denoted by X.

the results of one of the laboratories, the Building Research Institute, Ministry of Construction, Japan, have not been included in the present analysis so that the data of the remaining six laboratories form a balanced incomplete block design. The data of the Building Research Institute, Ministry of Construction, Japan, or any other laboratory not examined here will be compared separately with the data of other laboratories in order to estimate its bias.

This design was repeated twice for each of four different combinations of fire load and ventilation, this replication giving an estimate of experimental variation within each laboratory. The following table defines the combinations of fire-load and ventilation studied in this series of experiments.

Table 2

Fire load-ventilation combinations

Fireload	Ventilation	
	$\frac{1}{4}$	1
20	2	2
40	2	2

All of these experiments were conducted on compartments 1 metre high with (2.1) stick size and spacing and as far as possible the materials and experimental techniques used were standardized. During the course of each experiment, the following quantities were recorded.

I_o intensity of radiation from the window opening.

I_F intensity of radiation from the flames above the window opening.

θ_b temperature near the floor of compartment.

θ_c temperature near the ceiling of compartment.

R rate of burning of fuel.

The position at which each of these readings was taken, in relation to the shape and scale of the compartment, is defined in Appendix 1. The results of each laboratory have been circulated to each of the participating laboratories and will not be reproduced in the present report in which certain average statistics only will be considered, as described below.

1. Presentation of results

(1.1) Time-mean statistics

The period of the fire in the compartment of greatest relevance to the prediction of fire resistance and for which useful results are available from the present series of experiments is the approximately steady period when the fire is fully developed, defined approximately by the period during which the weight of the fuel falls from 80 per cent to 30 per cent of its initial value. This excludes the early growth period when the rate of burning varies most with time and the final period during which the residual charcoal burns. The 80/30 period is most conveniently studied by averaging the values of intensity of radiation, temperature and weight loss during the period or over shorter periods within this period. The values of these time-mean statistics have been calculated from the recorded values and are presented in Table 3. The notation used may be defined by the following example:

θ_b 80/55 denotes the time-mean value of θ_b over the period during which the weight of the fuel falls from 80 per cent to 55 per cent of its initial value and 55/30 denotes a similar mean between times corresponding to 55 per cent and 30 per cent of the initial weight.

t_{80} is the time from ignition to the time when the weight is 80 per cent of its initial value.

During the 80/55 and 55/30 periods the loss of weight is one-quarter of the initial weight. A comparison between an 80/55 value and a 55/30 value is a measure of the variation in the approximately steady period, whilst t_{80} is one measure of the duration of the early growth period.

(1.2) Recalculations by J.F.R.O.

Each of the time-mean values of Table 1 was calculated initially by the laboratory of its origin, but inspection of the data showed a few obvious errors which have been recalculated from the original data. Values missing in the original data because, for example, of instrumental limitations or failure have been inserted by interpolation where possible or by comparison with replicates, since for the statistical calculations it was essential for the data to be complete. Details of alteration to all values calculated by the different laboratories are given in Appendix 2.

Laboratory L1 experienced difficulty with the material out of which the model compartment was constructed. The original material was specially imported but failed before completion of the planned series of experiments, and in order to avoid delays a different material, locally obtainable, was employed which also proved unsatisfactory. Thus during the course of the experiments, three different materials were used. In order to minimise any effects due to different materials the results of this laboratory's experiments have been normalised to one of the materials used, by finding for each fire load and ventilation, at least one value for an experiment conducted with a compartment of that particular material, and then replacing this value by two values whose mean is that of the value they are replacing, separated by a value commensurate with the differences between replicates of other laboratories. The details of the calculations are illustrated by the following example.

Table 4 shows the Australian results for R80/55 and the figures in brackets beside each value indicate the box materials used during the experiment.

Table 4

Original Australian data for R80/55, showing compartment materials used

Fireload	20		40	
Ventilation	$\frac{1}{4}$	1	$\frac{1}{4}$	1
121	1.19 (2) 1.47 (2)	1.92 (1) 2.38 (2)	1.39 (1) 1.85 (2)	2.00 (1) 2.94 (2)
221	2.94 (1) 3.70 (3)	3.33 (1) 5.26 (3)	3.20 (2) 3.54 (3)	4.12 (1) 5.71 (3)

(1) Turnalls asbestos board

(2) Asbestolux

(3) Asbestos millboard

Since there is one value for Material 1 for each fire load-ventilation combination except 121/20/$\frac{1}{4}$ and 221/40/$\frac{1}{4}$*, these data will be normalized to

*121/20/$\frac{1}{4}$ refers to the experiment with a compartment of shape 121, fireload 20 kg/m^2 and ventilation $\frac{1}{4}$.

Table 3a)

Time-mean statistics - rates of burning, R (kg/min)

Shape	Laboratory	FIRELOAD 20		40		20		40		20		40	
		VENTILATION ¼	1	¼	1	¼	1	¼	1	¼	1	¼	1
		R 80/55				R 55/30				R 80/30			
211	L1	-	-	-	-	-	-	-	-	-	-	-	-
	L2	3.04 2.78	2.44 2.64	2.94 3.34	4.17 4.00	3.12 2.71	1.76 2.22	2.64 2.36	2.25 2.54	3.08 2.74	2.04 2.42	2.78 2.76	2.92 3.11
	L3	3.57 3.57	2.50 2.27	3.13 3.13	(4.25) 3.85	2.50 2.78	1.67 1.72	2.50 2.38	2.27 2.00	2.94 3.12	2.00 1.96	2.78 2.70	2.96 2.63
	L4	-	-	-	-	-	-	-	-	-	-	-	-
	L5	3.45 3.45	2.33 2.56	3.23 3.28	3.64 3.70	2.22 2.22	1.47 1.96	2.56 2.50	2.53 2.67	2.70 2.70	1.80 2.22	2.86 2.84	2.98 3.10
	L6	3.45 3.64	1.82 2.40	3.02 3.16	4.21 4.18	2.88 3.88	1.59 2.03	2.76 2.78	2.62 2.68	3.14 3.76	1.70 2.20	2.89 2.96	3.23 3.27
121	L1	1.02 0.98	2.06 1.78	1.44 1.34	2.08 1.92	1.02 0.98	1.53 1.29	1.26 1.18	1.24 1.12	1.04 0.98	1.71 1.55	1.34 1.26	1.54 1.42
	L2	-	-	-	-	-	-	-	-	-	-	-	-
	L3	1.25 1.25	2.38 2.50	1.25 1.43	2.50 2.78	1.14 (1.14)*	1.56 1.67	0.89 1.02	1.56 1.67	1.19 1.19	1.88 2.00	1.04 1.19	1.92 2.08
	L4	1.4 1.50	2.66 2.36	1.45 1.47	2.76 2.86	1.4 1.49	2.13 2.69	1.21 1.24	2.08 2.29	1.4 1.49	2.36 2.51	1.32 1.35	2.37 2.54
	L5	-	-	-	-	-	-	-	-	-	-	-	-
	L6	1.34 (1.23)	2.0 2.4	1.38 1.32	2.7 2.63	1.36 (1.33)	2.02 2.03	1.22 1.18	2.12 2.13	1.35 1.28	2.01 2.20	1.29 1.25	2.38 2.35
221	L1	3.10 2.78	3.60 3.06	2.84 2.78	4.47 3.77	2.11 2.01	3.30 3.16	1.94 1.84	2.99 2.35	2.47 2.37	3.43 3.13	2.28 2.24	3.59 2.89
	L2	3.51 4.17	6.25 6.90	3.20 3.33	5.34 6.45	3.18 2.94	4.55 4.65	2.76 2.50	3.01 3.96	3.34 3.45	5.27 5.56	2.96 2.86	3.85 4.90
	L3	-	-	-	-	-	-	-	-	-	-	-	-
	L4	3.62 3.33	5.55 5.00	3.66 3.61	5.50 5.50	3.30 3.28	4.40 (4.09)	2.81 2.82	4.10 4.05	3.45 3.30	4.91 4.50	3.18 3.17	4.70 4.67
	L5	3.54 3.56	(5.69) 5.26	3.32 3.32	4.88 5.88	2.87 2.93	4.00 4.00	2.44 2.44	3.20 4.12	3.19 3.21	4.70 4.54	2.81 2.81	3.87 4.85
	L6	-	-	-	-	-	-	-	-	-	-	-	-

Table 3b)

Time-mean statistics - intensity of radiation from the window openings, I_o (cal cm^{-2} sec^{-1})

Shape	Laboratory	FIRELOAD 20		40		20		40		20		40	
		VENTILATION ¼	1	¼	1	¼	1	¼	1	¼	1	¼	1
		I_o 80/55				I_o 55/30				I_o 80/30			
211	L1	-	-	-	-	-	-	-	-	-	-	-	-
	L2	.070	.100	.100	.310	.130	.130	.140	.240	.10	.12	.12	.26
		.070	.110	.120	.280	.130	.175	.140	.260	.10	.15	.13	.27
	L3	.10	.11	.10	.22	.14	.11	.12	.20	.12	.11	.11	.21
		.11	.11	.11	.21	.14	.12	.13	.19	.13	.12	.12	.20
	L4	-	-	-	-	-	-	-	-	-	-	-	-
	L5	.140	.174	.154	.360	.169	.146	.164	.308	.16	.16	.16	.33
		.173	.194	.151	.374	.176	.181	.163	.312	.18	.19	.16	.34
	L6	.14	.080	.15	.308	.19	.085	.19	.283	.17	.08	.17	.29
		.103	.12	.146	.29	.166	.14	.193	.27	.13	.13	.17	.28
121	L1	.153	.34	.175	.365	.196	.35	.203	.32	.17	.35	.19	.34
		.133	.22	.165	.355	.186	.25	.197	.26	.16	.24	.18	.30
	L2	-	-	-	-	-	-	-	-	-	-	-	-
	L3	.13	.34	.16	.50	.20	.35	.18	.38	.17	.35	.17	.43
		.14	.40	.19	.51	(.20)*	.42	.19	.43	.17	.41	.19	.46
	L4	.21	.52	.21	.61	.25	.62	.22	.57	.23	.57	.22	.59
		.17	.32	.21	(.60)	.24	.47	.22	(.64)	.21	.38	.22	.62
	L5	-	-	-	-	-	-	-	-	-	-	-	-
	L6	.14	.26	.18	.53	.21	.35	.19	(.52)*	.17	.30	.19	.53
		.13	.35	.17	.53	.18	.43	.185	.52	.15	.39	.18	.52
221	L1	.121	.247	.112	.359	.149	.223	.141	.296	.14	.23	.13	.32
		.099	.153	.108	.321	.131	.177	.139	.224	.12	.17	.13	.26
	L2	.100	.320	.115	.350	.130	.335	.155	.290	.12	.33	.14	.31
		.140	.456	.125	.360	.170	.380	.160	.435	.16	.41	.15	.41
	L3	-	-	-	-	-	-	-	-	-	-	-	-
	L4	.14	.35	.14	.24	.19	.36	.16	.34	.17	.36	.15	.30
		.13	.24	.14	.32	.18	.33	.16	.34	.16	.29	.15	.33
	L5	.181	.406	.148	.396	.161	.317	.143	.291	.17	.35	.15	.33
		.164	.440	.146	.421	.156	.378	.141	.359	.16	.40	.14	.39
	L6	-	-	-	-	-	-	-	-	-	-	-	-

Table 30)

Time-mean statistics - intensity of radiation from the flames above the window, I_F (cal cm^{-2} sec^{-1})

Shape	Laboratory	FIRELOAD 20, VENTILATION ¼	FIRELOAD 20, VENTILATION 1	FIRELOAD 40, VENTILATION ¼	FIRELOAD 40, VENTILATION 1	FIRELOAD 20, VENTILATION ¼	FIRELOAD 20, VENTILATION 1	FIRELOAD 40, VENTILATION ¼	FIRELOAD 40, VENTILATION 1	FIRELOAD 20, VENTILATION ¼	FIRELOAD 20, VENTILATION 1	FIRELOAD 40, VENTILATION ¼	FIRELOAD 40, VENTILATION 1
		I_F 80/55				I_F 55/30				I_F 80/30			
211	L1	-	-	-	-	-	-	-	-	-	-	-	-
	L2	.230 .230	.040 .060	.505 .830	.400 .360	.700 .715	.050 .080	.770 .790	.160 .170	.46 .48	.05 .07	.65 .80	.24 .24
	L3	.60 .49	.08 .07	.55 .55	.38 .37	.58 .42	.07 .08	.63 .51	.25 .27	.59 .45	.07 .08	.60 .53	.30 .30
	L4	-	-	-	-	-	-	-	-	-	-	-	-
	L5	.694 .628	.080 .102	.808 .805	.407 .534	.482 .417	.041 .054	.672 .684	.225 .318	.57 .50	.06 .08	.73 .74	.30 .41
	L6	.15 .118	.09 .11	.23 .208	.38 .33	.20 .163	.10 .13	.16 .165	.30 .26	.17 .14	.095 .12	.19 .19	.34 .29
121	L1	.122 .068	.113 .047	.196 .144	.27 .21	.136 .108	.106 .074	.184 .156	.145 .075	.13 .088	.11 .06	.19 .15	.19 .13
	L2	-	-	-	-	-	-	-	-	-	-	-	-
	L3	.15 .17	.16 .18	.19 .28	.39 .46	.22 (.19)	.14 .16	.14 .17	.21 .30	.19 .18	.15 .17	.16 .22	.28 .36
	L4	.402 .527	.318 .474	.379 .424	.438 (.438)*	.478 .492	.243 .198	.314 .267	.260 (.260)*	.44 .51	.28 .34	.34 .34	.34 .34
	L5	-	-	-	-	-	-	-	-	-	-	-	-
	L6	.33 .255	.015 .04	.723 .633	.305 .28	.42 .348	.018 .05	.785 .73	.208 .21	.38 .30	.017 .045	.76 .69	.25 .24
221	L1	.57 .13	.314 .106	.529 .277	.49 .45	.499 .181	.142 .078	.411 .159	.273 .227	.53 .16	.23 .09	.46 .21	.36 .31
	L2	.635 (1.15)*	.525 1.010	.595 .915	(.965)* .965	.730 (1.15)*	.440 .405	.320 .700	(.430)* .430	.69 1.15	.48 .64	.45 .79	.62 .63
	L3	-	-	-	-	-	-	-	-	-	-	-	-
	L4	(.65)* .250	.554 .618	.729 .562	.778 .738	(.70)* .216	.291 .370	.624 .438	.405 .359	.68 .23	.42 .48	.67 .49	.57 .52
	L5	(.65)* .250	.554 .618	.729 .562	.778 .738	(.70)* .216	.291 .370	.624 .438	.405 .359	.68 .23	.40 .48	.67 .49	.55 .52
	L6	-	-	-	-	-	-	-	-	-	-	-	-

Table 3d)

Time-mean statistics - floor temperature, θ_b (°C)

Shape	Laboratory	FIRELOAD 20		40		20		40		20		40	
		VENTILATION ¼	1	¼	1	¼	1	¼	1	¼	1	¼	1
		θ_b 80/55				θ_b 55/30				θ_b 80/30			
211	L1	-	-	-	-	-	-	-	-	-	-	-	-
	L2	611 720	460 486	997 (997)*	982 412	855 934	578 595	1095 (1095)*	798 504	730 830	530 550	1050 1050	860 470
	L3	955 945	745 610	810 695	685 585	990 1160	703 565	1020 (1040)	740 680	980 1070	720 580	930 890	720 650
	L4	-	-	-	-	-	-	-	-	-	-	-	-
	L5	1016 1055	639 737	947 927	981 1006	1031 1023	542 709	974 958	949 990	1020 1040	580 720	970 950	960 1000
	L6	793 690	573 665	623 805	683 615	950 870	535 630	890 965	835 730	880 780	550 650	760 890	780 690
121	L1	700 625	910 820	750 630	750 690	830 800	920 810	890 820	695 655	770 710	920 810	820 730	720 670
	L2	-	-	-	-	-	-	-	-	-	-	-	-
	L3	660 645	890 875	730 505	845 930	910 (910)*	860 890	870 970	835 905	790 780	870 880	810 780	840 910
	L4	785 700	995 860	595 725	615 520	940 895	1070 980	835 950	760 740	860 800	1040 900	730 850	700 640
	L5	-	-	-	-	-	-	-	-	-	-	-	-
	L6	640 (545)	675 785	615 640	780 775	900 890	700 910	855 850	860 875	770 710	690 850	740 750	830 830
221	L1	880 840	1020 940	995 895	1060 780	1040 1000	945 905	1050 940	1155 655	980 930	980 920	1030 920	1120 700
	L2	947 881	1018 1060	454 597	901 150	1110 1106	1028 1088	639 845	1065 234	1030 1010	1020 1080	550 740	1010 200
	L3	-	-	-	-	-	-	-	-	-	-	-	-
	L4	860 830	995 800	715 535	345 390	970 1060	1000 960	940 845	780 625	920 950	1000 890	850 710	600 530
	L5	906 895	959 949	872 857	980 943	1048 1009	980 998	985 952	984 995	980 960	970 980	940 910	980 980
	L6	-	-	-	-	-	-	-	-	-	-	-	-

Table 3e)

Time-mean statistics - ceiling temperature, θ_c (°C)

Shape	Laboratory	FIRELOAD 20		40		20		40		20		40	
		VENTILATION ¼	1	¼	1	¼	1	¼	1	¼	1	¼	1
		θ_c 80/55				θ_c 55/30				θ_c 80/30			
211	L1	-	-	-	-	-	-	-	-	-	-	-	-
	L2	769 828	552 530	884 624	895 996	1030 1068	590 608	963 1065	805 879	900 950	570 570	930 1050	840 930
	L3	890 1023	496 650	930 975	830 895	1065 1070	498 525	1030 1070	745 825	990 1050	500 580	990 1030	780 850
	L4	-	-	-	-	-	-	-	-	-	-	-	-
	L5	1027 1074	598 660	964 936	969 991	1078 1093	500 556	1056 1027	934 961	1060 1090	540 600	1020 990	950 970
	L6	875 800	465 475	940 955	950 915	1100 1010	490 543	1070 1085	830 845	990 900	480 510	1010 1030	880 870
121	L1	730 670	925 825	750 720	910 860	875 845	930 830	890 860	960 880	800 760	930 830	820 790	940 870
	L2	-	-	-	-	-	-	-	-	-	-	-	-
	L3	675 720	815 815	795 815	930 785	940 (940)*	805 790	905 895	(945) 760	810 830	810 800	860 860	940 770
	L4	810 760	980 760	770 830	960 960	1005 995	1060 905	965 1005	1085 1090	910 880	1020 820	880 930	1030 1030
	L5	-	-	-	-	-	-	-	-	-	-	-	
	L6	700 (612)	700 780	735 748	950 955	965 916	830 960	930 955	1055 1080	830 760	770 880	840 860	1010 1020
221	L1	815 765	990 880	870 860	1055 955	955 885	900 840	950 930	1050 1020	900 830	940 860	920 900	1050 990
	L2	876 798	1000 1093	716 724	955 908	1110 986	975 1100	955 951	1089 1088	1000 910	990 1100	840 860	1040 1020
	L3	-	-	-	-	-	-	-	-	-	-	-	-
	L4	900 860	975 770	850 845	665 890	1050 1060	970 930	985 1000	927 995	980 960	970 860	930 930	820 950
	L5	919 902	977 959	870 857	982 946	1090 1028	1002 1028	995 952	1049 1027	1010 970	990 1000	940 910	1020 1000
	L6	-	-	-	-	-	-	-	-	-	-	-	-

Table 3f)

Time-mean statistics - time from ignition to 80% of the initial weight, t_{80} (min)

Shape	Laboratory	Fireload 20, Ventilation ¼	Fireload 20, Ventilation 1	Fireload 40, Ventilation ¼	Fireload 40, Ventilation 1
		t_{80}			
211	L1	-	-	-	-
	L2	6.10 6.60	7.10 6.80	11.80 9.50	8.60 9.00
	L3	7.2 7.2	8.4 8.4	12.8 11.6	(10.9) 11.6
	L4	-	-	-	-
	L5	5.4 5.6	7.1 5.8	8.4 8.6	8.7 8.1
	L6	6.90 8.08	8.22 7.11	9.57 9.69	8.79 8.31
121	L1	11.3 10.1	10.3 9.1	15.6 14.0	12.5 11.5
	L2	-	-	-	-
	L3	16.4 14.4	11.8 9.4	(18.9) 15.2	12.8 12.0
	L4	12.50 13.64	7.37 8.51	15.57 16.31	10.58 9.23
	L5	-	-	-	-
	L6	14.17 13.54	9.36 9.13	17.4 17.59	11.15 11.96
221	L1	10.9 8.9	8.7 7.3	16.9 14.5	10.3 9.1
	L2	10.70 7.50	7.40 4.80	16.40 12.00	7.60 9.30
	L3	-	-	-	-
	L4	9.08 8.44	6.21 7.02	15.21 13.47	8.7 8.9
	L5	6.1 8.0	6.2 5.5	14.5 13.7	9.8 8.8
	L6	-	-	-	-

Table 3g)

Data of Commonwealth Experimental Building Station, Australia, before correction for the effects of different compartment materials

Statistic	Shape	F	20		40	
		V	¼	1	¼	1
R 80/55	121		1.19 1.47	1.92 2.38	1.39 1.85	2.00 2.94
	221		2.94 3.70	3.33 5.26	3.20 3.54	4.12 5.71
R 55/30	121		1.06 1.04	1.41 1.52	1.22 1.28	1.18 1.72
	221		2.06 2.56	3.23 3.13	2.19 2.34	2.67 2.50
I_o 80/55	121		.15 .22	.28 .43	.17 .22	.36 .50
	221		.11 .14	.20 .32	.14 .14	.34 .33
I_o 55/30	121		.20 .24	.30 .37	.20 .23	.29 .45
	221		.14 .18	.20 .32	.16 .18	.26 .31
I_F 80/55	121		.14 .25	.08 .16	.17 .35	.24 .52
	221		.35 .73	.21 .53	.55 .84	.47 .65
I_F 55/30	121		.14 .22	.09 .11	.17 .25	.11 .32
	221		.34 .75	.11 .31	.37 .63	.25 .39

(Cont'd) .....

Table 3g) (cont'd)

Statistic	Shape	F	20		40	
		V	$\frac{1}{4}$	1	$\frac{1}{4}$	1
θ_b 80/55	121		725 810	863 925	690 800	720 790
	221		860 830	978 975	910 920	920 790
θ_b 55/30	121		873 855	865 875	855 908	676 840
	221		1020 1080	925 1025	1040 1055	905 1070
θ_c 80/55	121		750 785	874 910	735 810	884 955
	221		790 840	934 950	890 915	1005 1030
θ_c 55/30	121		940 850	880 870	875 908	920 1010
	221		918 1015	870 995	1005 1040	1035 1050
t_{80}	121		13.2 10.0	9.7 7.8	14.8 16.0	12.0 9.2
	221		9.9 8.3	8.0 6.2	15.5 13.2	9.7 10.4

Material 1. In the cases in which there is no value for Material 1, the missing value has been inserted by multiplying the existing readings for other box materials by suitable ratios calculated from the experiment with the same shape and ventilation. Thus, the value for Material 1 in the experiment 221/40/$\frac{1}{4}$ is 3.54 x 2.94 ÷ 3.70 = 2.72 and for 121/20/$\frac{1}{4}$ the appropriate Material 1 value is (1.19 + 1.47) ÷ 2 x 1.39 ÷ 1.85 = 1.00. We now have a table of values for Material 1 as follows:

	2o		40	
	$\frac{1}{4}$	1	$\frac{1}{4}$	1
121	1.00	1.92	1.39	2.00
221	2.94	3.33	2.72	4.12

A table of the original form has been constructed by taking replicates with the above values as mean, separated by the mean value of the difference between the replicates obtained by other laboratories for the same experiment.

2. Investigation of significant differences between laboratories

The initial stage of the analysis is concerned with investigating whether there are any significant differences between laboratories, before proceeding to the calculation of biases. For this purpose an analysis of variance technique is appropriate, but as there are grounds for believing that rates of burning, for example, do not satisfy the normality postulate necessary for the statistical interpretation of the results, it is necessary to find a suitable transformation with the following objects, a) to render the data normally distributed, b) to produce a constant standard deviation in all parts of the table, c) to minimise any interaction between factors. This transformation may then be applied to the data and an analysis of variance performed on the balanced incomplete block of transformed data.

(2.1) Transformation of the results

A transformation is sought from the family of transformations of the form

$$\left.\begin{aligned} z_{ijs} &= \frac{x_{ijs}^{\alpha}}{\alpha \hat{x}^{\alpha-1}} && \alpha \neq 0 \\ &= \hat{x} \log x_{ijs} && \alpha = 0 \end{aligned}\right\} \qquad (1)$$

where x_{ijs} is the sth replicate time-mean value corresponding to laboratory i and shape j.

z_{ijs} is its transformed value.

$\hat{x}$ is the geometric mean of the x_{ijs}.

α is a parameter to be determined.

This transformation is not a continuous function of α at $\alpha = 0$ but it can be made so by the addition of a constant, and therefore the different sums of squares of the analysis of variance and in particular the residual sum of squares, are continuous functions of α. The continuous form of the transformation is not used in the present report, since when $\alpha \ll 1$ considerable numerical accuracy would be lost.

A range of suitable values of α may now be found so that the transformed data z_{ijs} satisfy the conditions of normality and constancy of variance with minimum interaction between factors, by first minimising the residual sum of squares with respect to α at, say, $\alpha = \alpha_{min}$ and then choosing the limits of the range about α_{min} by the methods of Box and Cox[6]. From this range a convenient integral value of α is chosen as near as possible to α_{min}, for ease of interpretation, although any value in the range found is satisfactory.

Since the distribution of errors is likely to be characteristic of the type of observation being considered and not a function of the current experimental configuration, it is probable that the value of α found by this procedure is itself characteristic of the type of observation for which it is calculated. That is, we should expect one transformation to be

appropriate for all rates of burning and another for all intensities and so on. With this in mind, and in view of the extreme length of the calculations involved, only a selection of the experimental configurations for each statistic have been examined.

The values of the transformation calculated are given in Table 5. The first two columns give the limits of the range of α, the next the middle of the range corresponding approximately to the value of α_{min} giving a minimum residual sum of squares, and the last column gives the integral value of α chosen. The results confirm that for the experimental configurations examined, the same transformation is applicable to observations of the same type. The transformation for both R and I is logarithmic, of the form

$$z_{ijs} = \hat{x} \log x_{ijs}$$

implying that errors are proportional to the observation. No transformation is required for temperatures, but for t_{80} the value of α varies with fire load and ventilation. No explanation for this behaviour has yet been found, but it is thought that it may be associated with the different rate-controlling processes in the different conditions.

(2.2) Analysis of transformed data

An analysis of variance was now performed on the transformed data given by equation 1 and the values of α given in Table 5. These values form a balanced incomplete block design, for which the analysis is given in standard textbooks. The mean squares calculated are given in Table 7 and the degrees of freedom to be associated with each are given in Table 6.

It is observed that for rates of burning the differences between shapes are considerably greater than the differences between laboratories, but although for intensities, in general, the differences between the shapes are greater than the differences between laboratories, this is not always statistically significant. In many cases the interaction between laboratory and shape is significantly greater than the residual sum of squares obtained by considering the differences between replicates. It is believed that this interaction is real and the part it plays in the subsequent analysis will now be discussed.

Table 5

Values of the parameter α.

Statistic	Period	F	V	Range of Min.	Range of Max.	Centre of Range	Integral value of α
R	80/55	40	$\frac{1}{4}$	-1.0	0.6	-0.2	0
	55/30	40	1	-0.5	0.8	0.15	0
I_o	80/55	20	$\frac{1}{4}$	-0.5	1.9	0.7	0
	55/30	20	1	-0.4	0.7	0.15	0
I_F	80/55	40	$\frac{1}{4}$	-0.6	0.9	0.15	0
	55/30	20	1	-0.2	0.6	0.2	0
θ_b	55/30	20	1	-0.4	2.3	1.35	1
θ_c	80/55	40	$\frac{1}{4}$	-0.5	2.3	1.4	1
t_{80}		20	$\frac{1}{4}$	-2.2	0.3	-0.95	-1
		20	1	-0.5	2.0	0.75	1
		40	$\frac{1}{4}$	-1.3	1.3	0.0	0
		40	1	-0.5	2.4	0.95	1

Table 6

Degrees of freedom to be associated with the mean squares of Table 7

Source of Variation	Degrees of freedom
Between shapes	2
Between laboratories	5
Interaction	4
Residual	12

Table 7

Mean squares calculated from transformed time-mean data

Time-mean Statistic	F	V	Geometric Mean	Mean Squares			
				Shapes	Laboratory	Interaction	Residual
R 80/55	20	$\frac{1}{4}$	2.4225	11.8879	.2282	0.1181	0.0179
		1	2.9833	10.4872	1.0382	0.1226	0.0836
	40	$\frac{1}{4}$	2.4174	7.9331	0.0654	0.0358	0.0113
		1	3.7243	11.2530	0.8321	0.0364	0.0756
55/30	20	$\frac{1}{4}$	2.1049	6.0465	0.4645	0.0845	0.0249
		1	2.3496	6.7027	0.4946	0.0782	0.0701
	40	$\frac{1}{4}$	1.9183	4.3048	0.1157	0.1216	0.0081
		1	2.4277	4.0990	0.8555	[illegible].0423	0.0628
80/30	20	$\frac{1}{4}$	2.2464	8.3030	0.3175	0.0531	0.0136
		1	2.6225	8.2560	0.6062	0.0404	0.0532
	40	$\frac{1}{4}$	2.1374	5.6977	0.0878	0.0842	0.0050
		1	2.9325	6.3928	0.8573	0.0201	0.0694
I_o 80/55	20	$\frac{1}{4}$	1.2849	0.2657	0.2759	0.0927	0.0270
		1	2.3130	1.3855	1.3630	0.1962	0.2740
	40	$\frac{1}{4}$	1.4355	0.5923	0.1328	0.0384	0.0076
		1	3.6460	9.2987	1.1213	1.0564	0.0658
55/30	20	$\frac{1}{4}$	1.7082	0.3952	0.1415	0.0483	0.0171
		1	2.5073 $\times 10^{-1}$	14.8532	1.3422	0.0139	0.2022
	40	$\frac{1}{4}$	1.6537	0.3883	0.0771	0.0908	0.0014
		1	3.2774	6.5934	1.7450	0.4623	0.1653
80/30	20	$\frac{1}{4}$	1.5195	0.2571	0.1883	0.0722	0.0225
		1	2.4287	13.9651	1.2514	0.0480	0.2277
	40	$\frac{1}{4}$	1.5652	0.4927	0.0891	0.0660	0.0043
		1	3.4366	7.6800	1.3406	0.6002	0.0921

All Mean Squares $\times 10^{-2}$

(Cont'd) .....

Table 7 (Cont'd)

Time-mean Statistic	F	V	Geometric Mean	Mean Squares: Shape	Laboratory	Interaction	Residual
I_F 80/55	20	¼	3.1053	10.7350	5.2225	7.3716	1.9966
		1	1.5388	16.1062	3.2081	0.4834	0.3767
	40	¼	4.5385	28.5782	5.0484	1.1524	1.0916
		1	4.5508	18.7079	4.6468	0.5887	0.1864
55/30	20	¼	3.6398	9.1836	7.8510	3.0263	2.3616
		1	1.2174	6.9224	1.0968	0.1810	0.1295
	40	¼	3.8055	33.5260	3.1427	0.9662	1.1515
		1	2.5363	5.3811	2.0400	0.5789	0.2077
80/30	20	¼	3.1416	10.7879	4.0838	1.8425	2.6634
		1	1.4004	10.6158	1.9790	0.2195	0.2166
	40	¼	4.1610	31.0376	3.9112	0.6889	0.9759
		1	3.3507	9.7883	2.7546	0.5768	0.1712
t_{80}	20	¼	9.0467	45.5745	6.8811	0.8915	1.2516
		1	7.6334	5.9802	3.2267	0.2760	0.8929
	40	¼	13.3714	66.1014	4.0118	3.3872	1.9211
		1	9.8163	7.2868	3.3251	0.8056	0.4470

Geometric Mean: $\times 10^{-1}$

All Mean Squares: $\times 10^{-2}$

(Cont'd) .....

Table 7 (Cont'd)

Time-mean Statistic	F	V	Geometric Mean	Mean Squares				
				Shape	Laboratory	Interaction	Residual	
θ_b 80/55	20	$\frac{1}{4}$	7.8466	6.9928	2.1856	2.5085	0.2216	All Mean Squares x 10^4
		1	7.9101	18.4346	0.6400	2.2723	0.5080	
	40	$\frac{1}{4}$	7.2871	7.3824	3.6503	4.2969	0.8016	
		1	6.7258	1.8173	12.7647	3.8590	4.1909	
55/30	20	$\frac{1}{4}$	9.6365	4.1820	0.6145	1.0232	0.2328	
		1	8.0832 x 10^2	21.7480	0.8381	0.8174	0.5357	
	40	$\frac{1}{4}$	9.2233	3.6391	0.5419	2.2289	0.4128	
		1	7.6306	0.9478	5.1405	1.7357	4.4774	
80/30	20	$\frac{1}{4}$	8.7935	5.7917	1.0452	1.7079	0.1817	
		1	8.0042	20.2179	0.4372	1.2185	0.5267	
	40	$\frac{1}{4}$	8.3888	5.1163	1.3413	3.0663	0.4629	
		1	7.3077	0.6979	7.2234	2.3004	4.2295	
θ_c 80/55	20	$\frac{1}{4}$	8.1710	5.7666	1.8075	0.5725	0.2306	All Mean Squares x 10^4
		1	7.5387	23.8733	1.0711	0.7014	0.6502	
	40	$\frac{1}{4}$	8.4381	6.3057	0.3624	0.4868	0.1169	
		1	9.1756	0.1232	0.8589	1.1530	0.4326	
55/30	20	$\frac{1}{4}$	10.0372	1.7311	0.9271	0.0518	0.1559	
		1	7.7124 x 10^2	31.7303	1.1461	0.5265	0.3319	
	40	$\frac{1}{4}$	9.7678	2.5200	0.3681	0.0738	0.0787	
		1	9.4866	5.0335	1.3503	1.3741	0.2505	
80/30	20	$\frac{1}{4}$	9.1492	3.6262	1.0348	0.2738	0.1579	
		1	7.6351	28.4054	0.6867	0.4423	0.4325	
	40	$\frac{1}{4}$	9.1883	4.1850	0.2765	0.1338	0.0950	
		1	9.3650	1.7663	0.9733	1.0913	0.2862	

Table 8

Ratios of mean squares of Table 7

NS means not significant at 5% level

Time Mean	F	V	Interaction Mean Square / Residual Mean Square	Level of Significance	Labs. Mean Square / Interaction Mean Square	Level of Significance
R 80/55	20	$\frac{1}{4}$	6.6	1%	1.93	NS
		1	1.466	NS	8.5	5%
	40	$\frac{1}{4}$	3.18	NS	1.82	NS
		1	0.4818	NS	22.9	0.5%
55/30	20	$\frac{1}{4}$	3.39	5%	5.5	NS
		1	1.16	NS	6.3	5%
	40	$\frac{1}{4}$	15.0	1%	0.95	NS
		1	0.6734	NS	20.2	1%
80/30	20	$\frac{1}{4}$	3.9	5%	6.0	5%
		1	0.76	NS	15.0	1%
	40	$\frac{1}{4}$	16.71	1%	1.04	NS
		1	0.29	NS	42.6	0.5%
I_o 80/55	20	$\frac{1}{4}$	3.4	5%	2.98	NS
		1	0.7	NS	6.95	5%
	40	$\frac{1}{4}$	5.1	5%	3.46	NS
		1	16.0	1%	1.06	NS
55/30	20	$\frac{1}{4}$	2.8	NS	2.93	NS
		1	0.07	NS	9.65	2.5%
	40	$\frac{1}{4}$	63.1	1%	0.85	NS
		1	2.8	10%	3.79	NS
80/30	20	$\frac{1}{4}$	3.2	5%	2.61	NS
		1	0.2	NS	26.1	0.5%
	40	$\frac{1}{4}$	15.5	1%	1.35	NS
		1	6.5	1%	2.24	NS

(Cont'd) ...

Table 8 (Cont'd)

Time mean	F	V	Interaction Mean Square / Residual Mean Square	Level of Significance	Labs. Mean Square / Interaction Mean Square	Level of Significance
I_F 80/55	20	$\frac{1}{4}$	3.7	5%	.71	NS
		1	1.3	NS	6.65	5%
	40	$\frac{1}{4}$	1.1	NS	4.37	NS
		1	3.2	5%	7.9	5%
55/30	20	$\frac{1}{4}$	1.3	NS	2.6	NS
		1	1.4	NS	6.05	5%
	40	$\frac{1}{4}$	.8	NS	3.25	NS
		1	2.8	NS	3.53	NS
80/30	20	$\frac{1}{4}$	.7	NS	2.22	NS
		1	1.0	NS	9.0	5%
	40	$\frac{1}{4}$	.7	NS	5.68	NS
		1	3.4	5%	4.78	NS
t_{80}	20	$\frac{1}{4}$	.7	NS	7.72	5%
		1	.3	NS	11.7	2.5%
	40	$\frac{1}{4}$	1.8	NS	1.18	NS
		1	1.8	NS	4.12	NS

(Cont'd) ...

Table 8 (Cont'd)

Time mean	F	V	Interaction Mean Square / Residual Mean Square	Level of Significance	Labs. Mean Square / Interaction Mean Square	Level of Significance
θ_b 80/55	20	$\frac{1}{4}$	11.3	1%	0.87	
		1	4.5	5%	0.28	
	40	$\frac{1}{4}$	5.4	1%	0.84	
		1	.9	NS	3.31	
55/30	20	$\frac{1}{4}$	4.4	5%	0.6	
		1	1.5	NS	1.025	
	40	$\frac{1}{4}$	5.4	1%	0.243	NS
		1	0.4	NS	2.96	
80/30	20	$\frac{1}{4}$	9.4	1%	0.61	
		1	2.3	NS	0.36	
	40	$\frac{1}{4}$	6.6	1%	0.44	
		1	0.5	NS	3.14	
θ_c 80/55	20	$\frac{1}{4}$	2.5	NS	3.16	
		1	1.1	NS	1.53	
	40	$\frac{1}{4}$	4.2	5%	0.75	
		1	2.7	NS	0.74	
55/30	20	$\frac{1}{4}$	0.3	NS	17.9	
		1	1.6	NS	2.18	
	40	$\frac{1}{4}$	0.9	NS	4.98	NS
		1	5.5	1%	0.98	
80/30	20	$\frac{1}{4}$	1.7	NS	3.78	
		1	1.0	NS	1.55	
	40	$\frac{1}{4}$	1.4	NS	2.07	
		1	3.8	5%	0.89	

(2.2.1) Interaction

The ratio of the interaction to the residual mean squares is given in Table 8. In many cases the interaction is significantly greater than the residual sum of squares and its significance tends to follow a pattern according to either the fire load or ventilation. Thus the laboratory-shape interaction for R and θ_b tends to be significant (at 5 per cent level) when V is $\frac{1}{4}$, but not significant when the ventilation is 1. This pattern of significance is generated by an increase in the residual mean squares, whilst the interaction mean squares remain approximately constant, and one explanation may be that, for compartments in which V is 1, the fires tend to be controlled by the fuel bed, so that any variation existing in the initial, less controllable, ignition period is likely to have a more marked effect during the period in which the fire is fully developed. However, the interaction for I_o tends to follow fire load, and is significant when F is 40 and not significant when F is 20. The interactions for I_F, t_{80} and θ_c tend to be not significant, although they are nearly always larger than the residuals.

Thus, in general the interaction mean squares are greater than the residual mean squares and since the F ratio for significance of the other mean squares compared with the interaction is twice that for comparison with the residual, clearly a comparison with the interaction is a far more stringent test for significance. This analysis indicates that the laboratory-shape interaction is a more important source of variation than the residual sum of squares. The laboratory-shape interaction is essentially a measure of all the variation that cannot be ascribed either to systematic variation between shapes, laboratories or between replicates. In subsequent analyses therefore, comparisons for significance will be made with reference to the interaction sum of squares.

(2.2.2) Differences between laboratories

We are now in a position to examine whether there are any significant differences between laboratories and the ratios of laboratory mean squares to interaction mean squares are given in Table 8. There are significant differences between laboratories for the rates of burning, but for radiation intensities only the experiments in which F is 20 and V is 1 appear to

produce significant differences. This may be due to a redistribution between interaction and residual, but strictly we are only justified in considering the laboratory bias for this particular fire load ventilation combination. However, the object of the subsequent analysis will be to calculate one bias for each particular statistic irrespective of fire load or ventilation and it would be pointless therefore to study this fire load ventilation combination only.

There are no significant differences between laboratories for the temperatures and therefore no biases will be calculated.

3. Calculation of Laboratory Biases

The object of Part 3 is to estimate the bias to be attributed to each laboratory, and to express it in a convenient form for application to the data of the present report and to data to be obtained in future experiments. Initially, one bias will be calculated for each laboratory for each time mean statistic and fire load - ventilation combination, but as the next series of experiments will be conducted on model compartments with different fire load and ventilation to the present series, clearly it is desirable to see if the changes in the biases from one fire load - ventilation combination to another are significant. If not, then it is possible to simplify considerably the subsequent application of the biases. Thus, although in Part 2 it was found that only one fire load and ventilation produced significant differences in intensities of radiation between laboratories, it will be necessary to calculate the biases for all fire loads and ventilation so that it may be ascertained whether there are any significant differences between the biases calculated for the different fire load - ventilation combinations. Thus the laboratory biases will be calculated for all the statistics except temperatures.

(3.1) Definition and calculation of biases

We define laboratory and shape biases b_i and y_j respectively, where $i = 1, 2, 3, 4, 5, 6$, $j = 1, 2, 3$, such that any component of the balanced incomplete block design, x_{ijs}, defined as the sth replicate of the ith laboratory for the compartment of shape j, may be expressed as

$$x_{ijs} = \bar{x} + b_i + y_j + \varepsilon \qquad (2)$$

where ε is some error term and

$$\sum b_i = \sum y_j = 0 \qquad (3)$$

The data x_{ijs} may thus be corrected for laboratory bias by subtracting the laboratory bias:

$$x'_{ijs} = x_{ijs} - b_i$$

where x'_{ijs} is the value of x_{ijs} corrected for laboratory bias. Similarly the data may be corrected for shape bias, or using both b_i and y_j the missing values, demanded by the balanced design, may be inserted for each laboratory by the use of (2) . However, this requires an analysis of the shape biases, which is outside the scope of the present report.

However, the original data has been transformed to z_{ijs} using a logarithmic transformation and the biases b_i calculated from the transformed data. It can be shown (Appendix 3) that the value of x_{ijs} corrected for laboratory bias is given by

$$x'_{ijs} = x_{ijs}\, e^{\frac{-b_i}{\hat{x}}} \qquad (4)$$

where $b_i \equiv b_i(z)$ denotes the biases calculated from the values z_{ijs} .

Thus a correction factor for each laboratory can be calculated from the values of $b_i/\hat{x}$, $b_i \equiv b_i(z)$, which will be defined as the relative bias of Laboratory L_i .

(3.2) Calculation procedure

Consider one of the time-mean statistics x , say, arranged in the balanced incomplete block design. Let B_i be the total of all the observation of x by Laboratory L_i ,

S_j be the total of all observations of x by all laboratories for shape j .

T be the total of all the readings of $x = \sum_i B_i = \sum_j S_j$

p = number of laboratories with at least one shape in common.

q = number of shapes studied by one laboratory.

n = number of laboratories with two shapes in common.

Let $1 \leqslant i \leqslant P, \quad 1 \leqslant j \leqslant Q, \quad 1 \leqslant s \leqslant R$

Then the bias to be attributed to Laboratory L_i ,

$$b_i = \frac{B_i}{qR} - \frac{T}{qPR} - \frac{1}{q}\sum_{\substack{j=1 \\ \left(j \neq i,\ j \neq i-3\right)}}^{Q} y_j \qquad (8)$$

where y_j is the bias to be attributed to shape j, given by

$$y_j = \frac{1}{nQR}\left(q S_j - \sum_{\substack{i=1 \\ \left(\substack{i \neq j \\ i \neq j+3}\right)}}^{p} B_i\right)$$

Table 9

Relative Laboratory biases b_i

Statistic	Period	F	V	L_1	L_2	L_3	L_4	L_5	L_6
R	80/55	20	¼	- .200	- .015	.051	.070	.033	.061
			1	- .321	.212	.041	.045	.101	- .078
		40	¼	- .067	.005	- .027	.087	.031	- .029
			1	- .251	.084	.046	.066	- .015	.070
	55/30	20	¼	- .264	.074	- .039	.154	- .088	.162
			1	- .246	.138	- .092	.157	- .008	.050
		40	¼	- .088	.035	- .123	.114	.005	.056
			1	- .334	.007	- .091	.189	.074	.155
	80/30	20	¼	- .232	.033	.002	.114	- .033	.115
			1	- .276	.172	- .034	.105	.039	- .006
		40	¼	- .079	.021	- .081	.104	.018	.018
			1	- .301	.037	- .038	.139	.040	.123

(Cont'd) .....

Table 9 (Cont'd)

Statistic	Period	F	V	L_1	L_2	L_3	L_4	L_5	L_6
I_o	80/55	20	$\frac{1}{4}$	- .011	- .026	- .008	.013	.032	- .001
			1	- .037	.011	- .002	.002	.044	- .018
		40	$\frac{1}{4}$	- .011	- .010	- .013	.012	.017	.005
			1	- .019	.007	- .015	- .003	.025	.004
	55/30	20	$\frac{1}{4}$	- .009	- .012	- .007	.018	.005	.004
			1	- .037	.020	- .011	.020	.022	- .013
		40	$\frac{1}{4}$	- .002	- .002	- .014	.010	.001	.008
			1	- .033	.008	- .018	.018	.014	.012
	80/30	20	$\frac{1}{4}$	- .009	- .018	- .006	.017	.017	- .001
			1	- .036	.017	- .007	.012	.031	- .018
		40	$\frac{1}{4}$	- .006	- .005	- .014	.010	.008	.007
			1	- .027	.007	- .016	.009	.018	.009
I_F	80/55	20	$\frac{1}{4}$	- .058	.011	.009	.043	.026	- .031
			1	- .085	.028	.018	.056	.048	- .065
		40	$\frac{1}{4}$	- .041	.015	- .014	.028	.019	- .007
			1	- .045	.021	.009	.009	.019	- .013
	55/30	20	$\frac{1}{4}$	- .052	.060	- .007	.030	- .006	- .026
			1	- .072	.042	.023	.030	.014	- .036
		40	$\frac{1}{4}$	- .030	.015	- .023	.032	.013	- .006
			1	- .058	- .003	.022	.009	.015	.017
	80/30	20	$\frac{1}{4}$	- .037	- .001	- .001	.053	.016	- .031
			1	- .077	.036	.017	.046	.032	- .053
		40	$\frac{1}{4}$	- .036	.016	- .019	.030	.015	- .006
			1	- .052	.007	.013	.011	.018	.003

(3.3) Analysis of biases

Table 9 shows the values of the relative laboratory biases, $b_i/\hat{x}$ calculated for the different fire load ventilation combination for each time mean statistic. Now the values of b_i have been calculated from transformed data z_{ijs}, obtained from the original data by a logarithmic transformation. The correction necessary to the original data for laboratory bias is given by

Equation (4) but for small values of $b_i/\hat{x}$ it is clear that

$$x'_{ijs} \sim x_{ijs}\,(1 - b_i/\hat{x})$$

and thus $b_i/\hat{x}$ is approximately the relative correction to be applied to the original data for laboratory bias. i.e. $(b_i/\hat{x})$ x 100 is the percentage correction to be applied to the original data for laboratory bias. Thus $b_i/\hat{x}$ is defined as the relative bias of Laboratory L_i .

We now examine the biases to see whether they may be simplified by removing the variation between the different fire load-ventilation combinations and where possible by removing the variation between laboratories. For this purpose clearly an analysis of variance technique is once more appropriate, but some standard of variation must be determined for comparison with the mean squares obtained. One standard already exists in the highest order interaction obtained in each analysis, but a more meaningful standard would be the experimental variation already existing in the original data as measured by either the residual mean squares or the interaction mean squares of Table 7. The means by which the variation between the biases may be compared with this experimental variation will be discussed below.

(3.3.1) Rates of burning

For these statistics the magnitude of the correction necessary for laboratory bias is quite large, the largest being about 20-30 per cent in most cases. However, the size of these corrections seems to be mainly attributable to one laboratory, L_1, which has consistently large biases, and the calculated biases will therefore be examined to see whether the variation between laboratories is eliminated when L_1 is removed. In addition to this the biases are to be examined to see whether the variation between fire load and ventilation is significant. Two analyses of variance have therefore been performed on each of the tables of $b_i/\hat{x}$ for the rates of burning, R80/55, R55/30, R80/30, the first analysis including the biases of all six laboratories and the second excluding the biases of L1..

It should be noted that since $\Sigma\, b_i/\hat{x} = 0$, in the analysis including all six laboratories, the sums of squares due to differences between fire loads, differences between ventilations and the fire load-ventilation interaction are all zero and any effects due to differences between ventilations or fire loads would only be apparent in the laboratory-fire load and laboratory-ventilation interactions.

The mean squares obtained in the two analyses are shown in Table 10, in which A1 is the analysis excluding L1, A2 is the analysis including the biases of all laboratories. It is clear that the mean squares due to laboratory differences is considerably reduced by removal of the biases of L1 and it remains to discover whether the laboratory mean square is now significant. As mentioned above, the standard against which the variance should be tested is a measure of the variance already existing in the experiments. Previously, in testing for significance, the laboratory-shape interaction mean square obtained in Table 7 has been used and this would seem to be appropriate for examining differences between biases.

Since $b_i(z/\hat{x}) = b_i(z)/\hat{x}$

therefore $b_i/\hat{x}$ is the laboratory bias of $x_{ijs}/\hat{x}$. The interaction mean square to be used in examining the differences between $b_i/\hat{x}$ is therefore that obtained from an analysis of $x_{ijs}/\hat{x}$ and since the mean squares obtained in an analysis of variance are homogeneous, therefore the appropriate laboratory shape interaction mean square may be obtained from Table 7 by dividing the interaction mean square of Table 7 by $\hat{x}^2$.

However, for each mean statistic there are four values of interaction mean square, one for each fire load-ventilation combination, but testing each group of four values by a range test (7) shows that there are no significant differences between them and thus the arithmetic mean value may be taken as representative. These values are:

Time mean Statistic	Combined Interaction Mean Square
R 80/55	0.0107
R 55/30	0.0184
R 80/30	0.0093

Each value is based on four values, each of which is based on four degrees of freedom and thus each combined interaction mean square is based on 16 degrees of freedom.

Table 10

Mean squares obtained from an analysis of relative laboratory biases - rates of burning

	R 80/55		R 55/30		R 80/30		Degrees of Freedom	
Source of variation	A_1	A_2	A_1	A_2	A_1	A_2	A_1	A_2
Between F	.002	0	.0004	0	.0008	0	1	1
Between V	.005	0	.003	0	.004	0	1	1
Between L	.003	.045	.035	.080	.013	.058	4	5
F x V	.0002	0	.004	0	.002	0	1	1
V x L	.005	.010	.001	.004	.001	.005	4	5
L x F	.002	.004	.0004	.004	.002	.002	4	5
L x F x V	.006	.005	.003	.007	.001	.005	4	5

A_1 - analysis excluding L_1

A_2 - analysis of all laboratories

We are now in a position to test for significance in Table 10 with the following results:-

(i) None of the interactions F x V, V x L, L x F, L x F x V, are significant. This implies that there are no significant differences between the laboratory biases obtained for the different fire loads and ventilations for each statistic and thus one value of the bias may be taken for each laboratory for each time-mean value of R.

(ii) There are significant differences between biases of different laboratories when L_1 is included, but there are no significant differences between the remaining five laboratories. This implies that one bias may be used for each of L_2-L_6 and another for L_1. The biases to be applied are given in Table 11. On average, the data of L_1 must be increased by 25 per cent and the data of all other laboratories decreased by 4 per cent and within the accuracy of the data these figures may be taken to apply to each of the time-mean values of R.

Table 11

Biases and percentage corrections for
R 80/55, R 55/30, R 80/30

	Relative bias		Correction factor (per cent)	
Time-mean	L_1	L_2 to L_6	L_1	L_2 to L_6
R 80/55	- 0.209	0.042	123	96
R 55/30	- 0.233	0.047	126	95
R 80/30	- 0.222	0.044	125	96

There are no differences between the laboratories L_2, L_3, L_4, L_5, L_6, and any bias attributed to them arises only from a comparison with the results of L_1. It seems reasonable, therefore to adopt the results of L_2, L_3, L_4, L_5, L_6 as definitive and to adjust the data L_1 using these results as a standard. For this purpose a 130 per cent correction to the data of L_1 is necessary.

The experiments of laboratory L_1 were conducted with compartments constructed of three different materials and in section (1.2), the differences between materials have been minimised by deducing a Table of values for Turnalls Asbestos board (Material 1) from the original time-mean statistics. However, the experiments of all other laboratories were conducted with compartments constructed of Asbestos Millboard (Material 3) and it is apparent from the original time-mean statistics of laboratory L_1 that there are considerable differences between the rates of burning obtained with different compartment materials. The biases calculated above, therefore, may only reflect the differences between the compartment materials. We now examine the data to test this hypothesis.

The experiments of laboratory L_1 with a compartment of shape (221) include data from compartments constructed of both Material 1 and Material 3 and these data show that, on average, the Material 1 values are 20 per cent lower than the Material 3 values, although there is a large scatter about this mean value. Furthermore, comparing the Material 3 values of L_1 with the

(221) experiments of laboratories L_2, L_4, L_5 gives the following percentage relative biases for the laboratories.

Laboratory	L_1	L_2	L_4	L_5
Correction factor (per cent)	110	94	96	101

The average correction factor for L_2, L_4 and L_5 is thus approximately 97 per cent and if the results of these three laboratories are adopted as definitive, as suggested above, the percentage correction factor necessary to adjust the results of L_1 is then 113 per cent.

These calculations on the limited data available thus indicate that, of the 30 per cent adjustment necessary for the bias of laboratory L_1, approximately $\frac{2}{3}$ is due to the different materials used whilst the remaining adjustment may or may not be a true laboratory bias.

(3.3.2) Intensity of radiation I_o

The largest correction to be applied to the original data for laboratory bias for intensity of radiation is about 4 per cent, and since this is less than the accuracy of instrumentation, the biases for I_o can be ignored. It should be noted, however, that in Table 7 the laboratory mean squares are comparable with the shape mean squares, and hence there are unlikely to be any measurable effects on radiation due to shape.

(3.3.3) Intensity of radiation from flames above the window, I_F

The largest correction for laboratory bias is approximately 8 per cent, occurring in the experiments where F is 20, V is 1, but as for the rates of burning analysis, consistently large biases are given by laboratory L_1, although some of the correction factors for other laboratories are almost as large. A similar analysis to that of R has been carried out, therefore, in which the relative biases are examined for significant differences between laboratories, fireloads and ventilations when the results of L_1 are removed. The results of this analysis are shown in Table 12. It can be seen that at least 50 per cent of the variance due to laboratories can be attributed to L_1.

The combined interaction mean squares obtained from Table 7 are shown below. Since there are significant differences between the 4 values obtained for I_F 80/55, these values have been grouped in pairs, providing two estimates

of the combined interaction mean square, one high and one low, to be used as a standard of comparison.

Time-mean Statistic	Combined Interaction Mean Square x 10^2
I_F 80/55	.4843) each based on .0372) 2 mean squares
I_F 55/30	.2536
I_F 80/30	.0974

The mean squares of Table 12 were then compared with the combined interaction mean squares above. The interaction terms L x V, L x F are not significant, and thus there are no real differences between the relative biases of the different combinations of fire load and ventilation. The laboratory mean square is significant except for I_F 55/30, but when the results of L_1 are removed the laboratory mean square is not significant although for I_F 80/55 it is just significant at the 25 per cent level compared with the lower estimate of the interaction mean square when the results of L_1 are removed. Since, in the latter case, such a comparison is unnecessarily stringent, a much higher level of significance is demanded. Thus one bias may be applied for each time-mean statistic, irrespective of fire load or ventilation and since there are no significant differences between the laboratories L_2, L_3, L_4, L_5, L_6, they have a common bias for each statistic. The values of the biases are given below in Table 13. A 5-6 per cent correction is necessary for each time-mean statistic of L_1, and a 1 per cent correction for each of the remaining laboratories, but within the limitations of the accuracy of the experiment it is sufficient to correct the data of laboratory L_1 only, for a 5 per cent bias. This 5 per cent bias is applied in spite of instrumental limitation on the accuracy, since the largest correction calculated in Table 9 is approximately 8 per cent: the value of 5 per cent is the mean value of the bias taken over fire load and ventilation.

In the analysis of the biases for rates of burning an attempt was made to attribute a large proportion of the bias of Laboratory L_1 to the

differences between the compartment materials. However, a similar analysis to determine the source of the bias is not possible for I_F since the values in which comparisons are possible, namely the Material 3 values for the compartment of shape (221) do not appear to be representative of data obtained from compartments of other shapes. For example, the average laboratory bias calculated for L_2 and L_4 from the Material 3 data of compartment shape (221) is large, and this is not so for data from other compartment shapes.

It should be noted in Appendix II that since no I_F values were recorded by laboratory L_4, it has been necessary to insert the values found from experiments by National Bureau of Standards (L_5). Thus the bias of laboratory L_4 for I_F is in fact the bias of N.B.S. (L_5) and thus no bias has been found for I_F for laboratory L_4.

Table 12

Mean squares obtained from an analysis of relative laboratory biases – intensities I_F

	I_F 80/55		I_F 55/30		I_F 80/30		Degrees of Freedom	
Source of variation	A_1	A_2	A_1	A_2	A_1	A_2	A_1	A_2
Between F	.0002	0	0	0	0	0	1	1
Between V	0	0	.0001	0	0	0	1	1
Between L	.002	.005	.001	.004	.002	.004	4	5
F x V	0	0	0	0	0	0	1	1
V x L	.0002	.0002	.0005	.0005	.0004	.0004	4	5
L x F	.0007	.0008	.0009	.0008	.0005	.0006	4	5
L x F x V	.0002	.0002	.0001	.0001	.0002	.0002	4	5

A_1 – analysis excluding L_1

A_2 – analysis of all laboratories

Table 13

Relative biases and percentage correction factors for I_F 80/55, I_F 55/30, I_F 80/30

	Relative bias b_i/Ω		Correction factor (per cent)	
Statistic	L_1	$L_2 - L_6$	L_1	$L_2 - L_6$
I_F 80/55	- .057	.011	106	99
I_F 55/30	- .053	.011	105	99
I_F 80/30	- .050	.010	105	99

(3.3.4) Time from ignition to time when weight is 80 per cent of initial value, t_{80}

The biases to be applied for t_{80} have not yet been analysed. The interpretation is not altogether clear since a different transformation has been found for each fire load-ventilation combination, and thus a common standard of variance, as employed above in the value of the combined interaction mean squares, would be inappropriate. These biases will be the subject of a further report when work is complete.

(3.4) Application of biases

The laboratory biases derived and analysed in this report will have to be applied to many different situations to those from which the biases have been derived. However, the results may be extended to some other situation: since it has been shown that one bias is appropriate to each laboratory irrespective of fire load, ventilation or shape, it follows that for compartments in which other factors, such as scale, are the same, the biases derived may also be applied to compartments whose shape, fire load and ventilation lie within the range studied, e.g. F = 30, V = $\frac{1}{2}$. Series II of the C.I.B. programme also includes experiments with different scale compartments, and with other stick spacings. Strictly, the biases derived above do not apply to these situations, but in the absence of more complete

data taking variation of these other factors into account, the same biases will be applied, since on the whole they are not large and are not significant for most laboratories.

A further problem arises in the use of composite statistics, such as R/W, R/A where A and W are the areas of window and floor, or I_o/ψ the equivalent intensity of radiation in the plane of the window opening, being the configuration factor of the opening with respect to the radiometer measuring I_o. Since A varies with shape, and W varies with both shape and ventilation, and since the biases derived for R have been averaged over shape and ventilation, the way in which division by A or W will affect the averaged biases is not clear.

a) Multiplication by a factor varying with shape

Consider some factor A_j, varying with shape, and suppose new data ϕ_{ijs} formed by multiplying the original data by A_j, so that

$$\phi_{ijs} = A_j x_{ijs} \tag{9}$$

Suppose the original data was transformed to z_{ijs} by a logarithmic transformation, so that

$$z_{ijs} = \hat{x} \log x_{ijs}$$

Let ϕ_{ijs} be transformed to ζ_{ijs} by the logarithmic transformation

$$\beta_{ijs} = \hat{\phi} \log \phi_{ijs}$$

Then

$$\zeta_{ijs} = \hat{A}\hat{x} (\log x_{ijs} + \log A_j)$$
$$= \hat{A} (z_{ijs} + \hat{x} \log A_j)$$

Now $\quad b_i(x+y) = b_i(x) + b_i(y)$

and $\quad b_i(ax) = a\, b_i(x)$

where a = const, and x and y are two sets of data.

$$\therefore b_i(\zeta_{ijs}) = \hat{A}\, b_i(z_{ijs}) + \hat{A}\hat{x}\, b_i(\log A_j)$$

But, by definition, A_j does not vary with i, so that

$$b_i(\log A_j) = 0$$

$$\therefore \quad b_i(\zeta_{ijs}) = \hat{A}\, b_i(z_{ijs}) \tag{10}$$

Now consider the correction factor for the original data $C = e^{-b_i/\hat{x}}$, and let the correction factor for the ϕ_{ijs} be C_ϕ.

Then
$$\log C_\phi = \frac{b_i(\zeta_{ijs})}{\hat{\phi}}$$
$$= \frac{b_i(z_{ijs})}{\hat{x}} \qquad \text{from (9) and (10)}$$
$$= \log C$$
$$\therefore \quad C_\phi = C \tag{11}$$

Thus the same correction factor is appropriate to the composite data formed by multiplying by a shape factor and hence also by a ventilation or fire load factor. Thus the averaged correction factors are unaltered by multiplication by shape, ventilation or fire load factors.

b) Multiplication and division of two different statistics, for both of which correction factors $e^{-b_i/\hat{x}}$ have been obtained.

Consider two such statistics $x_{ijs}^{(1)}$ and $x_{ijs}^{(2)}$ and let new data ϕ_{ijs} be formed by multiplying the two sets of data so that

$$\phi_{ijs} = x_{ijs}^{(1)}\, x_{ijs}^{(2)}$$

Suppose that $x_{ijs}^{(1)}$ and $x_{ijs}^{(2)}$ are transformed to $z_{ijs}^{(1)}$ and $z_{ijs}^{(2)}$ by the transformation

$$z^{(p)} = \hat{x}^{(p)} \log x_{ijs}^{(p)} \qquad p = 1, 2.$$

and that ϕ_{ijs} is transformed to ζ_{ijs} by

$$\zeta_{ijs} = \hat{\phi} \log \phi_{ijs}$$

Then $$z_{ijs} = \hat{x}^{(1)}\,\hat{x}^{(2)}\left(\log x_{ijs}^{(1)} + \log x_{ijs}^{(2)}\right)$$

and $$b_i\left(z_{ijs}\right) = \hat{x}^{(2)}\, b_i\left(z_{ijs}^{(1)}\right) + \hat{x}^{(1)}\, b_i\left(z_{ijs}^{(2)}\right) \qquad (12)$$

Now consider the correction factors for the original data $C^{(1)}$ and $C^{(2)}$ where $C^{(p)} = \exp\left(-b_i\left(z_{ijs}^{(p)}\right)/\hat{x}^{(p)}\right)$ and let the correction factor for the ϕ_{ijs} be C_ϕ.

Then $$\log C_\phi = \frac{b_i\left(z_{ijs}\right)}{\hat{\phi}}$$

$$= \frac{b_i\left(z_{ijs}^{(1)}\right)}{\hat{x}^{(1)}} + \frac{b_i\left(z_{ijs}^{(2)}\right)}{\hat{x}^{(2)}}$$

$$= \log C^{(1)} + \log C^{(2)}$$

$$\therefore \quad C_\phi = C^{(1)}\, C^{(2)} \qquad (13)$$

Thus the correction factors for data formed by multiplying together two different sets of data are obtained by multiplying the corresponding correction factors together.

Now the index $b_i/\hat{x}$ for the composite data is obtained by adding the corresponding indices, and it follows that the value of the correction factor averaged over fire load and ventilation for the composite data may be obtained by multiplying the two mean correction factors as in (13).

Conclusions

Values of rates of burning, intensities of radiation and temperatures averaged over significant periods of the fire have been examined in order to estimate, and where necessary, allow for differences between 6 of the participating laboratories. The results show that there are no significant differences between laboratories for temperatures, and the correction factor for intensity of radiation from the window is not significant compared with the limitations on the accuracy of instrumentation. However, correction

factors have to be applied for the time-mean values of rate of burning, R, and intensity of radiation from the flames above the window opening, I_F, although in the latter case the mean correction factor is comparable with the accuracy of instrumentation and is only applied because the correction factor for one of the fire load-ventilation combination is significantly larger. Most of the variation between the laboratories is caused by laboratory L_1, whose data have been normalised by J.F.R.O. to a single compartment material different from that of other laboratories. The correction factors are as follows:

Observation	L_1	Correction Factors (per cent) L_2, L_3, L_4, L_5, L_6
R	125	96
I_F	105	-

However, it is suggested that the data of L_2, L_3, L_4, L_5, L_6 be adopted as definitive and the data of laboratory L_1 for Turnalls asbestos board be adjusted using these results as a standard. For this purpose a 130 per cent correction for rates of burning and a 105-106 per cent correction for I_F is appropriate. The data indicates that, for rates of burning, of the 30 per cent correction, the greater part, about two-thirds, is due to differences between materials, but the remaining third may or may not be a true laboratory bias.

These correction factors may also be applied to the results of experiments with compartments of the same scale whose shape, fire load and ventilation fall within the range studied and in the absence of more complete data, and since they are small and non-significant for most laboratories, they will also be applied where the compartment is of a different scale, as in Series II of the C.I.B. experiments.

It has been shown that the biases for combinations of the various data, in the form of a product, or for data modified by shape, fire load or ventilation factors, may be derived by simple combinations of the correction factors for the various data and thus the results of the analysis are applicable to a far wider range of time-mean statistics than those studied.

Acknowledgements

The authors would like to thank their colleagues for considerable help with this work. In particular Mr. P. G. Smith was responsible for the considerable task of arranging and checking the data received from the laboratories and helping prepare the data for the statistical analysis. Mrs. J. M. Hogg* and Mrs. J. E. Dunn formulated the original experimental design and advised on its analysis.

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* Formerly Mrs. J. M. Mather.

Notations

A_j	shape factor for shape j - (c.f. (3.4)).
B_i	total of observations of a statistic by laboratory L (c.f. (3.2))
b_i	bias of laboratory L i (3.1)
$b_i(z)$	bias of laboratory L i calculated from the values of z_{ijs} (3.1)
C	Correction factor = $e^{-b_i/\hat{x}}$ for original data (3.4)
C_ϕ	Correction factor for the data ϕ_{ijs} (3.4)
$C^{(p)}$	Correction factor for statistic p (3.4)
F	fire load (Appendix 1)
I_o, I_F	intensities of radiation (Appendix 1)
L	Laboratory i (Table 1)
n	Number of laboratories with two shapes in common (3.2)
p	Number of laboratories with at least two shapes in common (3.2)
q	Number of shapes studied by one laboratory (3.2)
R	Rate of burning (Appendix 1)
S_j	Total of all observations of a statistic by all laboratories for shape j (3.2)
T	Total of all readings of a statistic (3.2)
t_{80}	Time for the weight of fuel to fall to 80 per cent of its initial value (Appendix 1)
V	Ventilation (Appendix 1)
x_{ijs}	s^{th} replicate time mean value of laboratory L i for shape j (2.1)
$x_{ijs}^{(p)}$	Value of x_{ijs} for the pth statistic (3.4)
$\hat{x}$	Geometric mean of x_{ijs} (2.1)

x'_{ijs}	Value of x_{ijs} corrected laboratory bias (3.1)
y_j	Bias of shape j (3.1)
z_{ijs}	Transformed value of x_{ijs} (2.1)
ζ_{ijs}	Transformed value of ϕ_{ijs} (3.4)
α	Parameter defining transformation (2.1)
ε	Error term (3.1)
ϕ_{ijs}	Composite statistic (3.4)
θ_b θ_c	Temperatures (Appendix 1)
(221) (211) (121)	Shapes (Appendix 1)
80/55 55/30 80/30	Time-mean period (1.1)
ψ	Configuration factor of window opening w.r. to radiometer.

APPENDIX I

Definition of terms

This appendix defines the geometry of compartments, and fuel, the measurements made in Series I of the C.I.B. experiments, and the notation used to denote them.

a) Apparatus

(1) Shape of compartment

The shape of a rectangular compartment is designated by a three figure code representing the three principal dimensions (a b c) as shown in Figure 1. Thus a (111) type of compartment is a cubical box; a (441) compartment is a box with a square ground plan area and having a height equal to $\frac{1}{4}$ that of one of the sides.

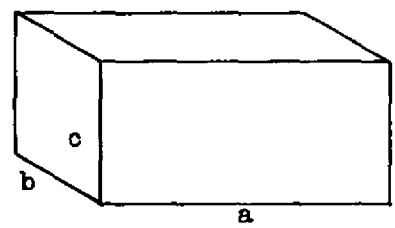

Figure 1

Shapes investigated in Series I are 221, 211 and 121.

(2) Size of compartment

The size of the compartment is determined by the smallest linear dimensions, for example, $\frac{1}{2}$, 1 or $1\frac{1}{2}$ metres. This is also the compartment height. In Series I the size is 1 m in all the experiments.

(3) Ventilation, V

Windows extend from the floor to the ceiling and are always placed in the a c side of the box, and V is defined as the ratio of the area of side a c. The following window openings have been explored:-

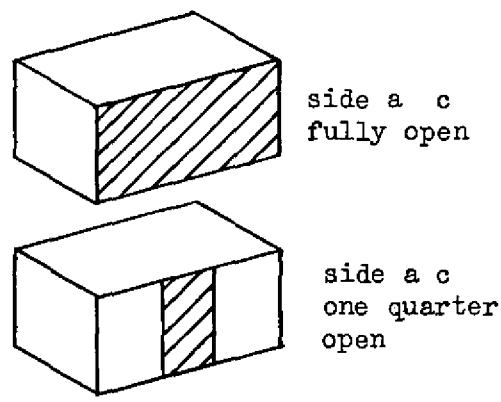

Figure 2

(a) Side a c fully open, denoted by V = 1.

(b) Side a c quarter open, denoted by V = $\frac{1}{4}$.

(4) Dispersion of fuel

The fuel used was 2 cm square section and was arranged in cribs with a cubic lattice as shown in Fig.3 with a 2 cm space between the sticks. In future work the dispersion of the fuel will be defined by a two figure code (p g) where

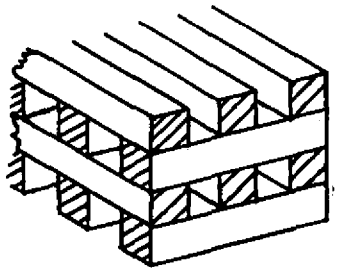

Figure 3

p = stick thickness in cm

g = space between sticks expressed as a multiple of the stick thickness.

Thus the dispersion in Series I is (2.1)

5) Fire load, F

F is defined as the amount of fuel/unit floor area, expressed in kilograms/sq.metre. The fire loads studied in Series I were $F = 20\ kg/m^2$ and $F = 40\ kg/m^2$.

b) Experimental procedure

The following quantities were recorded and values were reported by the laboratories at 2 min. intervals.

(1) Weight of fuel remaining. The rate of burning of fuel is denoted by R (kg/min.)

(2) Temperature in Celsius degrees at the intersection of diagonals on the plan and a quarter of the height below the ceiling and a quarter of the height above the floor. These quantities are denoted by θ_c and θ_b respectively.

(3) Intensity of radiation from the windows, I_o. The radiometer was placed centrally one 'a' dimension in front of the face containing the window opening, as in Fig.4, and shielded so that no radiation fell upon it from the flames above the window.

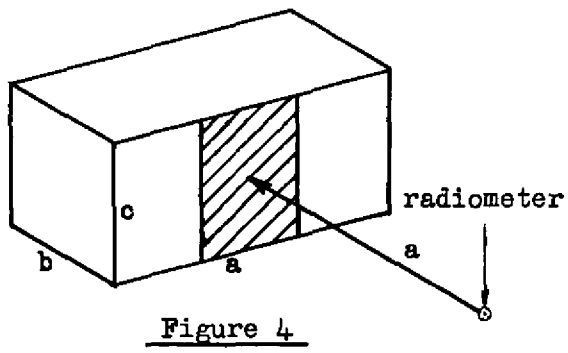

Figure 4

(4) Radiation from the flames above the window I_F. The radiometer was placed centrally in the plane of the window opening, c/10 above the window. In practice sooting proved a problem - the radiometer was often moved back a short distance.

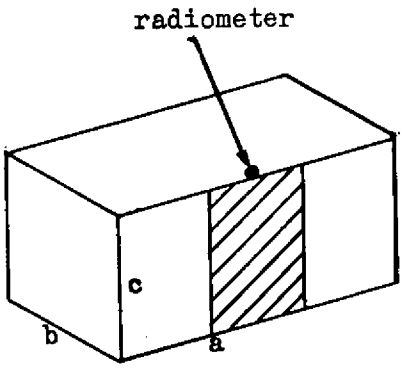

Figure 5

Appendix II

Details of recalculations in Table 3

1. Figures in brackets relate to recalculation by J.F.R.O.
2. Where there is no further indication such as * or a figure underlined, the values are recalculation of statistics found to be in error by inspection of the original data.
3. Other recalculations are indicated by * or underlining, and details are given in Table 14.

Table 14

Details of recalculations of time-mean statistics

Table	Statistic	Laboratory	Shape	F	V	Indication Symbol	Source of recalculation and comment
3a)	R 55/30	L_3	121	20	$\frac{1}{4}$	*	No measurements below 37.5 per cent fuel weight. The missing value has been inserted by assuming the value for the replicate, since the weight-time curves are similar apart from delayed ignition.
3b)	I_o 55/30	L_3	121	20	$\frac{1}{4}$	*	" " " "
		L_6	121	40	$\frac{1}{4}$	*	Missing value inserted from replicate.
	I_o	L_3					The original measurements were made in error at 1 m, and have been adjusted to the correct position at 2 m by multiplying the measured values by the ratio of the configuration factors of the window opening in the two positions. This procedure was agreed with laboratory L_3 and assumes that radiation is emitted only from the window.

(Cont'd) ...

Table 14 (Cont'd)

Table	Statistic	Laboratory	Shape	F	V	Indication Symbol	Source of recalculation and comment
3c)	I_F 80/55	L_2	221	20	$\frac{1}{4}$	*	The radiometer output exceeded full-scale. The missing values have been estimated by interpolation. This process of estimating an off scale peak is admittedly not very accurate but necessary.
		L_4	221	20	$\frac{1}{4}$	*	
		L_5	221	20	$\frac{1}{4}$	*	
	I_F 55/30	L_2	221	20	$\frac{1}{4}$	*	
		L_4	221	20	$\frac{1}{4}$	*	
		L_5	221	20	$\frac{1}{4}$	*	
	I_F 80/55	L_2	221	40	1	*	Missing values inserted from replicates.
		L_4	121	40	1	*	
	I_F 55/30	L_2	221	40	1	*	
		L_4	121	40	1	*	
	I_F	L_4				under-lining	No values of I_F were measured by L_4. The missing values inserted are those of N.B.S. for the same shape, fire load and ventilation. The 121 values are from Series I and the 221 values are obtained from experiments outside Series I.
3d)	θ_b 80/55	L_2	211	40	$\frac{1}{4}$	*	Missing values inserted from replicates
	θ_b 55/30	L_3	121	20	$\frac{1}{4}$	*	
	θ_b 55/30	L_2	211	40	$\frac{1}{4}$	*	
3e)	θ_c 55/30	L_3	121	20	$\frac{1}{4}$	*	Missing value inserted from replicate.

Appendix 3

To prove that, for data for which the logarithmic transformation is appropriate, the value of x_{ijs} corrected for laboratory bias is

$$x'_{ijs} = x_{ijs}\, e^{-b_i/\hat{x}}$$

We have $$z_{ijs} = \hat{x} \log x_{ijs} \qquad (1)$$

and hence $$z'_{ijs} = \hat{x}' \log x'_{ijs} \qquad (2)$$

But $$z'_{ijs} = z_{ijs} - b_i$$

and $$x'_{ijs} = e^{z'_{ijs}/\hat{x}} \qquad \text{from (2)}$$

$$\therefore \quad x'_{ijs} = e^{z_{ijs}/\hat{x}'}\, e^{-b_i/\hat{x}'}$$

$$\therefore \quad (x'_{ijs})^{\hat{x}'} = e^{z_{ijs}}\, e^{-b_i}$$

$$= (x_{ijs})^{\hat{x}}\, e^{-b_i} \qquad \text{from (1)} \qquad (3)$$

Now take the geometric means of both sides of the equation.

Then $$(\hat{x}')^{\hat{x}'} = (\hat{x})^{\hat{x}}\, e^{-\overline{b_i}}$$

But by definition $\Sigma b_i = 0$, so that

$$(\hat{x}')^{\hat{x}'} = (\hat{x})^{\hat{x}}$$

which is an increasing monotonic function.

$$\therefore \quad \hat{x}' = \hat{x}$$

Substituting in (6) we arrive at the result

$$x'_{ijs} = x_{ijs}\, e^{-b_i/\hat{x}}$$

PREPARATION OF DATA FOR ANALYSIS

by

Lynda Griffiths

SUMMARY

A description is given of the procedure by which the experimental data obtained from the C.I.B. programme studying fully-developed fires were prepared for analysis. The data on the report forms supplied by the laboratories were put on to punched paper tapes. The mean values of the rate of burning, temperatures and intensities over certain specified time periods were calculated and put on to one data tape which also contained a description of each experiment. Various adjustments were then made to some of the data for three laboratories to allow for differences between them and other laboratories. Finally an amended tape was prepared from which data could be extracted for analysis.

September 1968

PREPARATION OF DATA FOR ANALYSIS

by

Lynda Griffiths

INTRODUCTION

This report describes the treatment prior to analysis of the results from experiments on fully-developed fires in compartments. Various adjustments had to be applied to some data to allow for differences between laboratories and the data had to be checked and put into a suitable form for analysis.

The data consist of results from nine laboratories which participated in the first C.I.B. international programme making a total of 321 experiments.* The results were submitted on report forms as shown in Appendix 1. The types of experiment done were mainly as described in Table 1 of the report[1] presenting the proposals for the C.I.B. programme. Appendix 2 shows a complete list of experiments carried out excepting the experiments in wind which were not included.

Because the amount of data was large, it was put onto punched paper tape and calculations and adjustments were made by computer programs.

The first stage in the preparation of the data was the calculation of the mean values of rate of burning, temperatures and intensities of radiation over the 80/55, 55/30 and 80/30 time periods. The 80/55 period for example is the time interval during which the weight falls from 80 per cent to 55 per cent of its original value. These means were checked and a data tape prepared containing these values and a description of the experiment in terms of scale, shape etc.

The second stage was to adjust some of the data to eliminate as far as possible differences between laboratories. Adjustments were made to the data from laboratory 0 to normalize these to one of the three compartment materials used by them. A previous analysis[2] showed that an amendment should be applied to the rates of burning and flame radiation to allow for laboratory bias. Two laboratories which were not included in the previous analysis were compared separately with the other laboratories. This was done by analyses of variance and the necessary adjustments were made where the differences between laboratories were significant.

* In still air

PREPARATION OF THE DATA

This section refers to all the data except the 441 shape, 1.5 metre scale experiments for laboratory 1 which were treated in a similar way but added to the data tape at a later stage.

The first stage in the treatment of the data was to punch the original report form data on a separate paper tape for each laboratory. (These tapes are in five-hole Elliott code except for laboratories 5 and 9 which are in seven-hole Atlas code). Each experiment was given a heading which consisted of ten numbers forming a unique description of that experiment - a laboratory number, repeat number, test number, shape, scale, ventilation opening, fire load density, fuel spacing, fuel thickness and time of final reading. These are defined in detail in Appendix 3. This was followed by the readings at two-minute intervals of weight in kg, ceiling temperature and floor temperature in degrees C and radiation from window and flame radiation in $cal.cm^{-2}\ s^{-1}$. Next came the mean values of these readings over the 80/55 and 55/30 periods as given on the report form in the same order as above. These were followed by the time for the weight to fall to 80 per cent of its original value (t80) and the configuration factor for the experiment (which is a geometrical factor defined as the ratio of the intensity at the receiving element to the intensity near to the radiator). Any missing values in these and in other tapes were indicated by -99.

A computer program was written to calculate the means of the readings over the 80/30, 80/55 and 55/30 periods. The t80, t55 and t30 times were first calculated by working out 80 per cent, 55 per cent and 30 per cent of the weight at 0 minutes then finding the times at which these weights occurred by interpolation. The mean over the 80/30 period for a temperature or intensity reading was calculated by taking the mean of the first reading after t80 and all readings up to and including the reading before t30 e.g. if t80 was 5 min and t30 was 11 min then the 80/30 mean for each statistic would be the mean of the readings at 6, 8 and 10 minutes. Similarly, the 80/55 mean is the mean of all the readings after t80 and before t55 and the 55/30 mean is the mean of the readings after t55 and before t30. The mean values of rate of burning over the 80/30, 80/55 and 55/30 periods were calculated by dividing the weight loss over this period by the time interval.

On the output from the program for calculating the means, the computed 80/55 and 55/30 mean values were tabulated against the report form values so that they could be compared and errors due to incorrect punching corrected.

In most experiments where there were differences between means, it appeared that the above methods of calculation had not been used, so to ensure consistency the computed values were used for all experiments except in some cases where there was a missing value in the results. This meant that the computer gave a missing value (-99) for the mean also, while on the report form the missing value had been estimated by interpolation and the mean calculated. For these experiments, the report form values were checked and used.

The experiments were then sorted by scale, shape etc. into the order in which they appear in Appendix 2. A new tape was then prepared, using the computed means and corrected means where appropriate, consisting of the heading for each experiment followed by the 80/55, 55/30 and 80/30 means, t80, t55 and t30 values and the configuration factor. (This tape is in seven-hole Atlas code). The 441 shape, 1.5 metre scale experiments for laboratory 1 were added to this tape. For these experiments, the mean values of the readings were calculated by computer only in the same way as previously.

ADJUSTMENTS MADE TO THE DATA

Adjustments were made only to 1 metre scale data as for 0.5 metre and 1.5 metre there are not enough data to allow comparisons between laboratories to be made and accordingly no adjustments were made for these scales.

First it was necessary to normalize the data for laboratory 0 to one of the three compartment materials used as indicated in the report on the series I analysis[2]. This was done by taking the value given for this material where possible and adding and subtracting half the mean difference between repeats for the other laboratories to give two new values whose mean is the original value. Where this method was not applicable, that is, where neither value given was for the compartment material to which data were being converted, then ratios of the other materials to this one were applied as necessary. The values then applied to only one compartment material but one which was different from the material used by the other laboratories.

The series I results for six of the laboratories had been included in the previous analysis which showed that all the results could be pooled excepting those from laboratory 0, probably due to the effect of a different compartment material. It was found that applying a ratio of 1.3 to rates of burning and 1.05 to flame radiation results allowed for the laboratory bias, so these amendments were applied to all 1 metre scale results for laboratory 0 (both series I and series II).

Three laboratories were not included in the previous analysis. One of these, laboratory 1, did not do any series I experiments so no comparisons with

the other laboratories could be made. The other two, laboratories 3 and 8 were analyzed separately against the others. There were two shapes for each of these laboratories where repeat values by other laboratories were available: these were 121 and 211 for laboratory 3 and 211 and 221 for laboratory 8, both for 1 metre scale results. For each laboratory, values over the 80/30 period for rate of burning, ceiling temperature, floor temperature, radiation from window and flame radiation were analyzed separately. For each shape, the means of the repeat values for the laboratory in question were compared with the means of the repeats from the other laboratories. If the overall percentage difference was less than five per cent, then no adjustments were considered necessary. If however, the difference was larger than five per cent, then the data were examined to see whether the differences were systematic. Occasionally, a fairly large percentage difference was found to be due to one result which was very different from the mean result of the other laboratories; in this case the difference was ignored as no overall adjustment could be applied. However, where the differences appeared to be systematic the data were examined by analysis of variance.

The results for each shape were analyzed separately. If the laboratory effect was found to be significant at the five per cent level and there were no interaction effects, then all the data for that shape were adjusted. If there was a significant laboratory X ventilation interaction effect or laboratory X fireload interaction effect then the data were analyzed separately for each ventilation or fireload. Adjustments were then made to the results for which the laboratory effect was found to be significant.

The adjustments made to the results involved applying the ratio of the mean result of repeated experiments for the other laboratories to the mean result of repeats for the laboratory being tested. The ratios found for the 80/30 values were also applied to the 80/55 and 55/30 values (as ratios calculated from these values were found to be almost the same as those for 80/30 values). The actual ratios applied to the data are given in Appendix 4.

CONCLUSION

The final, amended version of the data tape was used to prepare tables of various values for inspection, also to prepare a data tape containing for each experiment the description of the experiment, the 80/30 values, t80 and other derived values (e.g. window area, Ic/Ø) which may be frequently used during the analyses. A program was written to extract from this tape any specified groups of data, such as all ¼ ventilation data for 1 and 3 spacings, upon which multiple regression analyses could be performed. (These tapes are in Atlas seven-hole code and the amended data together with the derived values are also stored on magnetic tape in I.C.T. 1900 code).

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APPENDIX 1

INTERNATIONAL EXPERIMENTS ON FIRES IN SIMPLE COMPARTMENTS

REPORT FORM

Name of laboratory

JOINT FIRE RESEARCH ORGANISATION, BOREHAM WOOD, HERTS, ENGLAND.

Description of experiment J.F.R.O. Test No. 205

(1)	Shape	441
(2)	Size	$1\frac{1}{2}$ metre
(3)	Window opening	fully
(4)	Amount of fuel	20 kg/m^2
(5)	Dispersion of fuel	1 spacing
(6)	Dimension of fuel	2 cm

Experimental results

Time (min)		0	7	4	6	8	10	12
Weight (kg)		720	717	711	695	661	609	555
Temperature (°C)	ceiling	15	128	200	356	755	792	803
	floor	15	56	92	200	635	686	694
Radiation ($cal\ cm^{-2}s^{-1}$)	from window	0.000	0.007	0.012	0.038	0.148	0.181	0.201
	from flame	0.000	0.006	0.013	0.058	0.272	0.298	0.456

14	16	18	20	22	24	26
499	443	388	327	267	209	167
836	830	911	988	1135	1105	1100
696	742	783	931	1049	1083	1079
0.209	0.214	0.214	0.216	0.203	0.201	0.198
0.570	0.547	0.503	0.775	0.467	0.409	0.224

28	30	32	34
119	84	47	16
1047	997	921	836
972	941	880	729
0.166	0.174	0.134	0.093
0.233	0.112	0.060	0.022

Statistics

Rate of weight loss ($kg\ min^{-1}$)		Mean radiation from flames ($cal\ cm^{-2}sec^{-1}$)		Mean radiation from window ($cal\ cm^{-2}sec^{-1}$)	
$R_{80/55}$	$R_{55/30}$	$I_{F80/55}$	$I_{F55/30}$	$I_{o80/55}$	$I_{o55/30}$
27.75	29.75	0.52	0.58	0.21	0.21

Mean Floor temperature (°C)		Mean ceiling temperature (°C)		Time to reach 80% of original crib weight (min)
$\theta_{b80/55}$	$\theta_{b55/30}$	$\theta_{o80/55}$	$\theta_{o55/30}$	t80
711	921	824	1011	11.22

APPENDIX 2
LIST OF EXPERIMENTS

Scale	Shape	Ventila-tion	Fireload Density	Stick Spacing	Stick Size	Lab. No.	Rpt. No.	Lab. Test No.	Expt. No. on Data tape
0.5	121	0.25	20	0.33	2	7	0	43	1
				1	2	7	0	46	2
				1	4	7	0	49	3
				3	1	7	0	52	4
				3	2	7	0	55	5
		0.5	20	0.33	2	7	0	44	6
				1	2	7	0	47	7
				1	4	7	0	50	8
				3	1	7	0	53	9
				3	2	7	0	56	10
		1.0	20	0.33	2	7	0	45	11
				1	2	7	0	48	12
				1	4	7	0	51	13
				3	1	7	0	54	14
				3	2	7	0	57	15
	211	0.25	20	0.33	2	8	0	15	16
				1	2	3	0	4	17
				1	2	8	0	16	18
				1	4	8	0	17	19
				3	1	3	0	1	20
				3	2	3	0	7	21
		0.5	20	0.33	2	8	0	18	22
				1	2	3	0	5	23
				1	2	8	0	19	24
				1	4	8	0	20	25
				3	1	3	0	2	26
				3	2	3	0	8	27
		1.0	20	0.33	2	8	0	21	28
				1	2	3	0	6	29
				1	2	8	0	22	30
				1	4	8	0	23	31
				3	1	3	0	3	32
				3	2	3	0	9	33
	221	0.25	20	0.33	2	0	0	31	34
				1	2	0	0	32	35
				1	2	4	0	36	36
				1	4	0	0	33	37
				3	1	4	0	34	38
				3	2	4	0	35	39
		0.5	20	0.33	2	0	0	34	40
				1	2	0	0	35	41
				1	2	4	0	38	42
				1	4	0	0	36	43
				3	1	4	0	39	44
				3	2	4	0	37	45
		1	20	0.33	2	0	0	37	46
				1	2	0	0	38	47
				1	2	4	0	32	48
				1	4	0	0	39	49
				3	1	4	0	33	50
				3	2	4	0	31	51
				3	2	4	1	40	52

Scale	Shape	Ventila-tion	Fireload Density	Stick Spacing	Stick Size	Lab. No.	Rpt. No.	Lab. Test No.	Expt. No. on Data tape
0.5	441	0.25	20	1	2	1	0	201	53
			30	1	2	1	0	199	54
		0.5	20	1	2	1	0	198	55
			30	1	2	1	0	200	56
		1	20	1	2	1	0	197	57
				1	2	1	1	203	58
			30	1	2	1	0	202	59
1.0	121	0.25	20	0.33	2	7	0	17	60
				1	2	0	0	7	61
				1	2	0	1	15	62
				1	2	3	0	20	63
				1	2	3	1	21	64
				1	2	5	0	30	65
				1	2	5	1	32	66
				1	2	6	0	1	67
				1	2	6	1	3	68
				1	2	7	0	8	69
				1	2	7	1	9	70
				1	4	7	0	26	71
				3	1	7	0	29	72
				3	2	7	0	38	73
			30	0.33	2	7	0	18	74
				1	2	5	0	31	75
				1	2	7	0	41	76
				1	4	7	0	27	77
				3	1	7	0	30	78
				3	2	7	0	39	79
			40	0.33	2	7	0	19	80
				1	2	0	0	6	81
				1	2	0	1	12	82
				1	2	3	0	10	83
				1	2	3	1	11	84
				1	2	5	0	28	85
				1	2	5	1	29	86
				1	2	6	0	5	87
				1	2	6	1	6	88
				1	2	7	0	7	89
				1	2	7	1	12	90
				1	4	7	0	28	91
				3	1	7	0	31	92
				3	2	7	0	40	93
		0.5	20	1	2	5	0	34	94
			30	1	2	5	0	35	95
			40	1	2	5	0	33	96

Scale	Shape	Venti-lation	Fireload Density	Stick Spacing	Stick Size	Lab. No.	Rpt. No.	Lab. Test No.	Expt. No. on Data tape
1.0	121	1.0	20	0.33	2	7	0	20	97
				1	2	0	0	5	98
				1	2	0	1	10	99
				1	2	3	0	22	100
				1	2	3	1	30	101
				1	2	5	0	7	102
				1	2	5	1	8	103
				1	2	6	0	2	104
				1	2	6	1	4	105
				1	2	7	0	1	106
				1	2	7	1	11	107
				1	4	7	0	23	108
				3	1	7	0	32	109
				3	2	7	0	35	110
			30	0.33	2	7	0	21	111
				1	2	5	0	39	112
				1	2	7	0	42	113
				1	4	7	0	24	114
				3	1	7	0	33	115
				3	2	7	0	36	116
			40	0.33	2	7	0	22	117
				1	2	0	0	2	118
				1	2	0	1	14	119
				1	2	3	0	12	120
				1	2	3	1	23	121
				1	2	5	0	36	122
				1	2	5	1	37	123
				1	2	6	0	7	124
				1	2	6	1	8	125
				1	2	7	0	5	126
				1	2	7	1	14	127
				1	4	7	0	25	128
				3	1	7	0	34	129
				3	2	7	0	37	130

Scale	Shape	Venti-lation	Fireload Density	Stick Spacing	Stick Size	Lab. No.	Rpt. No.	Lab. Test No.	Expt. No. on Data tape
1.0	211	0.25	20	0.33	2	8	0	1	131
				1	2	3	0	24	132
				1	2	3	1	25	133
				1	2	4	0	1	134
				1	2	4	1	6	135
				1	2	5	0	5	136
				1	2	6	0	9	137
				1	2	6	1	10	138
				1	2	7	0	4	139
				1	2	7	1	16	140
				1	2	8	0	26	141
				1	2	9	0	6	142
				1	2	9	1	14	143
				1	4	8	0	2	144
				3	1	3	0	15	145
				3	2	3	0	28	146
			30	0.33	2	8	0	5	147
				1	2	3	0	18	148
				1	2	5	0	6	149
				1	2	8	0	13	150
				1	4	8	0	6	151
			40	0.33	2	8	0	9	152
				1	2	3	0	13	153
				1	2	4	0	5	154
				1	2	4	1	8	155
				1	2	5	0	25	156
				1	2	6	0	13	157
				1	2	6	1	14	158
				1	2	7	0	2	159
				1	2	7	1	15	160
				1	2	8	0	27	161
				1	2	9	0	5	162
				1	2	9	1	13	163
				1	4	8	0	10	164
		0.5	20	1	2	5	0	3	165
			30	1	2	5	0	27	166
			40	1	2	3	0	32	167
				1	2	5	0	24	168
				3	1	3	0	33	169
				3	2	3	0	35	170
				3	2	3	1	38	171

Scale	Shape	Venti-lation	Fireload Density	Stick Spacing	Stick Size	Lab. No.	Rpt. No.	Lab. Test No.	Expt. No. on Data tape
1.0	211	0.75	40	3	2	3	0	37	172
		1.0	20	0.33	2	8	0	3	173
				1	2	3	0	26	174
				1	2	3	1	31	175
				1	2	4	0	2	176
				1	2	4	1	4	177
				1	2	5	0	9	178
				1	2	6	0	11	179
				1	2	6	1	12	180
				1	2	7	0	3	181
				1	2	7	1	13	182
				1	2	8	0	24	183
				1	2	9	0	8	184
				1	2	9	1	12	185
				1	4	8	0	4	186
				3	1	3	0	16	187
				3	2	3	0	29	188
			30	0.33	2	8	0	7	189
				1	2	3	0	19	190
				1	2	5	0	10	191
				1	2	8	0	14	192
				1	4	8	0	8	193
				3	1	3	0	17	194
			40	0.33	2	8	0	11	195
				1	2	3	0	14	196
				1	2	3	1	27	197
				1	2	4	0	3	198
				1	2	4	1	7	199
				1	2	5	0	26	200
				1	2	6	0	15	201
				1	2	6	1	16	202
				1	2	7	0	6	203
				1	2	7	1	10	204
				1	2	8	0	25	205
				1	2	9	0	7	206
				1	2	9	1	9	207
				1	4	8	0	12	208
				3	1	3	0	34	209
				3	2	3	0	36	210

Scale	Shape	Ventila-tion	Fireload Density	Stick Spacing	Stick Size	Lab. No.	Rpt. No.	Lab. Test No.	Expt. No. on Data tape
1.0	221	0.25	20	0.33	2	0	0	17	211
				1	2	0	0	3	212
				1	2	0	1	13	213
				1	2	4	0	10	214
				1	2	4	1	15	215
				1	2	5	0	14	216
				1	2	5	1	15	217
				1	2	8	0	30	218
				1	2	9	0	1	219
				1	2	9	1	10	220
				1	4	0	0	19	221
				3	1	4	0	28	222
				3	2	4	0	21	223
			30	0.33	2	0	0	21	224
				1	2	0	0	29	225
				1	2	4	0	24	226
				1	2	5	0	13	227
				1	4	0	0	23	228
				3	1	4	0	29	229
				3	2	4	0	22	230
			40	0.33	2	0	0	25	231
				1	2	0	0	8	232
				1	2	0	1	11	233
				1	2	4	0	11	234
				1	2	4	1	16	235
				1	2	5	0	11	236
				1	2	5	1	12	237
				1	2	8	0	31	238
				1	2	9	0	3	239
				1	2	9	1	16	240
				1	4	0	0	27	241
				3	1	4	0	30	242
				3	2	4	0	23	243
		0.5	20	1	2	5	0	18	244
			30	1	2	5	0	16	245
			40	1	2	5	0	17	246

Scale	Shape	Venti-lation	Fireload Density	Stick Spacing	Stick Size	Lab. No.	Rpt. No.	Lab. Test No.	Expt. No. on Data tape
1.0	221	1.0	20	0.33	2	0	0	18	247
				1	2	0	0	1	248
				1	2	0	1	16	249
				1	2	4	0	9	250
				1	2	4	1	12	251
				1	2	5	0	22	252
				1	2	5	1	23	253
				1	2	8	0	28	254
				1	2	9	0	2	255
				1	2	9	1	15	256
				1	4	0	0	20	257
				3	1	4	0	25	258
				3	2	4	0	17	259
			30	0.33	2	0	0	22	260
				1	2	0	0	30	261
				1	2	4	0	19	262
				1	2	5	0	20	263
				1	4	0	0	24	264
				3	1	4	0	26	265
				3	2	4	0	18	266
			40	0.33	2	0	0	26	267
				1	2	0	0	4	268
				1	2	0	1	9	269
				1	2	4	0	13	270
				1	2	4	1	14	271
				1	2	5	0	19	272
				1	2	5	1	21	273
				1	2	8	0	29	274
				1	2	9	0	4	275
				1	2	9	0	11	276
				1	4	0	0	28	277
				3	1	4	0	27	278
				3	2	4	0	20	279

Scale	Shape	Ventila-tion	Fireload Density	Stick Spacing	Stick Size	Lab. No.	Rpt. No.	Lab. Test No.	Expt. No. on Data tape
1.5	211	0.25	20	0.33	2	6	0	17	280
				1	2	6	0	23	281
				1	4	6	0	29	282
				3	1	6	0	35	283
				3	2	6	0	41	284
			30	0.33	2	6	0	18	285
				1	2	6	0	24	286
				1	4	6	0	30	287
				3	1	6	0	36	288
				3	2	6	0	42	289
			40	0.33	2	6	0	19	290
				1	2	6	0	25	291
				1	4	6	0	31	292
				3	1	6	0	37	293
				3	2	6	0	43	294
		1.0	20	0.33	2	6	0	20	295
				1	2	6	0	26	296
				1	4	6	0	32	297
				3	1	6	0	38	298
				3	2	6	0	44	299
			30	0.33	2	6	0	21	300
				1	2	6	0	27	301
				1	4	6	0	33	302
				3	1	6	0	39	303
				3	2	6	0	45	304
			40	0.33	2	6	0	22	305
				1	2	6	0	28	306
				1	4	6	0	34	307
				3	1	6	0	40	308
				3	2	6	0	46	309

Scale	Shape	Ventila-tion	Fireload Density	Stick Spacing	Stick Size	Lab. No.	Rpt. No.	Lab. Test No.	Expt. No. on Data tape
1.5	411	0.25	20	1	2	1	0	204	310
			30	1	2	1	0	211	311
			40	1	2	1	0	215	312
		0.5	10	1	2	1	0	209	313
			10	1	2	1	1	214	314
			20	1	2	1	0	207	315
			40	1	2	1	0	208	316
		0.75	10	1	2	1	0	212	317
			10	1	2	1	1	213	318
		1.0	20	1	2	1	0	205	319
			30	1	2	1	0	210	320
			40	1	2	1	0	206	321

APPENDIX 3

Explanation and values of terms used in the experiment description

Laboratory Number	Laboratory Name
0	Commonwealth Experimental Building Station, Australia.
1	Joint Fire Research Organisation, United Kingdom.
3	Centre Scientifique et Technique du Bâtiment, France.
4	Bundesanstalt für Materialprüfung, German Federal Republic.
5) 6)	Forschungsstelle für Brandschutztechnik an der Universität, Karlsruhe, German Federal Republic.
7	Centrum voor Brandveiligheid, Instituut T.N.O., Netherlands.
8	Building Research Institute, Ministry of Construction, Japan
9	National Bureau of Standards, U.S.A.
	(2 was originally designated to another laboratory which did not participate.)

Repeat Number	
0	First experiment of this type by the given laboratory.
1	Repeat experiment by the given laboratory.

Test Number - the original experiment number given by the laboratory or a sequence number assigned by J.F.R.O.

Shape - width, depth and height relative to height 121, 211, 211 or 441.

Scale - height of compartment in metres 0.5, 1.0 or 1.5.

Ventilation opening - fraction of width of compartment forming an opening 0.25, 0.5, 0.75 or 1.0.

Fireload density - density of fuel bed in kg/m^2 10, 20, 30 or 40.

Fuel spacing - ratio of space between sticks to stick thickness 0.33, 1 or 3.

Fuel thickness - thickness of stick in cm. 1, 2 or 4.

APPENDIX 4

Summary of ratios applied to laboratories 3 and 8

	Shape	Ventln.	Fireload	R	θ_c	θ_b	I_o
LABORATORY 3	121	0.25	20	0.87	0.92	0.905	
			40	0.87	0.97	0.934	
		1.0	20	0.875	0.92	0.967	
			40	0.875	0.94	0.827	
	211	0.25	20				1.07
			30				1.15
			40				1.23
		0.50	40				1.24
		0.75	40				1.24
		1.0	20				1.27
			30				1.26
			40				1.26
LABORATORY 8	211	0.25	20				0.89
			30				
			40				
		1.0	20	0.743			0.54
			30	0.743			
			40	0.743			
	221	0.25	20				
			40				
		1.0	20	1.263			
			40	1.263			

ANALYSIS OF THE EXPERIMENTS
PART 2. FIRES WITH RESTRICTED VENTILATION

by

A. J. M. Heselden and P. G. Smith

SUMMARY

An analysis by means of multiple regression has been made of the results of the fires in simple compartments with restricted ventilation openings, i.e. with ventilation openings $\frac{1}{4}$ of the area of the front face of the compartment. The quantity $R/AH^{\frac{1}{2}}$, where R is the mean rate of burning and A and H the ventilation opening area and height respectively was largely constant, depending to a significant but small extent on shape and scale and to a much smaller extent on fire load density and fuel spacing.

The variations of other measured quantities with the experimental conditions have been established; these included temperatures, intensity of radiation at the ventilation opening (I_o/ϕ) and time to burn the first 20 per cent of the fuel. The relation between I_o / ϕ, temperature and other variables suggests that I_o / ϕ may be a better measure of the 'Intensity' of a fire than that given by the temperature of thermocouples suspended within the compartment.

In general as the floor departs in shape from a square, fires tend to be both longer lasting and hotter.

The ratio between I_o / ϕ and R/A is 1440 J/g which is very close to the value obtained for large ventilation openings.

August 1968

ANALYSIS OF THE EXPERIMENTS

PART 2 . FIRES WITH RESTRICTED VENTILATION

by

A. J. M. Heselden and P. G. Smith

1. Introduction

Following the completion of the bulk of the projected experimental fires in the C.I.B. International Co-operative Programme on fully-developed fires in simple compartments, the experimental data have been processed and an analysis carried out, initially on those fires with a ventilation area of $\frac{1}{4}$ of the front wall of the compartment.

For brevity in this report reference to the compartment shapes and experimental conditions usually made by means of simple codes. These are defined in the Appendix.

A tape containing all the experimental data can be supplied to participating laboratories, and summary data tables have been produced .

2. Results

Adjustments have been made to some of the experimental data supplied. Firstly, some arithmetical errors were detected and rectified and values for all statistics calculated for the 80/30 period. Secondly, adjustments were made to the data ($R_{80/30}$*, $\theta_{o\ 80/30}$, $\theta_{b\ 80/30}$, $(I_o/\phi)_{80/30}$, but not t_{80}, t_{55} or t_{30}) from three laboratories whose results were systematically slightly different from those of the majority of the laboratories, so that all the data could be pooled. These differences appeared to be very largely due to differences in the material used for lining the compartment and the data were normalised to fires in compartments lined with the thermal equivalent of asbestos millboard (thickness 1.0 cm, density 1.1 g/cm^3 and thermal conductivity 3-4 x 10^{-4} cal $s^{-1}cm^{-1}$ $degC^{-1}$).

The corrections and adjustments made will be reported in detail separately.

3. Analysis

3.1. General

The analysis has been carried out on the 80/30 values of those variables which are averaged over a period of time.

Some of the experiments with $\frac{1}{3}$ spacing appeared to be anomalous and in any case many fires with fuel beds packed as closely as this tended to burn markedly differently from those with more widely packed fuel. The $\frac{1}{3}$ spacing data were

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* For explanation of symbols see Appendix.

3. Analysis (continued)

3.1. General (continued)

therefore omitted from most of the statistical calculations, and introduced for comparison at a later stage in the analysis.

The data were not in a balanced enough form for variance analysis and were therefore analysed by means of multiple regression. Certain parts of the programm could be analysed in a balanced form as was originally intended. This may be necessary later but the present regression analysis refers to all the data.

To simplify the selection of data on which multiple regression analyses were to be carried out, it was decided to omit all experiments for which one or more of the 80/30 statistics was missing (except for the statistic $I_{f\ 80/30}$ which was treated separately). The number of experiments thus omitted for $\frac{1}{4}$ ventilation was 3 viz: 211 shape, 40 kg/m^2, 2.1 crib; 221 shape, 40 kg/m^2, 2.1 crib and 441 shape, 30 kg/m^2, 2.1 crib, in a total of 123. This should not affect the analysis.

Multiple regressions were obtained for the dependent variables (e.g. burning rate, temperature, radiation intensity etc.) on various combinations of the following independent variables:-

1. Scale (i.e. height of compartment) - m
2. Fire load density - kg/m^2
3. Fuel stick spacing (relative)
4. Fuel stick thickness - cm
5. Width/Height ratio of compartment
6. Depth/Height ratio of compartment

Both dependent and independent variables were transformed by taking logarithms to base 10. The regression coefficients, and their significance levels, the constants and residual standard errors obtained are given in Tables 1 and 2. As far as possible regression equations containing only terms significant at least at the 5 per cent level, and no non-significant terms, were obtained.

As will be seen shortly, although the existence of a coefficient may be established statistically, this does not mean that it is of practical importance; it may govern only a small variation.

The variations produced in the dependent variables by changing the level of the independent variable from the lowest to the highest values in the experiment are also shown in Tables 1 and 2 where appropriate.

Owing to the design of the experiment, correlations between the independent variables are almost all weak*. Table 3 shows the correlation

* In a completely balanced arrangement they would of course be zero.

3. Analysis (continued)

3.1. General (continued)

coefficients between pairs of most of the variables used, dependent and independent. The highest correlation between independent variables is that between fuel thickness and fuel spacing (correlation coefficient $r = 0.56$). In some cases an equation was found in which neither of these factors was significant when both were included, but when the least significant one was omitted the other could reach significance. There are low correlations between scale and fire load density ($r = 0.32$), scale and depth/height ratio ($r = -0.21$) and depth/height and width/height ($r = -0.21$).

This correlation between fuel thickness and spacing can be avoided by taking distance between stick centres, which is less correlated with spacing, instead of fuel thickness (the distance between stick centres would be entirely uncorrelated with spacing if the data were symmetrical) and this was tried in some regressions but no appreciable changes in the regression coefficients of the remaining variables were caused.

3.2. Rate of burning

Preliminary plots of the data showed that the rate of burning of all the $\frac{1}{4}$ ventilation experiments (apart from those with $\frac{1}{3}$ spacing) was reasonably close to that predicted by the relation:

$$R = k \; A H^{\frac{1}{2}} \qquad (1)$$

where k is about $5.5 - 6$ [3]

R is the burning rate (kg/min)

A is the area of the ventilation opening (m^2)

and H is the height of the ventilation opening (m)

Accordingly the regression equations were calculated using $R/AH^{\frac{1}{2}}$ as the dependent variable.

It will be seen from regression 1 (Table 1) that although some systematic variations have been found, $R/AH^{\frac{1}{2}}$ was not very sensitive to changes in the independent variables, a 4 - fold increase in width/height causing a 35 per cent increase in $R/AH^{\frac{1}{2}}$, 3-fold increases in scale and fuel spacing causing a 15 per cent decrease and a 5 per cent increase respectively and a 2-fold increase in fire load density causing a 6 per cent decrease.

Further regression analyses were made to discover whether the effect of compartment shape could be adequately described in terms of the ratios compartment width/height and depth/height, and how much of the variation with scale could be ascribed to differences between $\frac{1}{2}$ and 1 m and between 1 and $1\frac{1}{2}$ m scale. These analyses were performed by replacing these independent variables by dummy variables which could assume the values 0 or 1 as in Table 4.

Table 4

Dummy variables used to explore variation with scale and shape

Shape of compartment	Dummy variable		
	A	B	C
441	1	0	0
221	0	0	0
121	0	1	0
211	0	0	1
Scale	**D**	**E**	
$\frac{1}{2}$	1	0	
1	0	0	
$1\frac{1}{2}$	0	1	

Dummy variables were not of course inserted in the regression equations as logarithms, for example the regression equation for $R/AH^{\frac{1}{2}}$ was of the form:-

$$\log_{10}(R/AH^{\frac{1}{2}}) = a_0 + a_4 \log_{10}(\text{Fire load density}) + a_5 \log_{10}(\text{Fuel spacing}) + a_{10}A + a_{11}B + a_{12}C + a_{13}D + a_{14}E$$

Dummy variable **A** for example gave a measure of the difference in $R/AH^{\frac{1}{2}}$ between shape 441 and the other 3 shapes, and variable **D** a measure of the difference in $R/AH^{\frac{1}{2}}$ between the $\frac{1}{2}$ m scale and the other two scales. Allowing for the different numbers of observations for each shape and scale, differences in $R/AH^{\frac{1}{2}}$ produced by deviations from an arbitrary standard shape (chosen as 221), or scale (chosen as 1 m), were calculated from the regression coefficient and are shown in Table 5.

Table 5

Relative values of $R/AH^{\frac{1}{2}}$ for various compartment shapes and scales

Shape	$R/AH^{\frac{1}{2}}$ (relative)	Number of observations	Scale m	$R/AH^{\frac{1}{2}}$ (relative)	Number of observations
221	1.00	34	$\frac{1}{2}$	1.09	16
121	0.71	35	1	1.00	90
211	0.80	47	$1\frac{1}{2}$	0.95	14
441	0.85	4			

These relative values of $R/AH^{\frac{1}{2}}$ for various shapes are shown in Fig.1. on scales of compartment depth/height and width/height.

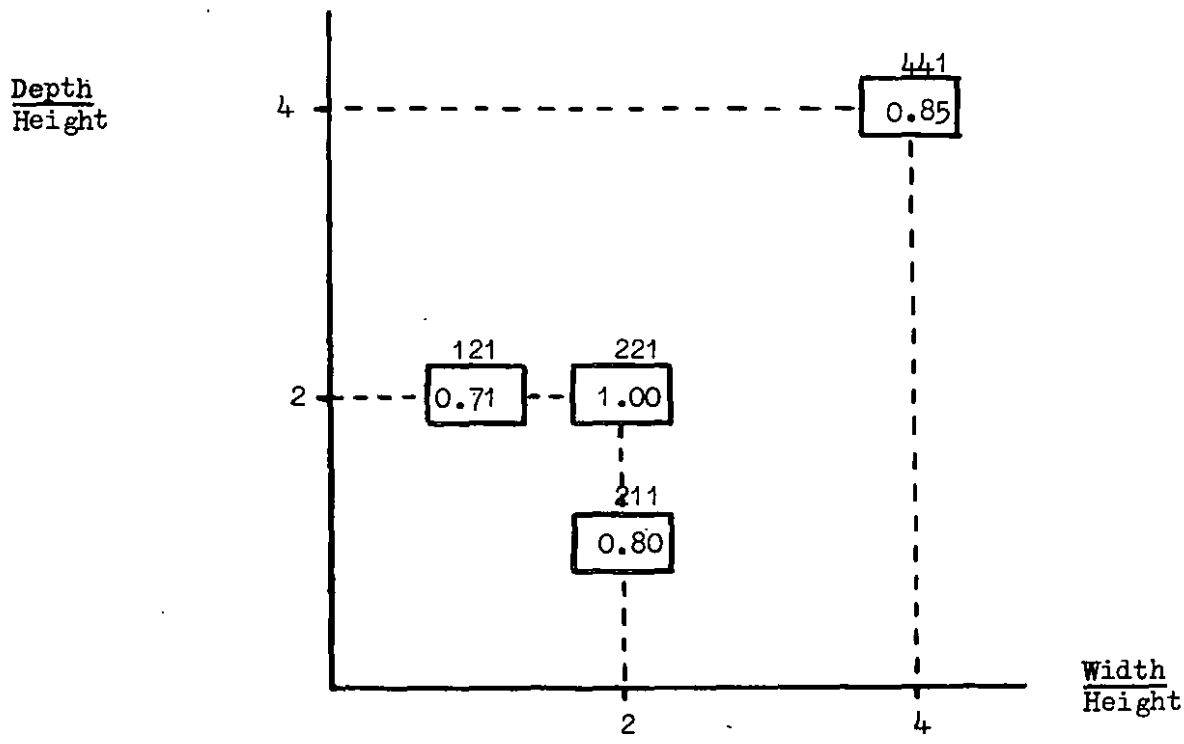

FIG.1. $R/AH^{\frac{1}{2}}$ for various shapes relative to the 221 compartment

Previous work[1,2] established a value for $R/AH^{\frac{1}{2}}$ in the region of 5.5 to 6.0 for fires in compartments of near cubical shape and a comparison with values derived from regression 8 is shown in Fig.2. taking a scale of 3 m, a stick spacing of 1 and a fire load density of 40 kg/m^2.

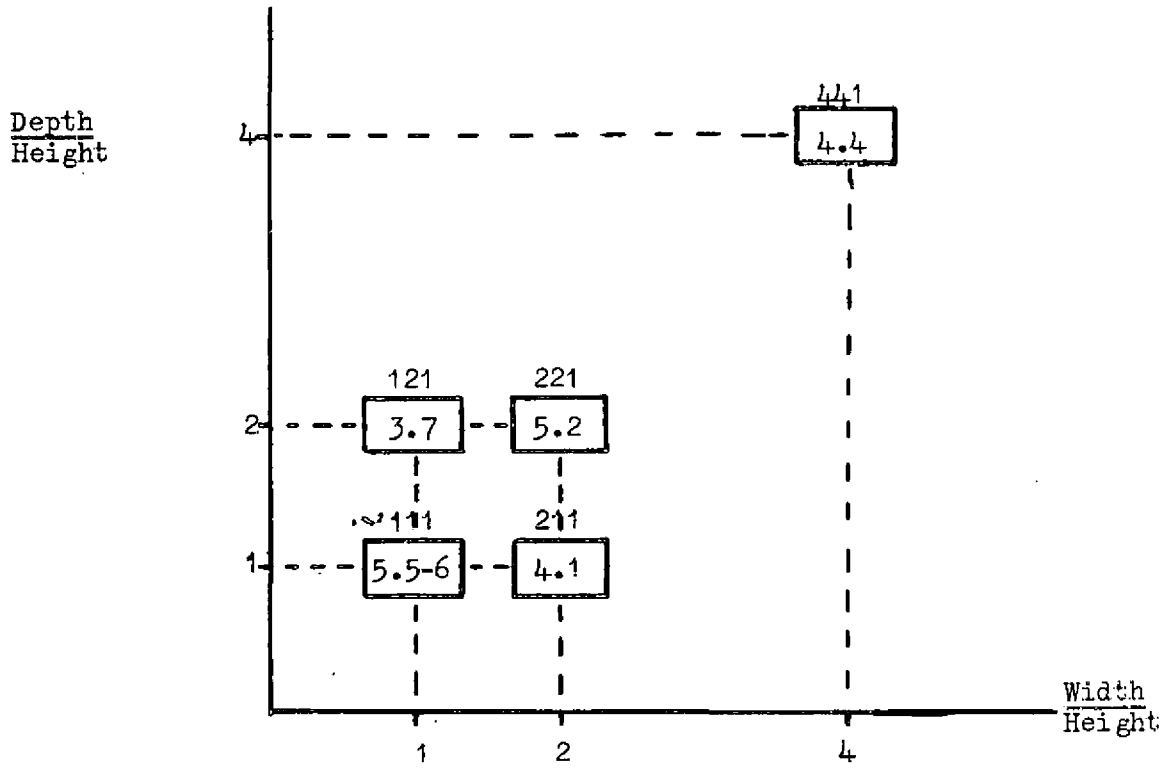

FIG.2. $R/AH^{\frac{1}{2}}$ for various shapes

scale 3 m
stick spacing 1
Fire load density 40 kg/m^2

The ratio of linear size in plan to the height is clearly less important than the relative size of the two sides of the floor.

Examination of the data showed that although interaction between variables was not likely to be large the terms (shape-fire load density) and (spacing-fire load density) were most likely to be significant. However, product terms for these combinations proved to be non-significant when included in the regressions*.

A check on whether the fit of the final equation was satisfactory was made by comparing the residual standard error about the regression with the standard deviation of the replicates. Table 6 shows that these two quantities were about the same showing that there is no point in trying to improve further the fit of the regression equation, except that perhaps for t_{80}.

Table 6
Comparison between the residual variation about the regressions and the standard deviation of replicates

Dependent variable	Regression number	Residual standard error about regression (per cent)	Standard deviation of replicates (per cent)
$R/AH^{\frac{1}{2}}$	1	12.3	11.3
	8	12.0	
	9	11.1	
θ_c °K	2	5.9	4.0
	3	5.4	
	10	5.8	
	11	6.8	
θ_b °K	4	10.3	10.0
I_o/ϕ	5	23.8	18.3
	6	20.7	
	12	20.4	
	13	23.5	
t_{80}	7	34	14.5
	14	33	

A regression analysis was also carried out using the means of replicated results (which are largely 2 cm stick thickness and 1 spacing) so that the bias towards this fuel bed was eliminated, the coefficients obtained being shown in Table 2. The general pattern is not very different from the regression with replicates included separately (compare regressions 8 & 9, Table 2) there are significant differences in the same direction between shapes, and between scales, but the fire load density and fuel spacing terms, which in any case

* These were included as log (spacing) x log (fire load density) etc.

were not large, have disappeared.

Values of $R/AH^{\frac{1}{2}}$ for $\frac{1}{3}$ spacing, calculated from regression 8, are shown in Table 7 to be greater, in some cases substantially greater, than measured values, indicating, perhaps, that the restriction to the air supply was controlled by the fuel bed itself, not the opening.

Table 7
Measured and calculated values of
$R/AH^{\frac{1}{2}}$ and θ_c for $\frac{1}{3}$ spacing cribs

Scale m	Fire load density kg/m²	Calculated or measured	$R/AH^{\frac{1}{2}}$ *			θ_c °C **		
			211	221	121	211	221	121
$\frac{1}{2}$	20	C	6.71	7.07	5.76	1151	1006	950
		M	7.13	6.79	4.75	945	825	712
1	20	C	6.11	6.44	5.24	1382	1187	1122
		M	5.12	4.80	3.56	699	828	873
	30	C	5.89	6.21	5.06	1319	1157	1094
		M	5.86	5.26	4.00	1058	927	937
	40	C	5.74	6.05	4.93	1295	1136	1074
		M	4.92	4.60	3.24	1051	956	746
$1\frac{1}{2}$	20	C	5.70	-	-	1572	-	-
		M	2.08			916		
	30	C	5.50	-	-	1534	-	-
		M	2.10			964		
	40	C	5.36	-	-	1508	-	-
		M	2.29			1048		

* Calculated from regression 8
** Calculated from regression 10 and converted from deg. absolute to deg.Centigrade.

3. Analysis (continued)

3.3. Temperature near ceiling (θ_c)

The statistical analysis of this variable proceeded in a similar manner to that for $R/AH^{\frac{1}{2}}$ but θ_c was found to depend on different variables and an interaction term (depth/height x fuel spacing) was found to be significant. Table 1 gives parameters for the regressions with and without the interaction term, and their relative effects on θ_c °K over their complete range. No improvement of fit was obtained by including an $R/AH^{\frac{1}{2}}$ term. The variables having most effect on θ_c °K are scale, fuel spacing and depth/height ratio.

3. Analysis (continued)

3.3. Temperature near ceiling (θ_c) (continued)

As with $R/AH^{\frac{1}{2}}$ the effect of separate shapes and scales was explored by means of dummy variables and the relative values of θ_c °K obtained are shown in Table 8. Since these were obtained without the interaction term they should be regarded as applying mainly to the 1 spacing data.

Table 8

Relative values of θ_c °K for various compartment shapes and scales

Shape	θ_c °K (relative)	Number of observations	Scale m	θ_c °K (relative)	Number of observations
221	1.00*	34	$\frac{1}{2}$	0.89	16
121	1.01*	35	1	1.00	90
211	1.11	47	$1\frac{1}{2}$	1.12	14
441	0.88	4			

* Not significantly different

These relative values of θ_c °K for various shapes are shown in Fig.3 on scales of compartment depth/height and width/height.

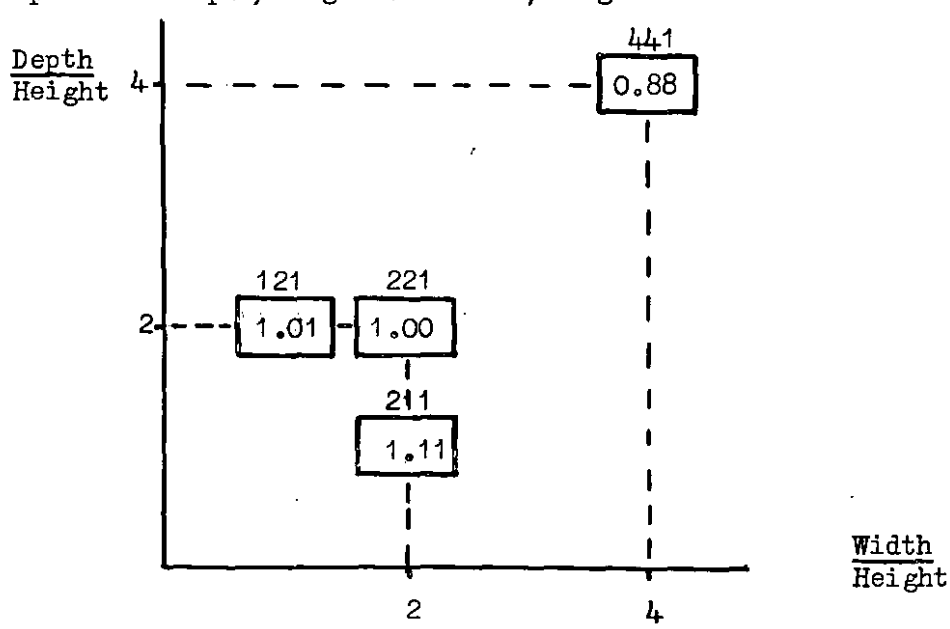

Fig.3. θ_c °K for various shapes relative to the 221 compartment

3. Analysis (continued)

3.3. Temperature near ceiling (θ_c) (continued)

The fall in θ_c °K with depth/height ratio predicted by regression 2 is well seen in Fig.3 but the rise with width/height ratio is more obscure. It must be remembered that there are far fewer observations for the 441 shape so that despite the low value for this shape regression 2 has just managed to find the increase of θ_c °K with width/height significant. The pattern of Fig 3 should represent the real situation more closely.

The effect on temperature of inserting the fuel spacing x depth/height interaction is shown in Table 9. Broadly temperature is raised for the (D/H = 1, spacing = 3), condition and lowered for the (D/H = 4, spacing = 3) condition.

Table 9
Variation of θ_c °K with and without spacing x depth/height interaction

			θ_c °K		
			D/H=1	D/H=2	D/H=4
Fuel spacing	No inter-action	1	1298	1140	1000
		3	1076	945	829*
	Inter-action	1	1283	1146	1023
		3	1139	912	730*

Each value in the table is a temperature calculated from regressions 2 or 3, using mean values for scale, fireload density, fuel thickness and width/height ratio.

*There are no experimental data for this combination of fuel spacing and depth/height ratio.

It is fortunate that only one interaction containing a property of of the crib design (stick spacing) has been found to be significant since there are more results for 2, 1 cribs than for any other stick size or spacing and the bias in favour of this stick thickness and spacing is not therefore of much importance. If, for example, for θ_c there was a substantial interaction between scale and stick spacing then the coefficient for scale would largely represent variation of θ_c with scale only for the 2,1 cribs.

The regression with the data containing averages of all replicated tests is very similar to that obtained with all the data (compare equations 10 and 11, Table 2) except that the fuel thickness term, which in any case was not very large, has disappeared.

Temperatures for the $\frac{1}{3}$ spacing experiments, calculated from regression 10 are higher, in some cases very much higher, than those measured (Table 7).

3.4. Temperature near floor (θ_b)

Table 1 shows that θ_b ^oK is closely related to θ_c ^oK; the coefficient of 0.99 is not significantly different from unity (the coefficient for direct proportionality). θ_b ^oK also depends on fuel spacing and fuel thickness. There is a substantially larger variation in θ_b than in θ_c. In some cases θ_b would have been measured at a point just inside the crib, but no systematic effect of this on θ_b could be detected.

3.5. Intensity of radiation at the ventilation opening (I_o/ϕ)

Two versions of a regression equation are shown in Table 1, the first (regression 5) having independent variables describing the compartment and fuel alone, the second (regression 6) including also $R/AH^{\frac{1}{2}}$ and θ_c ^oK, i.e. measurements made during the course of the fires. The fit of the second is substantially better than the first because of the heavy dependence of I_o/ϕ on the temperature. The effect of separate shapes and scales is shown in Table 10, and relative values for various shapes are shown in Fig.4 on scales of compartment depth/height and width/height.

Table 10
Relative values of I_o/ϕ for various scales and compartment shapes

Shape	I_o/ϕ (relative)	Number of observations	Scale m	I_o/ϕ (relative)	Number of observations
221	1.00*	34	$\frac{1}{2}$	0.72	16
121	1.08*	35	1	1.00+	90
211	1.25	47	$1\frac{1}{2}$	1.02+	14
441	1.54	4			

*,+ Not significantly different

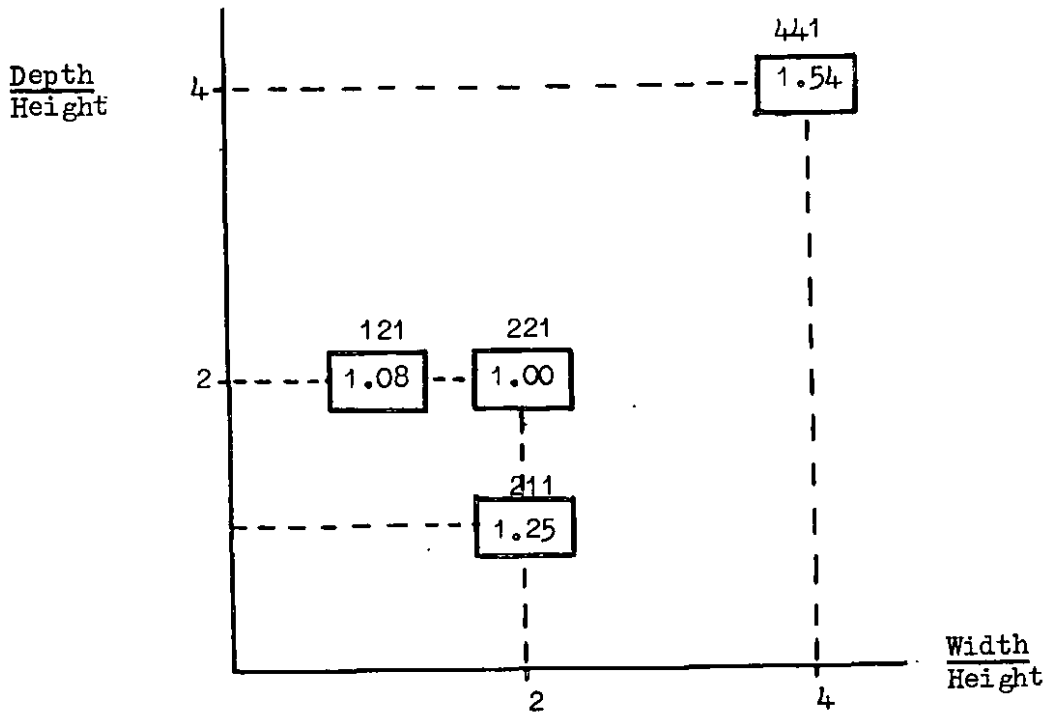

FIG.4. I_o/ϕ for various shapes relative to the 221 compartment.

Replacing the term $R/AH^{\frac{1}{2}}$ in regression 6 by a term R/A gives essentially the same equation, with an adjustment to the coefficient of scale (i.e. height, H).

Several sets of data for well ventilated fires in compartments[1] have given a relationship of the form:-

$$\frac{I_o/\phi}{R/A} = \text{a constant, of value about 1450 - 1650 J/g (350-400 cal/g)}$$

The mean value for this quantity in the present restricted ventilation experiments is 1440 J/g (340 cal/g) which is very close to the values obtained for well ventilated fires, emphasizing still further the fundamental importance of the quantity $(I_o/\phi)/(R/A)$. Regression 6a in Table 1 shows that this quantity, though not strongly dependent on any variable, does depend to some extent on a number of variables, particularly scale and depth/height ratio of the compartment.

The regression of I_o/ϕ with the data containing averages of all replicated tests is generally similar to that obtained with all the data (compare regressions 12 and 13, Table 2) except that the dependence of I_o/ϕ on temperature is weaker and on fire load density is opposite in sign but still small.

As for θ_c, values of I_o/ϕ for $\frac{1}{3}$ spacing calculated from regression 12 are much larger than the measured values but have not been included in Table 7.

3.6. Time to burn the first 20 per cent of fuel (t_{80})

The time to burn the first 20 per cent of the fuel is strongly influenced by many factors (Tables 1 and 2) and has a very high residual variance. No significant interactions could be found however. Relative values for various shapes and scales are shown in Table 11 and Fig.5.

Table 11
Relative values of t_{80} for various scales and compartment shapes

Shape	t_{80} (relative)	Number of observations	Scale m	t_{80} (relative)	Number of observations
221	1.00	34	$\frac{1}{2}$	1.24	16
121	1.12	35	1	1.00*	90
211	0.69	47	$1\frac{1}{2}$	1.02*	14
441	1.50	4			

*Not significantly different

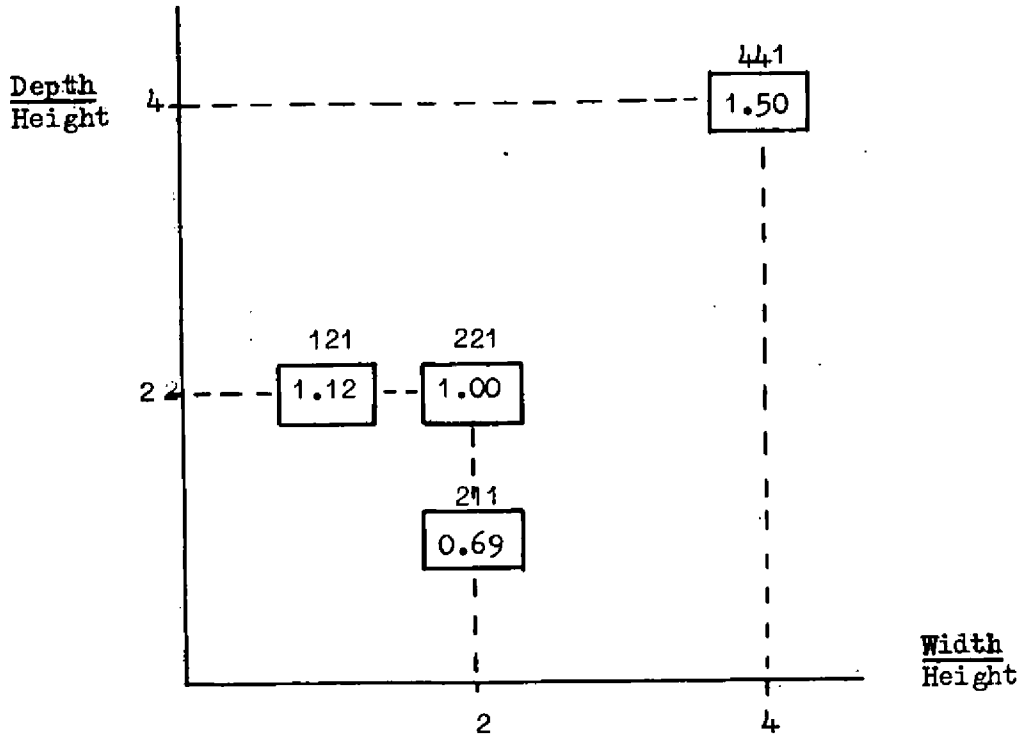

FIG.5. t_{80} for various shapes relative to the 221 compartment

4. Discussion

The relative constancy of the ratio $R/AH^{\frac{1}{2}}$ shows that these fires were substantially ventilation controlled as expected. The biggest variations in $R/AH^{\frac{1}{2}}$ were produced by changes in shape, the largest difference (some 30 per cent) being produced between shapes 121 and 221. Highest values of $R/AH^{\frac{1}{2}}$ were obtained with compartments having a square floor, although $R/AH^{\frac{1}{2}}$ appeared to fall slightly as the compartment became relatively less tall. As the floor shape departed from a square, $R/AH^{\frac{1}{2}}$ decreased somewhat.

A 3-fold increase in scale gave only an 18 per cent decrease in $R/AH^{\frac{1}{2}}$, and this was caused by differences between both the $\frac{1}{2}$ and 1 and the 1 and $1\frac{1}{2}$ m scales. The reason for this decrease with increasing scale is not clear. The effects of fire load density and fuel spacing were very small, although in some cases the closely packed cribs ($\frac{1}{3}$ spacing) burned at a much lower rate than the more loosely packed cribs indicating some control by the fuel bed. A number of fires with $\frac{1}{3}$ spacing cribs went out and had to be relit.

The temperature registered by a thermocouple near the ceiling depended mainly on the scale, the fuel spacing and the shape of the compartment. The substantial increase with increasing scale between both $\frac{1}{2}$ and 1 and 1 and $1\frac{1}{2}$ m scales is very much to be expected. Such an increase has been found before[3]. Although the heat release should depend, in these ventilation limited fires, on $AH^{\frac{1}{2}}$, i.e. on $L^{5/2}$ for a given shape where L is a characteristic length, the heat conducted into the walls and ceiling and the heat radiated from the ventilation opening will depend on areas, i.e. on L^2 terms, so that as L increases temperature must also increase.

Increasing the depth/height ratio of the compartment decreased the temperature, and this may be either because the depth of the flame zone was limited or because the wall and ceiling surfaces over which heat could be lost were increased in area.

Increasing the fuel spacing may affect the position of the flame zone to which the thermocouple may be sensitive. Increasing the fuel spacing with constant fire load density increases the height of the crib and so far as the flame above the crib is concerned may have some similarities with increasing the depth/height ratio of the compartment. Increasing the fire load density has the same effect, though much smaller Temperature near the ceiling was the most reproducible of all the measurements.

It is to be expected that I_o/ϕ should depend almost entirely on the temperature of the fire, indeed in one series of experimental fires at the Fire Research Station the expected 4th power relation with absolute temperature was found[4]. In the present experiments a substantially better fit is obtained in the regressions when a temperature term is included, but the coefficient, i.e. the power to which absolute temperature is raised is only about 1.6, and many other factors are found to be statistically significant, which would be expected to influence I_o/ϕ only through their effect on temperature. Some of these factors even had opposite effects on temperature and radiation intensity, e.g. increasing fire load density decreased temperature but increased the intensity of radiation.

The effect of scale is however understandable - thicker flames at the same temperature should radiate more. The change in radiation intensity for a 3-fold change in scale was less than would be expected from the change in flame thickness alone, and this is probably a reflection of the compound nature of the radiation from the opening. Part of the radiation was emitted from the flame and part from the walls and ceiling, emerging from the ventilation opening after transmission through the flame, so that although thicker flame should radiate more itself it would absorb more of the wall and ceiling radiation.

The presence of so many significant terms in regression 6 suggests that the thermocouple does not give a proper measure of the effective temperature of the radiator. For example, the thermocouple may not always be immersed in flame, but may be in relatively cooler gases recirculating behind the flame zone, or the radiation emitted from the fuel bed may be more important than expected. The former effect may explain why the 441 compartment gave a high value for I_o/ϕ but a low temperature. It has been observed that the crib in this shape of compartment quite clearly burns in a thin zone from the front and sides, towards the centre; the latter effect may explain why increasing either fire load density or fuel spacing (i.e. increasing the height of the crib) increases I_o/ϕ.

The residual standard error of I_o/ϕ is rather large.

Thus although the rate of burning of fires in compartments with restricted ventilation openings (and hence their duration) can be predicted with some accuracy from equation (1) using only the area and height of the ventilation opening, regressions 8 to 13 show that there are small residual effects of shape. These cause shapes differing from the 221 shape to give hotter and

slightly longer lasting fires than would be predicted by equation (1).

The time taken to burn the first 20 per cent of the fuel is a measure of the rate of growth of the fire in its early stages and is compounded of a time to attain full development, broadly "flashover" (this being determined in part by the linear rate of spread of fire through or over the fuel bed) and a time after full development when the rate of burning should approach that of the 80/30 period. Some factors may therefore influence t_{80} by their effect on the earliest stages of growth of the fire and some factors by their effect on the fully developed fire.

The regressions in Tables 1 and 2 show that a good many factors influenced t_{80}, some, for example compartment shape, quite strongly. The residual standard error is large, and much greater than that of the replicated tests (Table 6) but an examination of the residuals from the regressions failed to show any explanation beyond their considerable irregularity. No systematic non-linearity in the main effects, nor low order interactions, nor any correlations with additional variables could be found. Nevertheless several clearly defined relations emerge from the regressions as follows.

The largest effect was produced by the depth/height ratio of the compartment and this will be due to the larger fire load (total amount of fuel) of the deeper compartments, 20 per cent of which would take longer to burn. It is also probable that with deeper compartments the fire, lit at the front, had to travel further into the compartment before the transition to a fully developed fire occurred and if so should have given longer development times since the initial rate of spread is similar to that for the fuel in the open and is therefore largely set by the stick thickness and spacing in the early stages[5]. No direct evidence is however available to support this possibility.

t_{80} decreased strongly with increasing fuel spacing, a reflection of a faster initial rate of spread since fuel spacing had a very small effect on the fully developed rate of burning. It increased strongly with fire load density; although a taller fuel bed should have given an earlier flashover the major part of this effect will be related to the higher fire load.

It is hard to see why thicker fuel or larger scales should have given shorter times.

5. Conclusions

1. For $\frac{1}{4}$ ventilation the quantity $R/AH^{\frac{1}{2}}$ was reasonably constant but depended to a small extent on the scale and the shape of the compartment. Compartments with square floors gave the highest values of $R/AH^{\frac{1}{2}}$ and this quantity decreased slightly with increasing side/height ratio. Departure of floor area from a square led to a fall in $R/AH^{\frac{1}{2}}$.

2. The temperature of the thermocouples suspended within the compartment depended mainly on scale, fuel spacing and compartment shape. However the 'intensity' of a fire is probably better judged from the measured intensity of radiation at the ventilation opening, for the unexpected form of the relation between measured temperature and radiation intensity suggests that the temperature measurement may depend too much on whether or not the thermocouple was immersed in the flame zone.

3. The intensity of radiation increased mainly with increasing temperature, scale and $R/AH^{\frac{1}{2}}$. It also depended on the shape of the compartment, the 221 shape giving the lowest intensity.

4. As the compartment shape departed from the 221 shape fires were both hotter and longer lasting than would be expected if burning rate had been proportional to $AH^{\frac{1}{2}}$.

5. There are irregularities in the measurements of the time to burn the first 20 per cent of the fuel (t_{80}) which it has not been possible to explain. Nevertheless t_{80} has been found to depend significantly on many factors, particularly shape of compartment, fire load density and fuel spacing.

6. The ratio $(I_o/\emptyset)/(R/A)$ is not constant but its mean value for restricted ventilation is similar to earlier values based on a somewhat smaller range of conditions with non-restricted ventilation.

6. Acknowledgments

Miss Lynda Griffiths collated the data and was responsible for the preparation of the data tapes, the associated programmes for selecting data and the bulk of the regression analyses. Valuable assistance was also given by Mr. C. Gilmore.

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Table 1

Parameters of the regression equations
(First series)

Dependent variable	Regression number	Constant term	Coefficients a_1	a_2	a_3	a_4	a_5	a_6	a_7	a_8	a_9	Residual standard error
			$\frac{R}{AH^2}$	θ_c °K	Scale m	Fire load density kg/m²	Fuel spacing (rel.)	Fuel thickness cm	Width/Height W/H	Depth/Height D/H	Fuel spacing - D/H interaction +	
$\frac{R}{AH^2}$ kg min⁻¹m⁻⁵/²	H_c	0.8533	-	-	-0.153 *** -15%	-0.084 * -6%	0.046 * 5%	-	0.223 *** 35%	-	-	0.050 (12%)
T_c^2 °K²	T_c	3.1944	-	-	0.221 *** 27%	-0.053 ** -4%	-0.171 *** -17%	-0.037 * -5%	0.046 ** 6%	-0.188 *** -23%	-	0.025 (6%)
		3.1837	-	-	0.207 *** 25%	-0.048 ** -3%	-0.109 *** -11%	-0.035 * -5%	0.036 * 5%	-0.163 *** -20%	-0.330 *** -20%	0.023 (5%)
θ_b °K	θ_b	-0.0343	-	0.994 *** 75%	-	-	-0.051 * -6%	0.075 * 11%	-	-	-	0.042 (10%)

(Cont'd) ..

Table 1 (cont'd)

Dependent variable	Regression number	Constant term a_0	Coefficients a_1 $\frac{R}{AH^{\frac{1}{2}}}$	a_2 Θ_c °K	a_3 Scale m	a_4 Fire load density kg/m^2	a_5 Fuel spacing (rel.)	a_6 Fuel thickness cm	a_7 Width/Height W/H	a_8 Depth/Height D/H	a_9 Fuel spacing - D/H interaction +	Residual standard error
I_d/ϕ cal cm^{-2}s^{-1}	5	0.4627	-	-	0.592 *** 90%	0.064 NS	-0.128 * -13%	-0.039 * -5%	0.344 *** 60%	-0.301 *** -35%	-	0.093 (24%)
	6	-5.0297	0.287 * 19%	1.640 *** 150%	0.269 ** 35%	0.188 ** 14%	0.128 ** 15%	-	0.208 *** 35%	-	-	0.082 (21%)
$\frac{I_d/\phi}{R/A}$	6a	-0.4157	-	-	0.232 ** 30%	0.160 * 12%	-0.160 *** -16%	-	0.120 * 18%	-0.320 *** -35%	-	0.096 (25%)
t_{80} min	7	0.2842	-	-	-0.227 * -22%	0.486 *** 40%	-0.451 *** -40%	-0.220 * -26%	-0.305 *** -35%	0.760 *** +185%	-	0.126 (34%)

Notes: $\frac{1}{3}$ spacing data omitted
logarithmic transformation (to base 10) of all variables
+ inserted as $\log_{10}$ (spacing) x $\log_{10}$ (D/H)
* significant at 5% level
** " " 1% "
*** " " 0.1% "
NS Not significant

The % value quoted in the columns for a_1 to a_9 is the change in the dependent variable produced by changing the level of the independent variable from the lowest to the highest value of the experiment. (When $R/AH^{\frac{1}{2}}$ and Θ_c were used as independent variables a change of 4 standard deviations was taken)

Table 2

Parameters of the regression equations
(Second series)

Data	Dependent variable	Regression number	Constant term	Coefficients										Residual standard error
				a_1	a_2	Scale		a_4	a_5	a_6	Shape of compartment			
				$\frac{R}{AH^2}$	Θ_c °K	D ($\frac{1}{2}$m)	E ($1\frac{1}{2}$m)	Fire load density kg/m^2	Fuel spacing (rel.)	Fuel thickness (cm)	A (441)	B (121)	C (211)	
Including replicates	$\frac{R}{AH^2}$	8	0.9457	-	-	0.041	-0.030	-0.089 **	0.044 *	-	0.013	-0.089	-0.023	0.049 (12%)
						0.037	-0.023	-6%	5%		-0.071	-0.146	-0.097	
Averaging replicates	$\frac{R}{AH^2}$	9	0.8184	-	-	0.037	-0.067	0.004 NS	0.025 NS	-	0.030	-0.107	0.014	0.046 (11%)
						0.017	-0.062				-0.031	-0.137	-0.050	
Including replicates	Θ_c °K	10	3.1567	-	-	-0.057	0.055	-0.051 **	-0.184 ***	-0.046 *	-0.073	-0.020	0.047	0.024 (6%)
						-0.051	0.048	-4%	-18%	-6%	-0.054	0.003	0.045	
Averaging replicates	Θ_c °K	11	3.1908	-	-	-0.061	+0.050	-0.098 ***	-0.131 ***	-	-0.050	-0.017	0.060	0.029 (7%)
						-0.050	0.035	-7%	-13%		-0.019	0.014	0.064	

(Cont'd) .....

Table 2 (cont'd)

Data	Dependent variable	Regression number	Constant term	Coefficients										Residual standard error
				a_1	a_2	Scale		a_4	a_5	a_6	Shape of compartment			
				$\frac{R}{AH^{\frac{1}{2}}}$	θ_c °K	D ($\frac{1}{2}$m)	E ($1\frac{1}{2}$m)	Fire load density kg/m^2	Fuel spacing (rel.)	Fuel thick-ness (cm)	A (441)	B (121)	C (211)	
Including replicates	$\frac{I_o}{\phi}$	12	-3.4034	0.437	1.098	-0.144	0.031	0.159	-	-	0.138	-0.030	0.071	0.081
				**	***			*						(20%)
				30%	85%	-0.143	0.009	12%			0.187	0.033	0.097	
Averaging replicates	$\frac{I_o}{\phi}$	13	-1.5334	0.353	0.628	-0.215	-	-0.095	-	-	0.159	-0.050	0.137	0.092
				NS	*			NS						(23%)
					40%	-0.238	approx. -0.072	-6%			0.278	0.096	0.216	
Including replicates	t_{80}	14	0.3715	-	-	0.094	-0.006	0.499	-0.465	-0.230	0.228	0.134	-0.198	0.124
								***	***	*				(33%)
						0.095	0.009	40%	-40%	-27%	0.177	0.051	-0.164	

Notes: $\frac{1}{3}$ spacing data omitted
logarithmic transformation (to base 10) of all variables except scale and shape.
* significant at 5% level
** " " 1% level
*** " " 0.1% level
NS Not significant

For a given regression the values in the first line are the regression coefficients obtained for the variables shown. The second line gives the statistical significance level of the coefficients a_1, a_2, a_4, a_5 and a_6 and the third line gives the change in the dependent variable produced by changing the level of these variables from the lowest to the highest value of the experiment. For the dummy variables A, B, C (shape) and D, E (scale), described in Section 3.2 the values given in the third line are the differences in dependent variable between each shape and the 221 shape and each scale and 1 m scale. For example, in regression 8, increasing the scale from 1 m to $1\frac{1}{2}$ m decreases $\log_{10} R/AH^{\frac{1}{2}}$ by 0.023 and changing the shape from 221 to 121 decreases $\log_{10} R/AH^{\frac{1}{2}}$ by 0.146.

APPENDIX

Key to symbols and codes for the experimental conditions

R - is the rate of burning (kg/min)

I_o - is the intensity of radiation received at a radiometer in front of the ventilation opening (cal $cm^{-2}s^{-1}$)

ϕ - is the configuration factor of the ventilation opening with respect to the radiometer

θ_o and θ_b - are the temperatures attained by thermocouples placed centrally in the compartment and a quarter of the height below the ceiling and above the floor respectively

A - is the ventilation opening area (m^2)

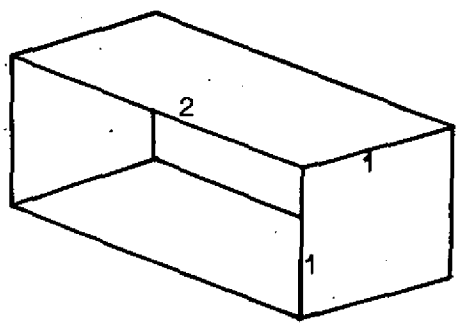
H - is the ventilation opening height (the same as the compartment height in these experiments) (m)

t_{80} - is the time for the fuel weight to fall to 80 per cent of its initial weight (min)

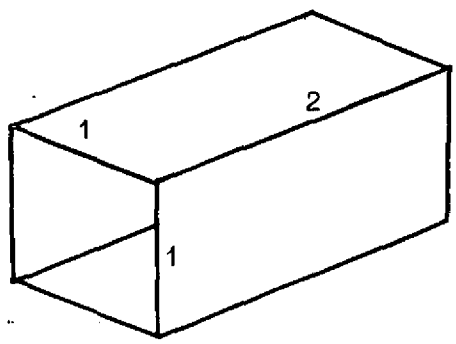
80/30 - refers to the period over which the weight of fuel fell from 80 to 30 per cent of its initial value

Shape The code describing shape gives in order the compartment width, depth and height, relative to the height:-

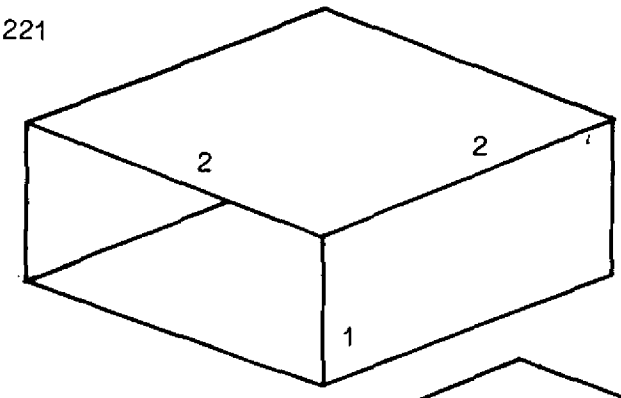
211



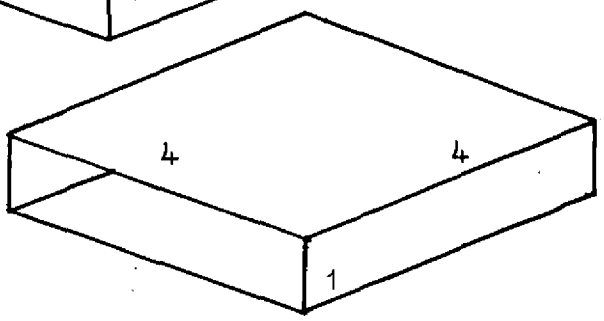
121



221

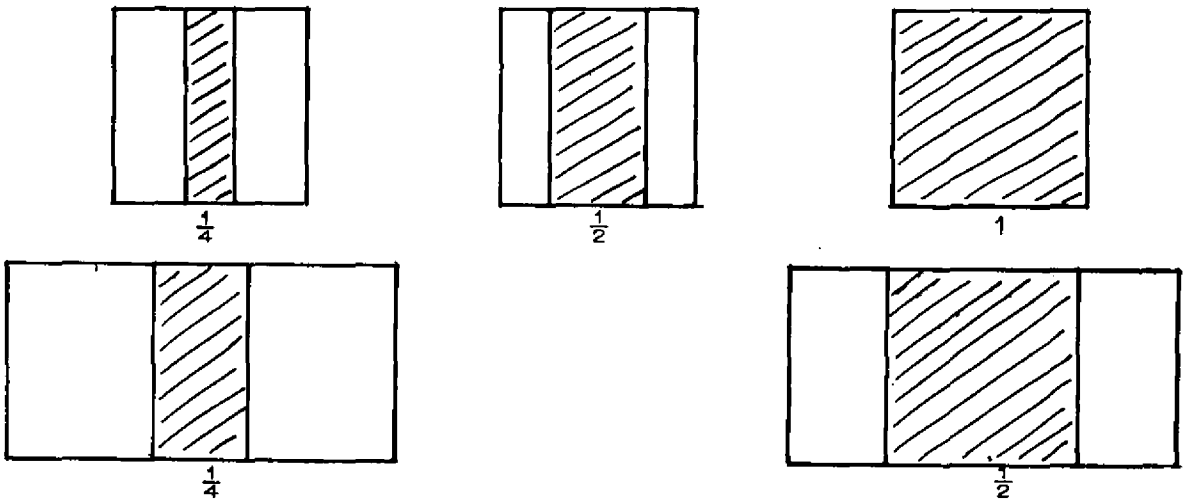


441



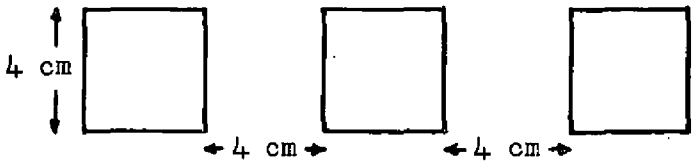
Scale This is the height of the compartment.

Ventilation This is the fraction of the area of the front of the compartment left open



Stick thickness and spacing

The first figure in the code is the stick thickness in cm, the second is the spacing between sticks expressed in stick widths. Thus 4,1 stands for 4 cm thick sticks 1 x 4 = 4 cm apart:



ANALYSIS OF THE EXPERIMENTS

PART 3. FIRES WITH LARGE VENTILATION OPENING AREAS

by

A. J. M. Heselden

SUMMARY

An analysis has been made by means of multiple regression of the results of the experimental fires in simple compartments with large ventilation openings, i.e. with the front of the compartment completely open. The rate of burning per unit floor area was independent of scale and stick thickness but varied substantially with the fuel spacing, fire load density and shape of compartment. Fuel spacing and fire load density had most effect on burning rate in those compartments which were shallow from back to front and little effect in deep compartments.

The variations of other measured quantities with the experimental conditions have been established; these included temperatures, intensity of radiation at the ventilation opening and time to burn the first 20 per cent of the fuel.

The temperature of a thermocouple near the ceiling varied strongly with the rate of burning per unit ventilation opening, as in previous experiments[6]. The intensity of radiation from the ventilation opening varied strongly with the rate of burning per unit ventilation opening area.

January 1970

ANALYSIS OF THE EXPERIMENTS

PART 3. FIRE WITH LARGE VENTILATION OPENING AREAS

by

A. J. M. Heselden

1. Introduction

Following the completion of the bulk of the projected experimental fires in the C.I.B. International Co-operative Programme on fully-developed fires in single compartments and an analysis of the data for fires with restricted ventilation[1] an analysis has now been performed on the results of those fires in which the front of the compartment was completely open ("Full ventilation" fires).

As before, for brevity, reference to the experimental conditions is usually made by means of simple codes, defined in the Appendix.

A tape containing all the experimental data can be supplied to participating laboratories and summary data tables have been produced.

2. Results and processing of results

Adjustments[2] have been made to some of the experimental data supplied. Firstly some arithmetical errors were detected and rectified and values for all statistics calculated for the 80/30 period. Secondly adjustments were made to the data from 3 laboratories whose results were systematically slightly different from those of the majority of the laboratories, so that all the data could be pooled. These differences appeared to be very largely due to differences in the material used for lining the compartment and the effect of the adjustments has been to normalise all the data to fires in compartments lined with the thermal equivalent of 1 cm thick asbestos millboard (density 1.1 g/cm^3 and thermal conductivity $3\text{-}4 \times 10^{-4}$ cal $s^{-1}cm^{-1}degC^{-1}$).

The corrections and adjustments have been reported in detail separately[2].

3. Analysis

3.1. General

The analysis has been carried out mainly on the 80/30 values of those variables which are averaged over a period of time.

Some of the experiments with $\frac{1}{3}$ spacing appeared to be anomalous and in any case many fires with fuel beds packed as closely as this tended to burn markedly differently from those with more widely spaced fuel. As before the $\frac{1}{3}$ spacing data were therefore omitted from most of the statistical calulations, and introduced for comparison at a later stage in the analysis.

3. Analysis (continued)

3.1. General (continued)

The data were not in a balanced enough form for variance analysis and were therefore analysed by means of multiple regression. Certain parts of the programme could be analysed in a balanced form as was originally intended. This may be necessary later but the present regression analysis refers to all the data.

To simplify the selection of data on which multiple regression analyses were to be carried out, it was decided to omit all experiments for which one or more of the 80/30 statistics was missing (except for the statistic $I_{f\ 80/30}$ which will be treated separately). The number of experiments thus omitted for full ventilation was 6 viz: 121 shape, 40 kg/m^2, 2.1 crib; 211 shape, 20 kg/m^2 4.1 crib; 221 shape, 40 kg/m^2, 2.1 and 1.3 cribs; 441 shape, 2.1 cribs , 30 and 40 kg/m^2 (Radiometer failure), with a remaining total of 123 experiments. This should not materially affect the analysis.

Multiple regressions were obtained for the dependent variables (e.g. burning rate, temperature, radiation intensity etc.) on various combinations of the following independent variables:-

1. Scale (i.e. height of compartment) - m
2. Fire load density - kg/m^2
3. Fuel stick spacing (relative)
4. Fuel stick thickness - cm
5. Width/Height ratio of compartment
6. Depth/Height ratio of compartment

Both dependent and independent variables were transformed by taking logarithms to base 10. The regression coefficients, and their significance levels, the constants and residual standard errors obtained are given in Tables 2 and 3. As far as possible regression equations containing only terms significant at least at the 5 per cent level, and no non-significant terms, were obtained.

Although the existence of a coefficient may be established statistically, this does not mean that it is of practical importance; it may govern only a small variation.

Owing to the design of the experiment, correlations between the independent variables are almost all weak*. Table 1 shows the correlation coefficients between pairs of most of the variables used, dependent and independent.

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*In a completely balanced arrangement they would of course be zero.

3. Analysis (continued)

3.1. General (continued)

Some of the values in this table were obtained with the complete data and some from the data with the replicates averaged. This is not very important in judging whether one variable is correlated with another since the change in correlation coefficient obtained when the data with replicates averaged are used is small.

The highest correlation between independent variables (apart from interaction terms) is that between fuel thickness and fuel spacing (correlation coefficient $r = 0.56$). There are low correlations between scale and fire load density ($r = 0.33$), scale and depth/height ratio ($r = -0.30$), and depth/height and width/height ($r = -0.22$).

In the regression equations for the full ventilation fires interaction terms are usually more important than in the equations of the $\frac{1}{4}$ ventilation data[1]. An interaction between two variables shows that the effect of each of the variables depends on the level of the other.

3.2. Rate of burning (R)

Preliminary examination of the data showed that the quantity R/A_F, where A_F is the floor area, appeared to be nearly independent of scale and accordingly this was used as the dependent variable in the regression for rate of burning; equations employing this variable can of course be converted into equations employing R/A_W, where A_W is the ventilation opening area, by introducing the Depth/Height ratio.

The best regression equations found are given in Table 2, and illustrate various possibilities in fitting regression equations to the data. These have been obtained with the replicates averaged.

Equation 1 offers the best overall fit to the C.I.B. data but employs 6 independent variables, one of the interaction terms being rather complicated*. It reproduces the fall of R/A_F with increasing fire load density in the 441 compartment (Fig. 2) discernible in the experimental data (Fig. 1) but because it has a very large W/H term predicts very low burning rates for cubical compartments. Although this shape has not formed part of the official C.I.B. programme, Webster et al[3] carried out a number of experimental fires in cubical compartments very similar in style to those of the C.I.B. programme and in Fig. 1 a value for R/A_F has been inserted derived from their data. This suggests that the extrapolation of equation 1 to cubical compartments is not permissible.

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*An interaction term of this power had to be used to enable the fire load density main effect term to be overridden at high D/H and W/H ratios.

3. Analysis (continued)

3.2. Rate of burning (R) (continued)

Equation 2, with only 4 independent variables, gives a better fit for shallow compartments at the expense of a worse fit for the 441 compartment (Fig. 3), by omitting all W/H terms and interactions. An attempt to improve the fit by including a W/H x D/H interaction term (Regression 3) was unsuccessful since this term was not significant.

One of these equations has also been obtained with the full data, i.e. without averaging the replicates, (Regression 15, Table 3). Very similar coefficients were obtained, although the D/H term is now just significant.

Figures 4 and 5 show how the rate of burning per unit ventilation opening area increases with depth, average experimental values being shown in Fig. 4 and values calculated from regression 2 being shown in Fig. 5.

The residual standard deviation about the various regression equations is compared in Table 4 with the standard deviation of replicated data.

We can compare the measured rate of burning with that calculated from the relation derived by Thomas and Smith[4] for cribs of wood burning in the open, viz

$$r = 0.0017\ (A_v\ A_s)^{0.448}\ H^{0.5}\ \text{g/s.}$$

where r is the rate of burning

A_v is the horizontal cross-sectional area of the vertical passages in the crib (cm^2)

A_s is the surface area of the exposed wood (cm^2)

H is the height of the crib. (cm)

The ratios of measured/calculated burning rates are given in Table 5 in full and a condensation of the data in Table 6. This has been formed by averaging 2 cm stick data over 1 and $1\frac{1}{2}$ m scales, which appear to give very similar ratios, and neglecting $\frac{1}{3}$ spacing data since they are irregular.

Slower burning cribs (20 kg/m^2 and '1' spacing) in the larger compartments (1 and $1\frac{1}{2}$ m scales) for all shapes of compartment burn at a rate about $\frac{3}{4}$ of that predicted by the relation. There is direct experimental evidence[5] that for fire load densities of up to 30 kg/m^2 fuel can burn in a shallow compartment at the same rate as in the open. Thus it is likely that there is a bias of about 25 per cent in the extrapolation of the relation to the present conditions and further that for the conditions described above the burning rate of the crib even in a deep compartment is virtually the same as that of the same crib in the open air.

3. Analysis (continued)

3.2. Rate of burning (R) (continued)

If we turn to conditions where the compartment might be expected to exert more influence on the rate of burning, e.g. higher fire load density, higher fuel spacing and deeper compartments we find generally that the measured burning rate falls well below that calculated from the relation.

For example, a '1' spacing 40 kg/m^2 crib has a ratio of R Measured/ R Calculated of 0.60 (Table 5) for the 211 compartment, a little below the values for this shape for 20 and 30 kg/m^2, but a ratio of only 0.22 for the 441 compartment.

At the $\frac{1}{2}$ m scale there is more change in the ratio with increasing depth of compartment than for the same fire load density at the larger scales.

The calculated values of R/A_F for $\frac{1}{3}$ spacing cribs are compared with measured values in Table 7. The differences, which are substantial, seem to be related to the laboratory carrying out the experiment, suggesting that the rate of burning of fires with very closely packed cribs is more sensitive to the experimental conditions than the fires with 1 or 3 spacing cribs.

3.3. Temperatures near ceiling (θc ^{o}K)

Regression 4 (Table 2) shows the equation obtained using properties of the compartment and fuel alone as independent variables. Only the fire load density coefficient is significant and the temperature rise produced by an increase of fire load density from 20 to 40 kg/m^2 is only 10 per cent. A substantially better fit, as judged by the reduction in residual standard error, is obtained when quantities which were measured during the tests such as burning rate and temperature near floor (θ_b ^{o}K) are included. Thus regression 5 shows that θ_c varies markedly with θ_b, though it is not proportional to it as was found for the $\frac{1}{4}$ ventilation fires[1]; although the coefficients of 5 other terms become significant none of these has a specially large effect on θ_c. As would be expected[5] θ_c varies markedly with R/A_W (Regression 6) in addition to fuel spacing and shape of compartment. Provided a D/H term is included the regression coefficient for a R/A_F term is the same as for a R/A_W term, but the regression with the latter is preferable since a smaller coefficient is then obtained for the D/H term.

3. Analysis (continued)

3.3. Temperature near ceiling (θ_c °K) (continued)

Regressions similar to numbers 4, 5 and 6 have also been obtained with replicates included (regression numbers 16, 17 and 18). The coefficients obtained are very similar, apart from the coefficient for D/H in regression 16 which is highly significant and accounts for a variation in θ_c °K as large as that of fire load density.

3.4. Intensity of radiation in the plane of the ventilation opening (I_o/ϕ)

Average experimental values for I_o/ϕ are given in Fig.6.

Table 2 gives four regression equations, numbers 7 and 8 with variables of compartment and fuel, number 8 having interaction terms which have reduced the residual standard error, and numbers 9 and 10 with R/A_w and θ_c terms.

As with θ_c, the inclusion of quantities measured during the fire has produced a substantially better fit.

Regressions 19 and 20 (Table 3) show that including replicates has little effect on the coefficients, apart from that for D/H in regression 19 which is about 50 per cent larger than that for D/H in regression 7.

3.5. $I_o/\phi \div R/A_w$

Three regression equations are given for $I_o/\phi \div R/A_w$ in Table 2, number 11 with variables of compartment and fuel but no interaction terms, number 12 with an interaction term added and number 13 with a θ_c term. The fit of number 13 is substantially better than that of number 11.

The coefficients of regression 22 with replicates included are similar to those of the corresponding regression with replicates averaged (13).

3.6. Time to reach 80 per cent of initial fuel weight (t_{80})

The regression (No.14) obtained for t_{80} with replicates averaged is given in Table 2. To illustrate the action of the interaction term, values for t_{80} calculated from equation 14 for one set of conditions are given in Table 8. The coefficients of regression 23 (replicates included) are similar to those of regression 14 (replicates averaged).

4. Discussion

4.1. Rate of burning (R)

Unlike the analyses for rate of burning of fires with $\frac{1}{4}$ ventilation opening all the independent variables appear in significant interaction terms and this means that the rate of burning depends in a much more complicated way on the independent variables. For example, in regression 2, Table 2, since the coefficient for (fire-load density) x (D/H ratio) is statistically significant and negative, whilst the coefficient for fire-load density is positive, the effect of a change in fire-load density is largest for small values of D/H and becomes smaller as D/H increases. This can also be seen in the experimental data in Fig. 1.

The factors which influence R/A_F are:-

(a) The relative spacing between the sticks

(b) The fire-load density

(c) The shape of the compartment

Scale and stick thickness have no detectable effect on R/A_F.

The relative spacing and the fire-load density have most effect on R/A_F for shallow compartments (D/H = 1) see Fig. 1. For D/H = 2 the effects of both are smaller and at D/H = 4, R/A_F actually decreases slightly with increasing fire-load density whilst the regression equations predict that the relative spacing has virtually no effect. However it must be remembered that since only one stick spacing was employed in the 441 compartment fires there is no direct experimental data to verify the predicted effect of spacing for this shape.

Increasing the width alone by changing from the 121 to the 221 shape appears to cause a slight increase in R/A_F (Fig. 1).

The sensitivity of burning rate, and hence fire duration, of these full ventilation fires, to the relative spacing of the fuel creates a difficulty in the application of these data since it is not known what types of wood cribs represent fire-loads encountered in practice. This is of little importance with a small ventilation opening since the burning rate largely depends only on the ventilation opening area and height and is insensitive to the stick spacing.

However there is a decided tendency for variation in burning rate to be accompanied by variation in temperature (Regression 6) so that a fire having a higher burning rate and hence a shorter duration will have a higher temperature whilst a longer fire will have a lower temperature. The fire resistance required of the compartment to contain the fire will thus be much less sensitive than the burning rate to the relative spacing of the fuel. This is being explored further.

4. Discussion (continued)

4.2. Temperature near ceiling (θ_c °K)

Table 2 shows that θ_c has highest correlations with R/A_w, θ_b and fire-load density. Regression 4 of Table 2 shows that fire-load density has much more effect on temperature than the relative fuel spacing and this is surprising since both factors might be expected to influence temperature through burning rate which is affected by both variables to a considerable extent (Fig. 1). The inclusion of a rate of burning term as R/A_w, in regression 6, renders the fire-load density term superfluous whilst the fuel spacing term is enhanced.

Although θ_c varies strongly with θ_b it is by no means proportional to it as was found for the $\frac{1}{4}$ ventilation data[1] and this shows that the temperature varies more within the compartment when the ventilation area is large.

A strong variation of θ_c with R/A_w is very much to be expected from previous experiments[5].

4.3. Intensity of radiation in the plane of the ventilation opening (I_o/ϕ)

I_o/ϕ cannot be very satisfactorily related to variables of the compartment or fuel since the residual standard error about regression 7 is 35 per cent. Only a small improvement results when interaction terms are included (Regression 8).

The residual standard error can only be reduced to a value comparable with that for rate of burning as dependent variable by including terms in θ_c (Regression 9) or R/A_w and θ_c (Regression 10). The coefficients for θ_c °K in equation 9 of 1.8 or in equation 10 of 1.4 are high, showing a strong variation with θ_c °K but they are not as high as the value of 4 that would be expected if the thermocouple indicated the radiating temperature of the enclosure.

Both for regressions 9 and 10 there are a number of significant independent variables which would be expected to influence I_o/ϕ only through their influence on temperature and this suggests that the thermocouples do not give a true measure of radiating temperature.

4.4. $I_o/\phi \div R/A_w$

There is a strong correlation between I_o/ϕ and R/A_w (Correlation coefficient = 0.68, Table 1) and this explains why the quantity $I_o/\phi \div R/A_w$, with a standard deviation of 29 per cent, has less variation than either I_o/ϕ (standard deviation 50 per cent) or R/A_w (standard deviation 43 per cent).

4. Discussion (continued)

4.4. $I_o/\emptyset \div R/A_W$ (continued)

The ratio does depend to some extent on the fuel thickness and spacing, the fire-load density and the compartment shape, but the mean value corresponds to 490 cal/g and this can be compared with the values of 350-400 cal/g obtained previously for well-ventilated fires in compartments[7].

4.5. Time to reach 80 per cent of initial fuel weight (t_{80})

Most of the parameters of fuel and compartment have a significant effect on t_{80} either because they influence the rate of growth from ignition to the stage of full development or because they influence the time the fire then takes, burning at a comparatively steady rate, to reach a point at which 20 per cent of the weight of the fuel has been lost.

With shallow compartments (D/H = 1) increasing scale increases t_{80} and this can only be due to an effect in the early stages of growth since it has been shown in Section 4.1 that the burning rate of the fully developed fire, per unit floor area, is independent of scale. The linear rate of spread soon after ignition depends only on the thickness and spacing of the sticks in the crib and it thus seems that as scale increases t_{80} increases because the cribs are larger and in some way the fire has to spread a longer distance before it can become fully developed; but t_{80} is not by any means proportional to the scale, i.e. the linear size of the crib.

However the negative interaction term (Scale x D/H) causes t_{80} to increase less with scale as D/H increases, indeed for D/H = 4, t_{80} actually appears to decrease with scale. This is what was found for the ¼ ventilation fires[1], suggesting that there are some similarities in behaviour between deep compartments and ventilation controlled fires.

A larger fire-load density should cause a fire to develop more rapidly and this is contrary to regression 14 which shows that t_{80} increases as fire-load density increases. The effect of fire-load density on t_{80} must be mainly due to the change in the absolute amount of fuel required to be burnt in the fully developed period to reach the 80 per cent point; the burning rate does not increase nearly in proportion to fire-load density, except for the 211 shape.

The stick spacing influences t_{80} more than any other variable and its influence is twofold. Firstly, in the earliest stages the fire will spread at a higher linear rate at wider stick spacings and secondly, for most compartment shapes the steady state burning rate is higher for wider stick spacings. No reasons can be advanced for the decreases observed in t_{80} with increasing stick thickness and with increasing W/H.

4. Discussion (continued)

4.5. Time to reach 80 per cent of initial fuel weight (t_{80}) (continued)

Increasing D/H increases t_{80} (although because of the Scale x D/H interaction the increase is less for larger scales), probably because of its effect on both periods. The initial linear rate of spread of a fire is set by the design of the crib and it is possible that the fires, lit at the front, have to travel further into the deeper compartments before transition to the fully-developed stage can occur. In any case the steady state rate of burning per unit floor area decreases as D/H is increased (Fig. 1).

5. Conclusions

1. The rate of burning per unit floor area (R/A_F), though independent of scale and stick thickness, depends markedly and in a complex way on fuel spacing, fire-load density and shape of compartment. Fuel spacing and fire-load density have most effect on burning rate for compartments which are shallow from back to front.

2. However the fire protection requirement will not vary so much as fire duration since an increase in the duration of a fire caused by a change in fuel spacing affecting burning rate is accompanied by a decrease in the temperature of the fire and this will compensate to some extent, though not completely.

3. The temperature of the thermocouple near the ceiling (θ_c °K) depends strongly on R/A_W, as in previous experiments[5]. Once the variation of θ_c °K with R/A_W is taken account of, the influences of fuel spacing and compartment shape, the only other statistically significant variables, are fairly small.

There is more variation of temperature within the compartment than with small ventilation openings.

4. Much more of the variation in I_o/ϕ can be accounted for if θ_c or R/A_W are included as independent variables. The variation with θ_c is less than would be expected if θ_c represents the radiating temperature, and other variables such as fire load density fuel spacing and compartment shape have a substantial influence on I_o/ϕ.

5. The mean ratio between I_o/ϕ and R/A_W is 490 cal/g, rather higher than the values obtained previously for well ventilated fires.

5. Conclusions (continued)

6. t_{80}, the time to obtain 80 per cent of the initial weight of fuel, depends on most of the parameters of fuel and compartment, particularly the stick spacing, the scale and the depth/height ratio. The signs of the coefficients are the same for those of the corresponding regression for ¼ ventilation fires[1], except for scale.

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Mr. P. G. Smith and Miss Lynda Griffiths prepared and collated the data and were responsible for the preparation of the data tapes, the associated programmes for selecting data, and the regression analyses. Mr. J. Leake also gave valuable assistance.

APPENDIX

Key to symbols and codes for the experimental conditions

R	-	is the rate of burning (kg/min)
I_o	-	is the intensity of radiation received at a radiometer in front of the ventilation opening (cal $cm^{-2}s^{-1}$)
ϕ	-	is the configuration factor of the ventilation opening with respect to the radiometer
θ_c and θ_b	-	are the temperatures attained by thermocouples placed centrally in the compartment and a quarter of the height below the ceiling and above the floor respectively
A	-	is the ventilation opening area (m^2)
H	-	is the ventilation opening height (the same as the compartment height in these experiments) (m)
t_{80}	-	is the time for the fuel weight to fall to 80 per cent of its initial weight (min)
80/30	-	refers to the period over which the weight of fuel fell from 80 to 30 per cent of its initial value

Shape The code describing shape gives in order the compartment width, depth and height, relative to the height:-

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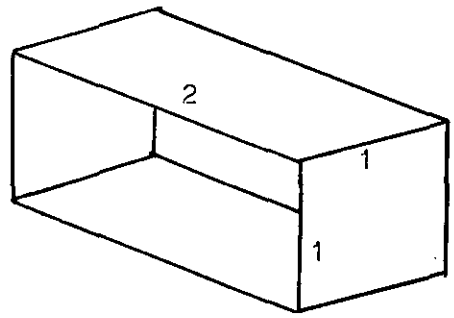

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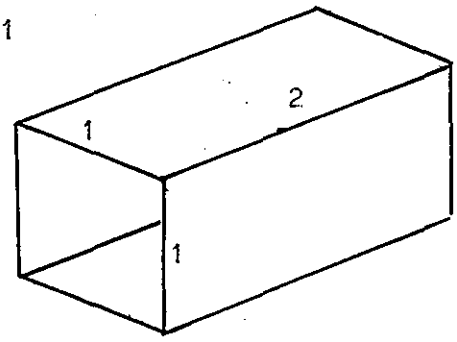
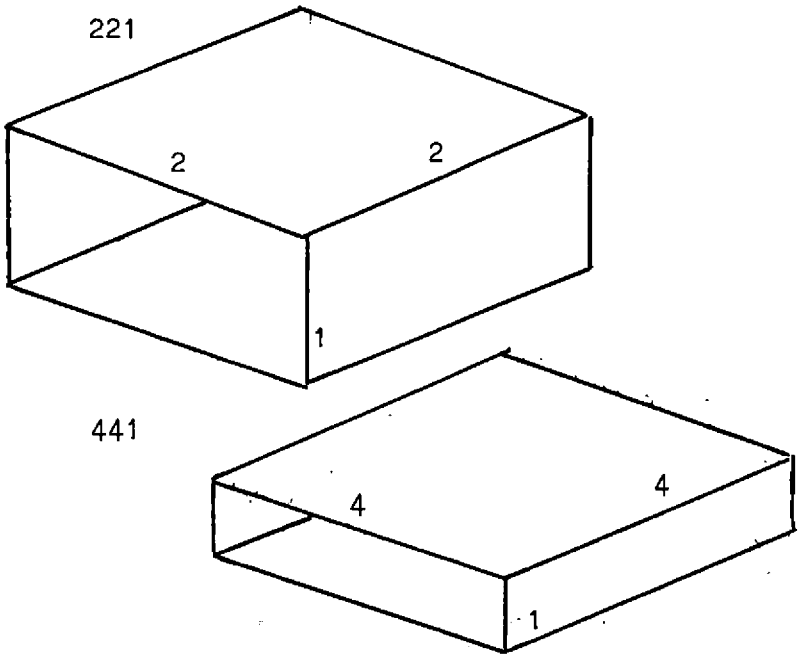
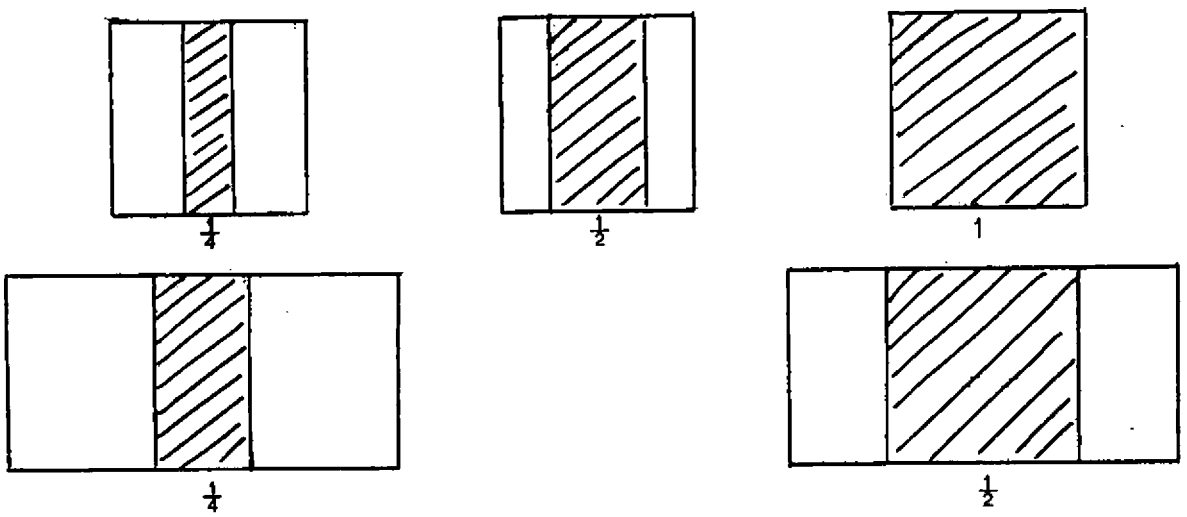




Scale This is the height of the compartment.

Ventilation This is the fraction of the area of the front of the compartment left open



Stick thickness and spacing

The first figure in the code is the stick thickness in cm, the second is the spacing between sticks expressed in stick widths. Thus 4,1 stands for 4 cm thick sticks 1 x 4 = 4 cm apart:

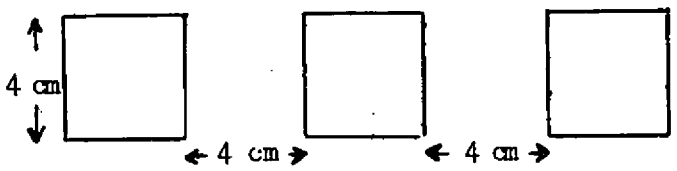


TABLE 1. CORRELATION MATRIX SHOWING CORRELATIONS BETWEEN THE DEPENDENT VARIABLES

	I_o/ϕ	R/A_w	Q_c	Q_b	Scale (H)	Fire load density	Fuel spacing (relative)	Fuel thickness	W/H	D/H	Spacing x D/H	W/H x D/H	D/H x Fire load density	W/H x thickness	Scale x D/H	W/H x D/H x Fire load density
I_o/ϕ	1															
R/A_w	0.68	1														
Q_c	0.73	0.53	1													
Q_b	0.09	-0.07	0.47	1												
Scale (H)	0.09	-0.10	0.09	0.30	1											
Fire load density	0.39	0.17	0.40	-0.02	0.33	1										
Fuel spacing	0.30	0.55	-0.04	-0.45	-0.05	-0.06	1									
Fuel thickness (relative)	-0.37	-0.31	-0.07	0.28	0.00	0.04	-0.56	1								
W/H	0.10	-0.09	-0.25	-0.13	-0.04	-0.05	-0.04	0.00	1							
D/H	0.19	0.55	0.27	-0.02	-0.30	-0.11	-0.07	0.03	-0.22	1						
Spacing x D/H	0.06	0.40	-0.14	-0.57	-0.21	-0.09	0.70	-0.35	-0.20	0.27	1					
W/H x D/H	0.22	0.37	0.00	-0.15	-0.28	-0.13	-0.09	0.02	0.58	0.65	0.05	1				
D/H x Fire load density	0.21	0.55	0.30	-0.21	-0.26	-0.01	-0.07	0.04	-0.24	0.99	0.26	0.63	1			
W/H x thickness	-0.28	*	-0.23	0.25	0.05	0.03	-0.51	0.63	0.67	-0.04	-0.38	0.44	-0.05	1		
Scale x D/H	0.18	*	0.26	0.37	0.72	0.23	-0.07	0.00	-0.17	-0.37	-0.10	-0.37	-0.37	-0.05	1	
W/H x D/H x Fire load density	*	*	*	*	*	-0.09	-0.10	*	0.58	0.66	0.04	0.996	*	*	*	1

Notes

(1) Each value in the table is the correlation coefficient between the logarithms of the variables named on the same line and column

(2) ½ spacing data are omitted

(3) * Not obtained

(4) For the line W/H x D/H and above the data includes replicates

(5) For the line D/H x Fire load density and below the replicates were averaged

TABLE 2. PARAMETERS OF THE REGRESSION EQUATIONS (REPLICATES AVERAGED)

Dependent variable	Regression number	Mean value of dependent variable	Standard deviation of dependent variable	Constant term	Coefficients															Residual standard error
					R/A_W kg min^{-1} m^{-2}	θ_c °K	θ_b °K	Scale (H) m	Fire load density kg/m^2	Fuel spacing (relative)	Fuel thickness cm	Width/Height W/H	Depth/Height D/H	Fuel spacing x D/H interaction +	W/H x D/H interaction	D/H x Fire load density interaction	W/H x thickness interaction	Scale x D/H interaction	W/H x D/H x Fire load density interaction	
R/A_F	1	1.48	53%	-0.817	-	-	-	-	0.458 ***	0.654 ***	-	0.978 ***	0.516 NS	-1.159 ***	-	-	-	-	-1.701 **	0.064 (16%)
	2			-0.501	-	-	-	-	0.446 ***	0.643 ***	-	-	-	-1.079 ***	-	-0.268 ***	-	-	-	0.0703 (18%)
	3			-0.517	-	-	-	-	0.462 ***	0.630 ***	-	-	-	-0.958 ***	0.208 NS	-0.329 ***	-	-	-	0.0699 (17%)
θ_c °K	4	1070	16%	2.852	-	-	-	0.002 NS 0%	0.144 * 10%	0.012 NS -1%	-0.051 NS -7%	-0.068 NS -9%	0.035 NS 5%	-	-	-	-	-	-	0.060 (15%)
	5			1.226	-	-	0.510 *** 65%	-0.107 ** -11%	0.201 *** 15%	0.079 * 9%	-0.082 * -10%	-0.032 NS -4%	0.086 ** 13%	-	-	-	-	-	-	0.040 (10%)
	6			2.978	0.457 *** 90%	-	-	-	-	-0.196 *** -19%	-	-0.152 *** -19%	-0.169 *** -21%	-	-	-	-	-	-	0.046 (11%)
I_o/ϕ	7	1.86	50%	-0.478	-	-	-	0.051 NS 6%	0.473 ** 39%	0.237 * 30%	-0.293 ** -33%	0.296 ** 51%	0.233 * 38%	-	-	-	-	-	-	0.130 (35%)
	8			-0.877	-	-	-	-	0.498 *** 41%	0.575 ***	-0.294 ** -33%	1.231 **	1.645 **	-2.093 ***	-2.970 *	-	-	-	-	0.105 (27%)
	9			-5.809	-	1.849 *** 190%	-	-	0.237 *** 18%	0.267 *** 34%	-	0.532 ***	-	-	0.427 ***	-	-0.883 ***	-	-	0.0589 (14.5%)
	10			-4.156	0.554 *** 115%	1.381 *** 120%	-	0.099 * 12%	-	-	-	0.566 ***	-0.053 NS -7%	-	-	-	-1.011 ***	-	-	0.051 (12%)
$\frac{I_o/\phi}{R/A_W}$	11	0.824	29%	0.039	-	-	-	0.113 NS 13%	0.037 NS 3%	-0.250 *** -24%	-0.322 *** -36%	0.087 NS 13%	-0.217 ** -26%	-	-	-	-	-	-	0.087 (22.2%)
	12			0.039	—	—	—	0.132 * 16%	—	—	-0.263 *** -30%	—	—	-1.116 ***	—	—	—	—	—	0.080 (20%)
	13			-2.858	-	0.965 *** 75%	-	-	-	-0.239 *** -23%	-0.275 *** -32%	0.161 ** 25%	-0.277 *** -32%	-	-	-	-	-	-	0.065 (16%)
t_{80}	14	5.35	55%	0.596	-	-	-	0.417 ***	0.255 ** 19%	-0.729 *** -55%	-0.243 *** -30%	-0.282 *** -30%	0.381 *** 70%	-	-	-	-	-0.874 **	-	0.072 (18%)

Notes

(1) All data 80/30 means (except t_{80})
(2) ½ spacing data omitted
(3) Logarithmic transformation to base 10 of all variables
(4) + inserted as $\log_{10}$ (Fuel spacing) x $\log_{10}$ (D/H ratio). Similarly for other interactions
(5) * significant at 5% level
** " " 1% "
*** " " 0.1% "
NS Not significant

(6) The % value quoted in the columns for the regression coefficients is the change in the dependent variable produced by changing the level of the independent variable from the lowest to the highest value of the experiment (when R/A_W, θ_c or θ_b were used as independent variables a change of 4 standard deviations was taken). A % value cannot be quoted for a variable if an interaction term containing it is significant.

TABLE 3. PARAMETERS OF THE REGRESSION EQUATIONS (INCLUDING REPLICATES)

Dependent variable	Regression number	Mean value of dependent variable	Standard deviation of dependent variable	Constant term	Coefficients															Residual standard error
					R/A_W kg min^{-1} m^{-2}	θ_c °K	θ_b °K	Scale (H) m	Fire load density kg/m^2	Fuel spacing (relative)	Fuel thickness cm	Width/Height W/H	Depth/Height D/H	Fuel spacing x D/H interaction +	W/H x D/H interaction	D/H x Fire load density interaction	W/H x thickness interaction	Scale x D/H interaction	W/H x D/H x Fire load density interaction	
R/A_F	15	1.31	42%	-0.655	-	-	-	-	0.348 *** 27%	0.689 ***	-	0.909 ***	0.568 *	-1.374 ***	-	-	-	-	-1.740 ***	0.068 (17%)
θ_c °K	16	1090	18%	2.757	-	-	-	0.013 NS 1%	0.209 *** 16%	-0.025 NS -3%	-0.066 NS -9%	-0.078 * -10%	0.116 *** 17%	-	-	-	-	-	-	0.058 (14%)
	17			1.366	-	-	0.441 *** 50%	-0.097 ** -10%	0.248 *** 19%	0.065 * 7%	-0.083 * -11%	-0.037 NS -5%	0.116 *** 17%	-	-	-	-	-	-	0.045 (11%)
	18			2.972	0.519 *** 110%	-	-	-	-	-0.243 *** -23%	-	-0.127 *** -16%	-0.198 *** -24%	-	-	-	-	-	-	0.044 (11%)
I_o/ϕ	19	1.83	50%	-0.568	-	-	-	0.083 NS 10%	0.559 *** 47%	0.174 * 21%	-0.350 *** -38%	0.239 ** 39%	0.339 *** 60%	-	-	-	-	-	-	0.137 (37%)
	20			-0.859	-	-	-	-	0.564 *** 48%	0.473 ***	-0.337 *** -37%	1.038 **	1.329 ***	-1.797 ***	-2.388 *	-	-	-	-	0.125 (33%)
$\frac{I_o/\phi}{R/A_W}$	21	0.908	36%	0.160	-	-	-	0.144 NS 17%	-	-0.307 *** -28%	-0.362 *** -39%	-	-	-	0.250 NS	-0.243 ***	-	-	-	0.110 (29%)
	22			-2.906	-	0.991 *** 90%	-	-	-	-0.279 *** -26%	-0.302 *** -34%	0.217 *** 35%	-0.389 *** -42%	-	-	-	-	-	-	0.088 (22%)
t_{80}	23	6.58	53%	0.493	-	-	-	0.346 ***	0.354 *** 28%	-0.766 *** -57%	-0.270 *** -31%	-0.255 *** -30%	0.227 ***	-	-	-	-	-0.955 **	-	0.086 (22%)

Notes as for Table 2.

TABLE 4. COMPARISON BETWEEN THE RESIDUAL VARIATION ABOUT THE REGRESSION AND THE STANDARD DEVIATION OF REPLICATES

Dependent variable	Regression number	Residual standard error about regression (per cent)	Standard deviation of replicates (per cent)
R/A_F	1 2 3 15	16 18 17 17	10.9
θ_c °K	4 5 6 16 17 18	15 10 11 14 11 11	8.1
I_o/ϕ	7 8 9 10 19 20	35 27 14.5 12 37 33	21.0
t_{80}	14 23	18 22	18.0

TABLE 5. RATIOS OF MEASURED AND CALCULATED BURNING RATES

Scale m	Stick thickness and spacing	Fireload density kg/m^2	$R_{Measured} \div R_{Calculated}$			
			211	221	121	441
$\frac{1}{2}$	2,$\frac{1}{3}$	20	2.00	1.35	0.1	-
	2,1		0.94	0.62	0.53	0.54
	4,1		1.08	1.15	0.56	-
	1,3		0.57	0.28	0.18	-
	2,3		0.87	0.39	0.30	-
1	2,$\frac{1}{3}$	20	1.96	1.09	-	-
		30	1.68	0.74	0.20	
		40	1.64	0.60	0.24	
	2,1	20	0.72	0.85	0.73	-
		30	0.74	0.57	0.53	
		40	0.55	0.42	0.39	
	4,1	20	0.79	1.12	0.60	-
		30	0.91	0.91	0.72	
		40	0.90	0.65	0.58	
	1,3	20	0.57	0.36	0.37	-
		30	0.45	0.27	0.27	
		40	0.47	0.22	0.20	
	2,3	20	0.68	0.55	0.43	-
		30	-	0.40	0.31	
		40	0.61	0.36	0.26	
$1\frac{1}{2}$	2,$\frac{1}{3}$	20	1.04	-	-	-
		30	0.54			
		40	0.59			
	2,1	20	0.75	-	-	0.74
		30	0.71			0.43
		40	0.64			0.22
	4,1	20	0.93	-	-	-
		30	0.94			
		40	0.88			
	1,3	20	0.51	-	-	-
		30	0.40			
		40	0.35			
	2,3	20	0.92	-	-	-
		30	0.70			
		40	0.60			

Calculated values from relation of Thomas and Smith[4] for wood cribs burning in the open. Wood density taken as 0.43 g/cm^3.

TABLE 6. CONDENSED TABLE OF RATIOS OF MEASURED AND CALCULATED BURNING RATES

Scale (m)	Relative stick spacing	Fire load density kg/m^2	$R_{Measured} \div R_{Calculated}$			
			211	221	121	441
$\frac{1}{2}$	1	20	0.94	0.62	0.53	0.54
	3	20	0.87	0.39	0.30	-
1 and $1\frac{1}{2}$	1	20	0.73	0.85	0.73	0.74
		30	0.72	0.57	0.53	0.43
		40	0.60	0.42	0.39	0.22
	3	20	0.80	0.55	0.43	-
		30	0.70	0.40	0.31	-
		40	0.60	0.36	0.26	-

Stick thickness : 2 cm

Derived from Table 5 by omitting $\frac{1}{3}$ spacing data and averaging data for 2 cm stick thickness over 1 and $1\frac{1}{2}$ m scales.

TABLE 7. MEASURED AND CALCULATED VALUES OF R/A_F FOR $\frac{1}{3}$ SPACING CRIBS

Scale m	Fire load density kg/m^2	Calculated* (C) or Measured (M)	R/A_F kg $min^{-1}m^{-2}$		
			211	221	121
$\frac{1}{2}$	20	C M	0.59 1.36 (J)	0.66 0.85 (A)	0.66 0.06 (N)
1	20	C M	0.59 1.15 (J)	0.66 0.60 (A)	-
	30	C M	0.71 1.44 (J)	0.77 0.59 (A)	0.77 0.17 (N)
	40	C M	0.81 1.85 (J)	0.86 0.63 (A)	0.86 0.27 (N)
$1\frac{1}{2}$	20	C M	0.59 0.56 (G_3)	-	-
	30	C M	0.71 0.42 (G_3)	-	-
	40	C M	0.81 0.61 (G_3)	-	-

*Calculated using regression 2.

J - Building Research Institute, Japan.

A - Commonwealth Experimental Building Station, Australia.

N - Brandveiligheidsinstituut T.N.O., Netherlands.

G_3 - Forschungsstelle für Brandschutztechnik an der Universitat, Karlsruhe, Germany.

TABLE 8. VALUES FOR t_{80} CALCULATED FROM EQUATION 14

Scale m	t_{80} - min					
	D/H = 1		D/H = 2		D/H = 4	
	1 Spacing	3 Spacing	1 Spacing	3 Spacing	1 Spacing	3 Spacing
$\frac{1}{2}$	5.4	2.4	8.4	3.8	13.1	5.9
1	7.2	3.2	9.3	4.2	12.1	5.4
$1\frac{1}{2}$	8.5	3.8	9.9	4.5	11.6	5.2

Values of t_{80} calculated from equation 14.

Fire load density - 20 kg/m^2

Stick thickness - 2 cm

W/H ratio - 1

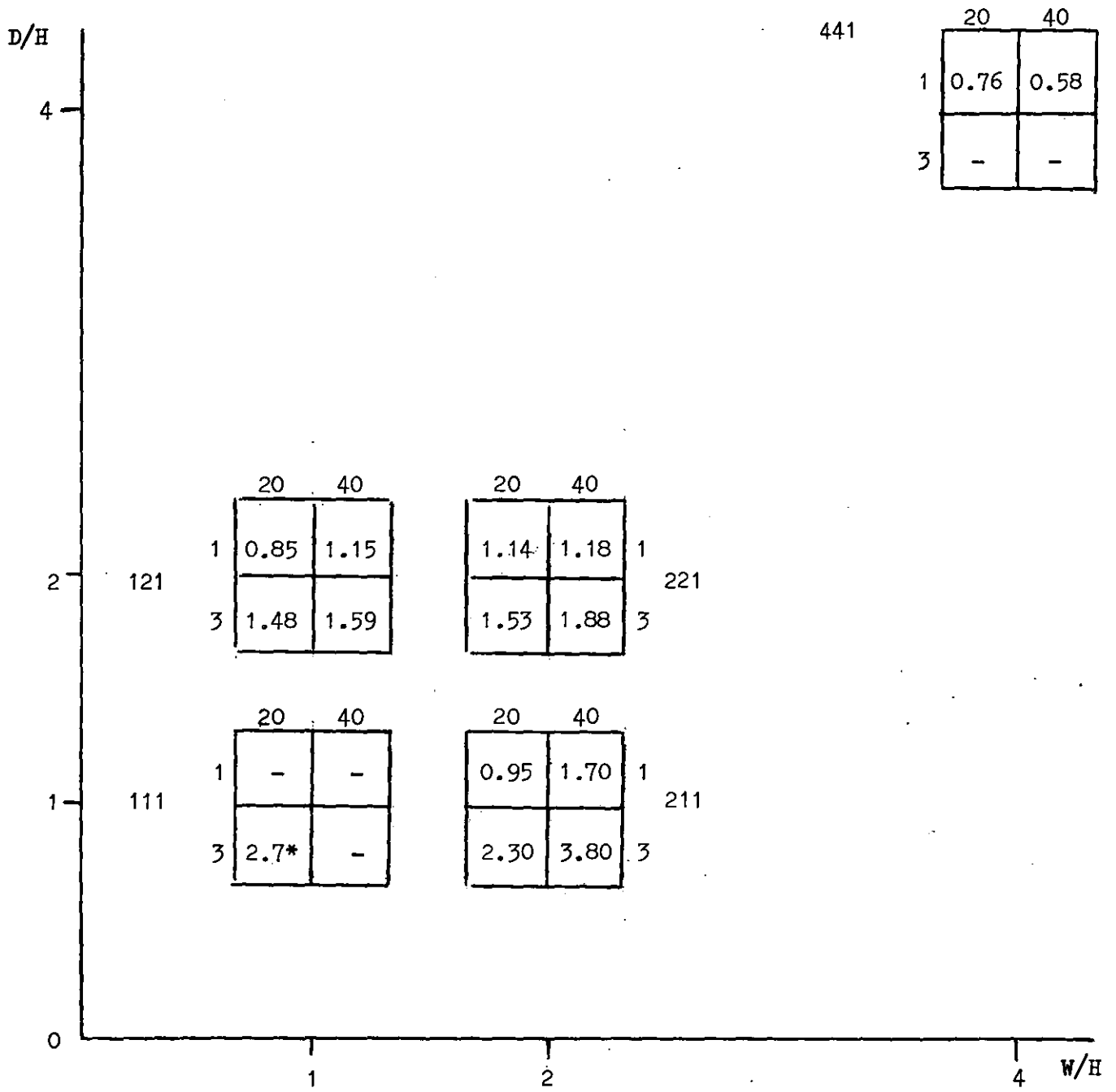


Fig.1. Mean experimental values of R/A_F (kg $min^{-1}m^{-2}$) for 1 m scale compartments averaged over all stick thicknesses

The entries for the 441 shape are interpolations between $\frac{1}{2}$ and $1\frac{1}{2}$ m scale data

Each entry in this and the following similar tables is in an abbreviated form, for example, in full, the top right hand entry would be:

Compartment shape 441		Fire load density (kg/m ^{2})	
		20	40
Relative stick spacing	1	0.76	0.58
	3	-	-

*Value from Webster's data[3] 0.9 m scale, 25 mm sticks.

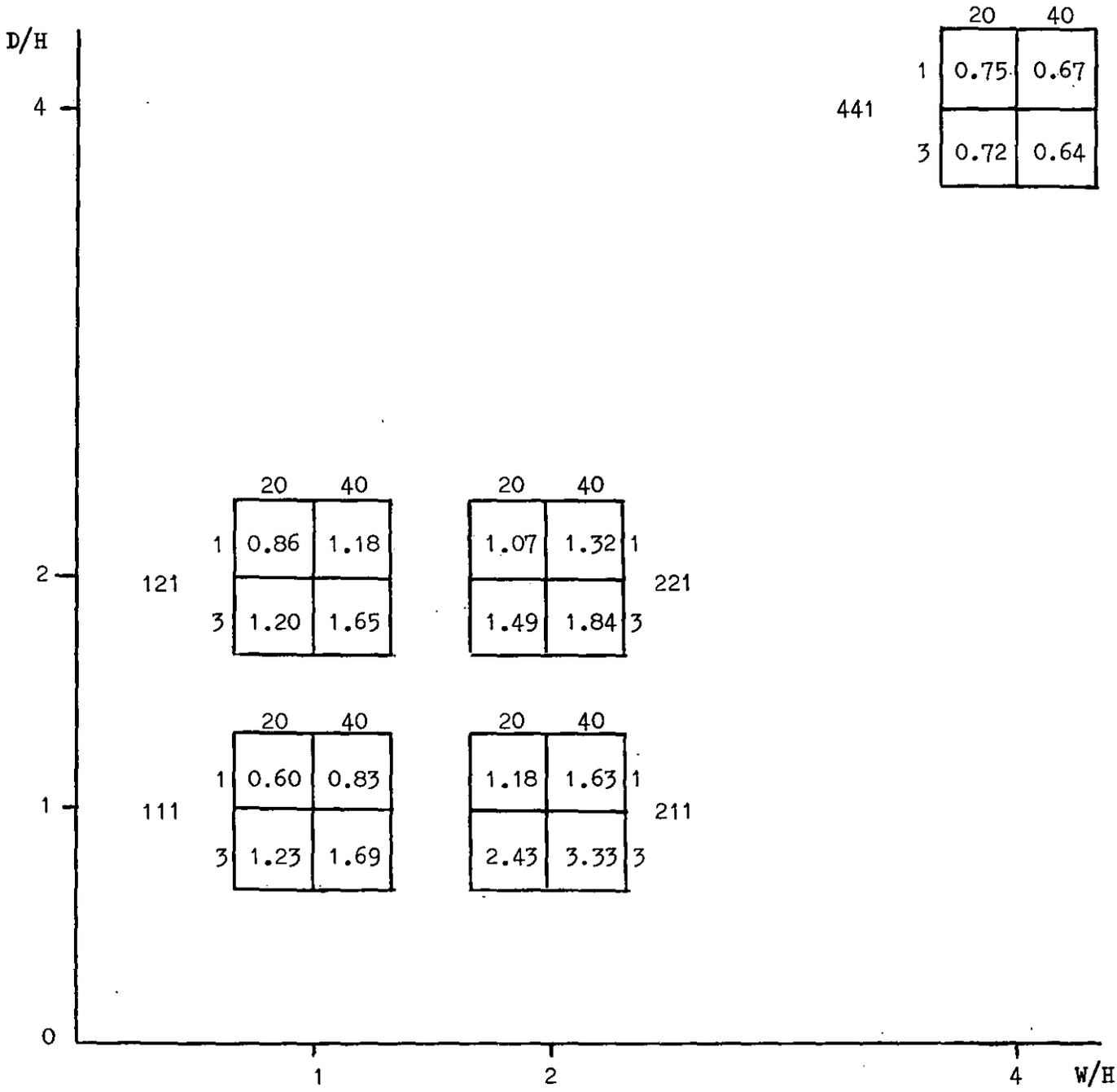


Fig.2. Values of R/A_F (kg $min^{-1}m^{-2}$) calculated using regression 1

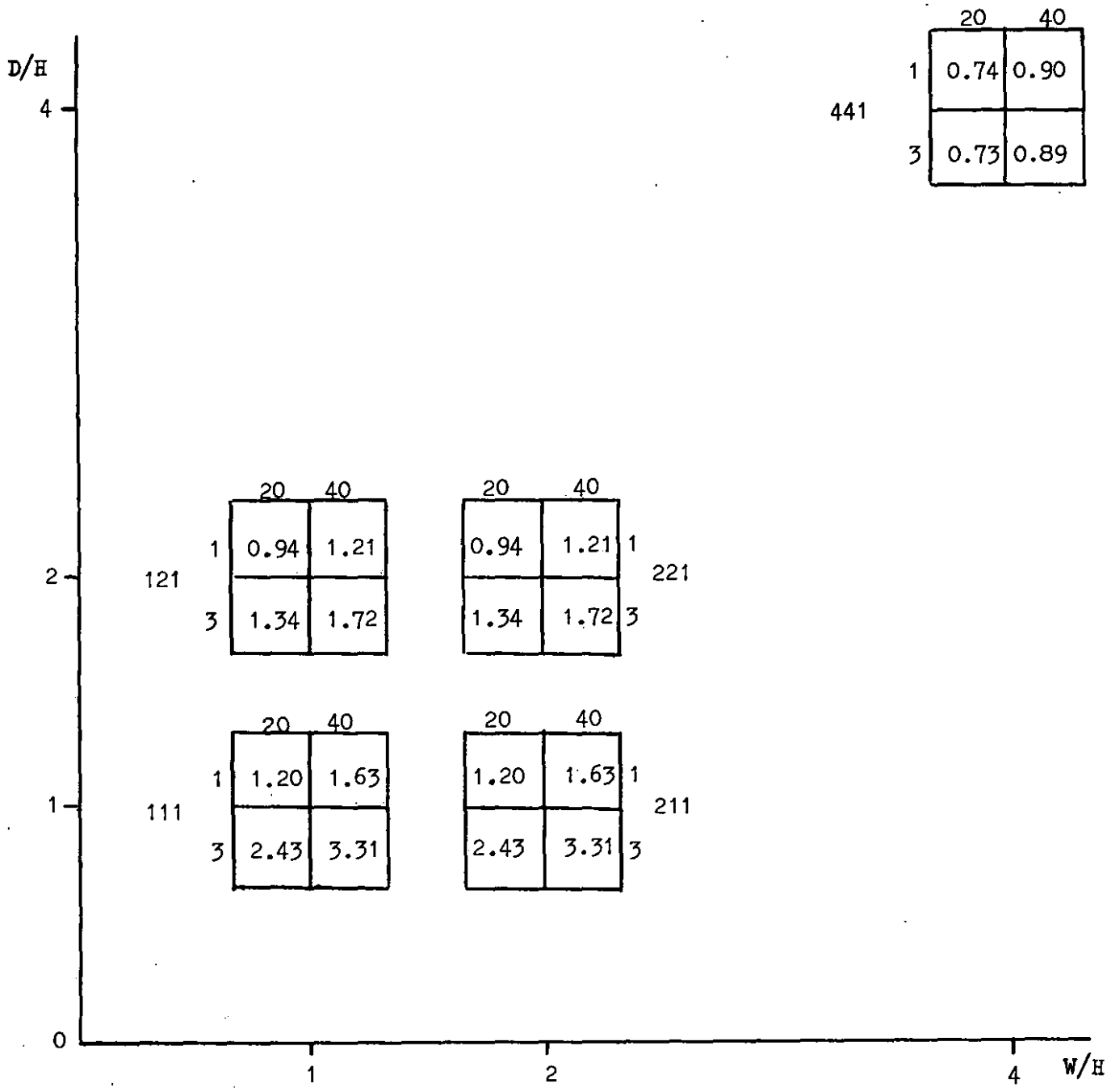


Fig.3. Values of R/A_F (kg $min^{-1}m^{-2}$) calculated using regression 2

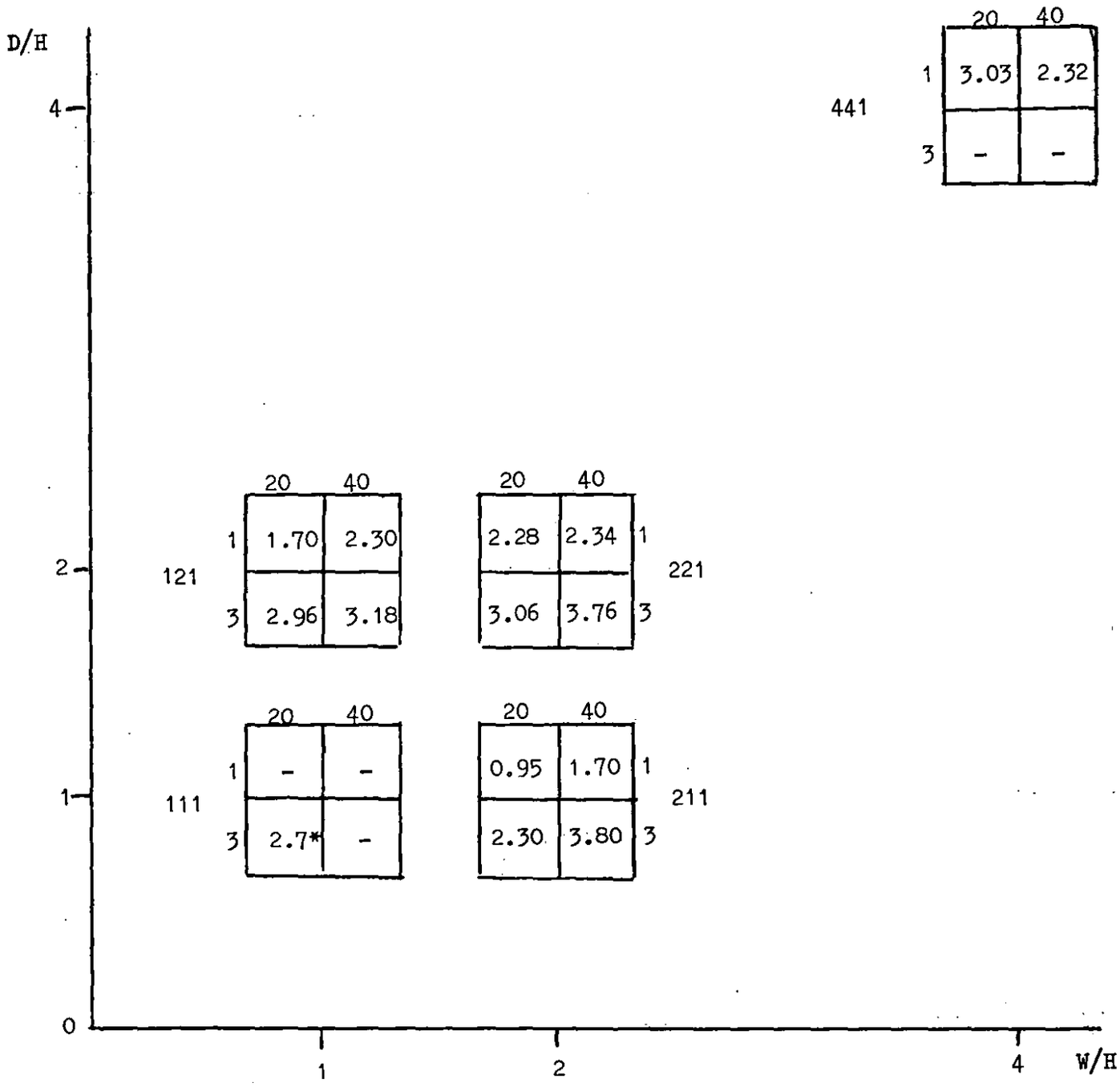


Fig.4. Experimental values of R/A_W or $R/A_W\sqrt{H}$ (kg $min^{-1}m^{-2}$) 1 m scale, averaged over all stick thicknesses

The values for the 441 shape are interpolations between $\frac{1}{2}$ and $1\frac{1}{2}$ m scale data.

*Value from Webster's data[3], 0.9 m scale, 25 mm sticks.

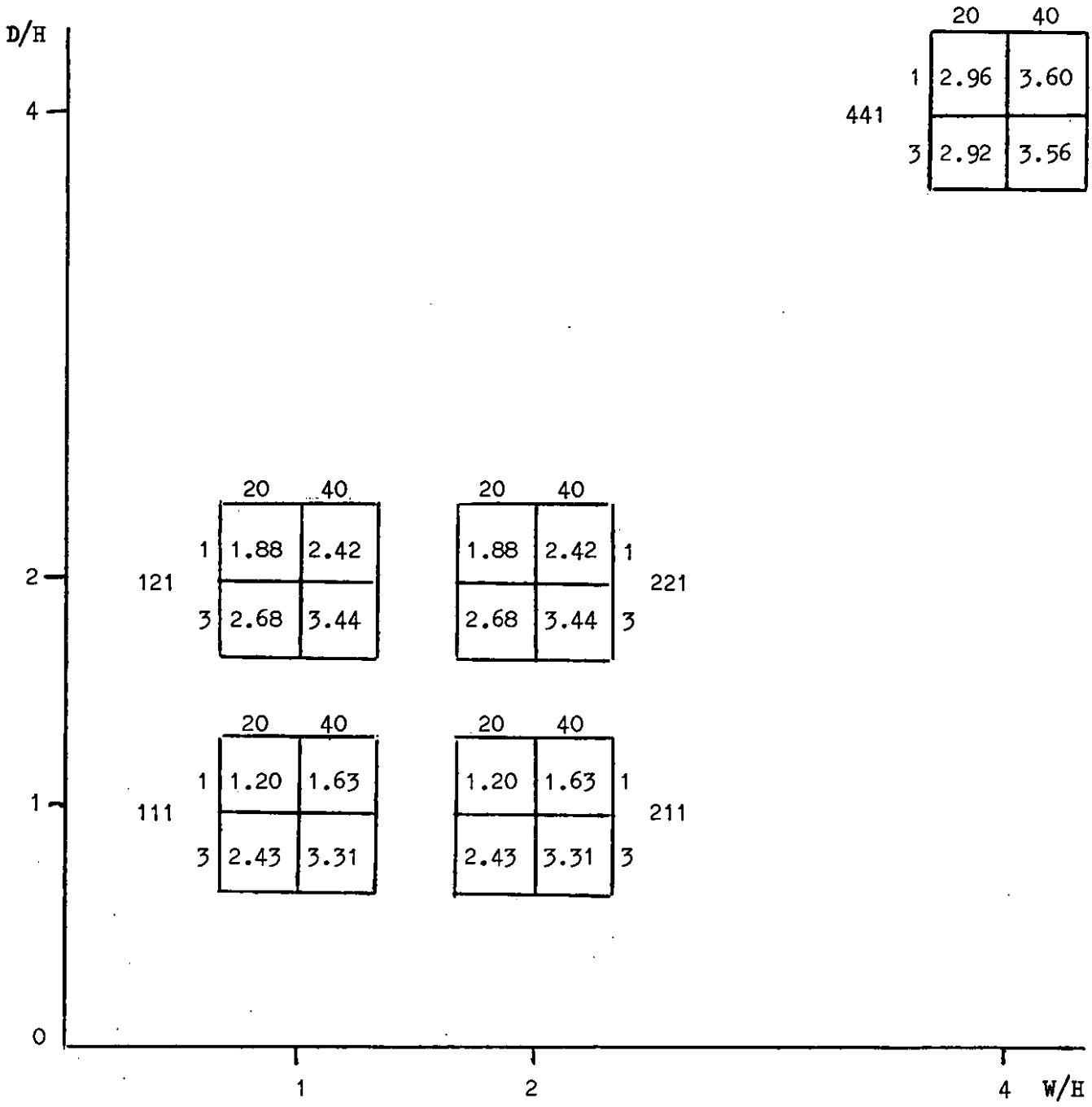


Fig.5. Values of R/A_W (or $\frac{R}{A_W H^2}$ on 1 m scale) calculated using regression 2

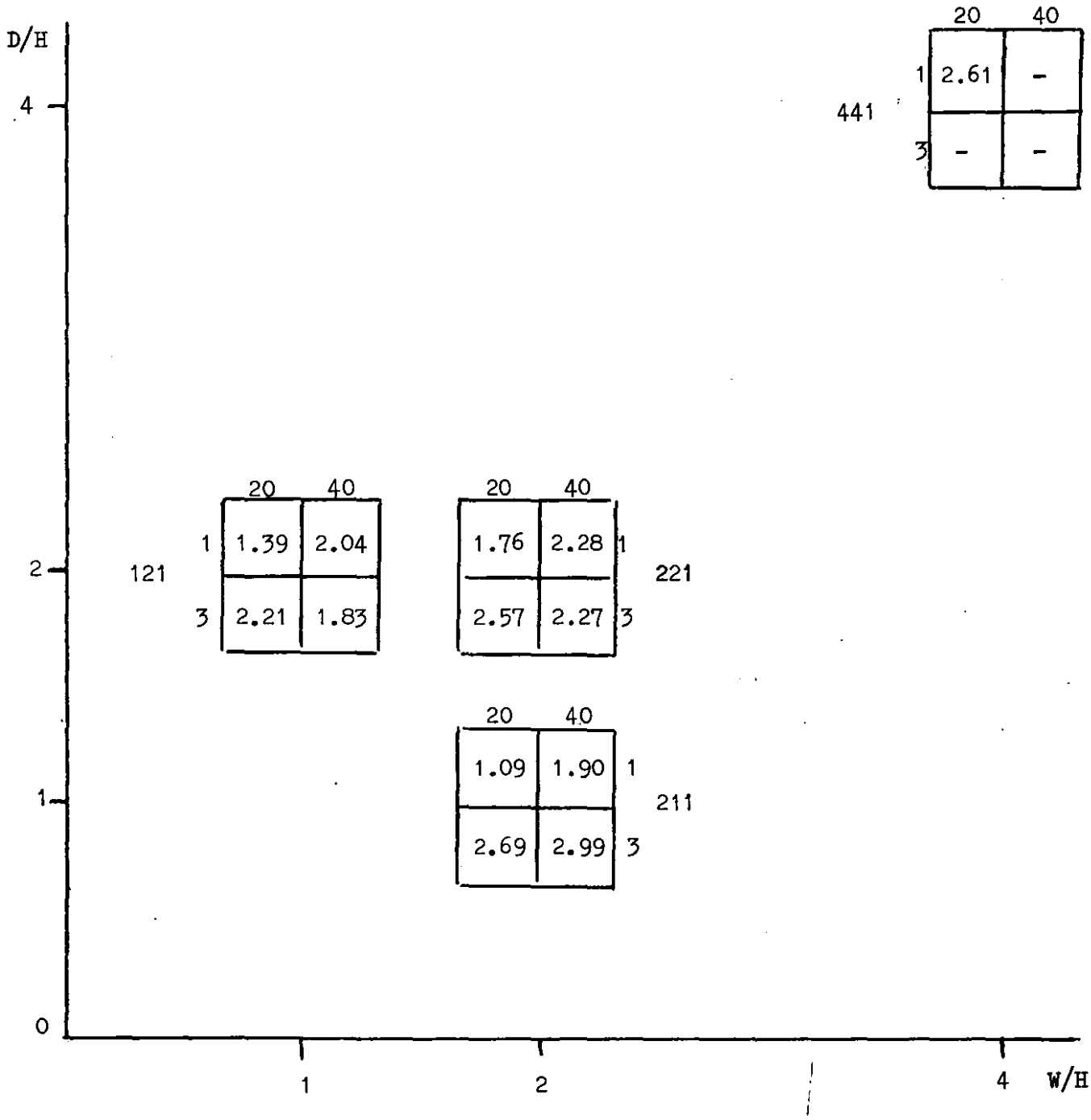


Fig.6. Experimental values of I_0/ϕ (cal $cm^{-2}s^{-1}$), 1 m scale, averaged over all stick thicknesses

The entry for the 441 shape is an interpolation between $\frac{1}{2}$ and $1\frac{1}{2}$ m scale data