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FULLY DEVELOPED COMPARTMENT FIRES:
NEW CORRELATIONS OF BURNING RATES

by

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SUMMARY

Three main regimes of behaviour can be identified for fully developed crib fires in compartments. In one of these crib porosity controls and in another fuel surface; these correspond to similar regimes for cribs in the open. The third regime is the well known ventilation controlled regime. Nilsson's data have accordingly been analysedin terms of these regimes and approximate criteria established for the boundaries between them.

It is shown from these that in the recent C.I.B.International programme the experiments with larger spacing between the crib sticks were representative of fires not significantly influenced by fuel porosity.

The transition between ventilation controlled and fuel surface controlled regimes may occur at values of the fire load per unit ventilation area, lower than previously estimated.

In view of the increase in interest in fuels other than wood on which most if not all empirical burning rates are based, a theoretical model of the rate of burning of window controlled compartment fires is formulated. With known and plausible physical properties inserted it shows that the ratio of burning rate R to the ventilation paramater $A_W\ H_W^{\frac{1}{2}}$, where A_W is window area and H_W is window height, is not strictly constant as often assumed but can increase for low values of $A_W H_W^{\frac{1}{2}}/A_T$ where A_T is the internal surface area of compartment. This is in qualitative accordance with

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SUMMARY (continued)

Nilsson's and the C.I.B data.

It is shown that $R/A_w H^{\frac{1}{2}}$ is, approximately the product of two quantities, one dependent on the fuel and the other on a heat transfer coupling between the fuel bed and its surroundings.

KEY WORDS: Enclosure fires, burning rate, wood fires, crib fires.

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1. INTRODUCTION

The problem of predicting the behaviour of fully developed fires in compartments is central to the structural design of fire resistance requirements for buildings[1] and to the practicalities of modelling fires. The subject has been reviewed recently by Harmathy[2] and we shall not do so again here in detail. The starting point of this report is the acknowledged lack of any theory of the rate of burning of fully developed fires in compartments. In particular there is no theoretical basis for extending the many results derived from fires with wood fuel to fires with plastics fuel, nor for the widely used correlation

$$R = k\ A_W H_W^{\frac{1}{2}} \qquad (1)$$

where R = rate of burning

A_W = area of single opening

H_W = height of opening

k = constant, approx 5-6 kg/m$^{5/2}$ min ($\approx$ 0.09 kg/m$^{5/2}$ s.) for wood.

$A_W H_W^{\frac{1}{2}}$, for a wide range of fire conditions, is a good measure of airflow into a single window and, if it can be assumed that all the oxygen is consumed, a first approximation to the heat release rate; so we can in fact speak of a theory of temperatures. When the fire is controlled by the window, the heat release may be taken as proportional to R, but only indirectly insofar as equation (1) applies.

Thomas[3] pointed out that a constancy of the fuel air ratio does not imply equation (1) because equation (1) refers to the air entering the window, there are sometimes very large flames and burning zones to be seen outside windows, and to the loss in solid fuel mass not all of which necessarily takes part in the combustion reactions.

Recent co-operative work by several laboratories on the burning of wood fires in compartments[4] has been reviewed by Thomas[5] in the context of other work on such fires but the burning rate data have not yet been correlated by any theory.

In this report we shall discuss a theoretical framework for fully developed fires and also put forward some correlations based on Nilsson's experiments[6]. These data refer, so far, to one compartment shape with a single square window (of variable size) using cribs of only one stick thickness and one fire load density. Despite these limitations these preliminary data illuminate some of the problems of fully developed fires and it is useful to examine them before considering further the data from the interlaboratory study. Nilsson measured the rate of burning and temperature in fully developed fires in enclosures. The experimental conditions are given in detail elsewhere[6] but their range is summarized in Table 1.

Table 1
Nilsson's experimental conditions

	No. of conditions	Description
Shape	1	Cubic
Scales	3	0.50 m 0.75 and 1.0 m
Fuel	1 (when expressed as amount per unit compartment surface)	Approx. 12 kg/m^2 of floor or 2 kg/m^2 of total surface
Window opening	Various	Single square opening
"Opening factor" $\frac{A_W H_W^{\frac{1}{2}}}{A_T}$	5	0.020 $m^{\frac{1}{2}}$ to 0.114 $m^{\frac{1}{2}}$
Stick thickness	1	25 mm
Design of crib	Various	Various numbers of sticks per layer and numbers of layers

Nilsson's data are suited to analysis because the cribs were used in a way similar to free burning fires; they were less restrictive to the air supply by not being as close to the compartment walls as in the C.I.B. work. We shall need first to discuss the behaviour of cribs because many experimental fires employ them as the fuel and the concepts developed by Gross[7] and Block[8] for interpreting the behaviour of cribs have been used by Nilsson[6] and Heskestad[9] as the basis for their discussions of compartment fires. Here the experimental results reported by Nilsson will be re-examined, and the three regimes of behaviour corresponding to the two for free burning cribs and one for window controlled fires will be discussed in some detail.

2. THE BEHAVIOURAL REGIMES OF FULLY-DEVELOPED COMPARTMENT FIRES - NILSSON'S DATA

A ventilation - or window - controlled fire was first identified by Fujita[10] and Kawagoe[11] and equation (1) was widely used to express many experimental data. It has more recently been used as the basis for structural design by Pettersson[12]. However, various limitations to the conventional equation (1) have come to light from the interlaboratory C.I.B. study[5] and have also been noted by Magnusson and Thelandersson[13] though these may well have little effect on estimates of the fire resistance required of a structure to withstand a fire, because this is a property which is an integral of temperature and time, affected in compensating ways by departures from the approximations[5]. With very low ventilation the fire may behave in a different way; flaming may be suppressed so that only smouldering persists. $R/A_W H_W^{\frac{1}{2}}$ can rise to high values and oscillations may develop; Tewarson[14] has recognized sub-divisions of this regime.

Thomas, Heselden and Law[15] refer to a ventilation and a fuel-controlled regime; and there are also distinctions to be clarified within this latter regime. We shall follow Gross who first distinguished between two such regimes for free burning crib fires.

In the first, the resistance within the crib to air flow controls the burning and in the second, faster burning, regime the extent of the exposed fuel surface limits it. Because we shall examine some aspects of compartment fires in terms of free burning crib fires as has Herkestad[9] we shall need first to re-examine the correlations of Gross[7] and Block[8].

2.1. The behaviour of cribs and the definition of fuel bed porosity

In correlating his data on the burning rates of cribs, Gross introduced a term

$$\phi = N^{\frac{1}{2}} b^{1.1} A_V/A_S \tag{2}$$

$$= h_c^{\frac{1}{2}} b^{0.6} A_V/A_S \tag{3}$$

where h_c is crib height (= Nb)

A_V is total open cross section of crib

A_S is total surface area of fuel

b is stick size

and N is number of layers

Nilsson also correlated his compartment data in terms of ϕ but here we shall depart from this use of ϕ for reasons to be described below. Gross described two regimes of crib behaviour, one in which the rate of weight loss of the crib

$$\left.\begin{array}{l} R \propto M_o\, b^{-1.6} \quad (\phi \text{ large}) \\ \text{i.e. } m'' \propto b^{-0.6} \end{array}\right\} \qquad (4A)$$

where M_o is the initial mass of fuel and m'' is R/A_s and the other where

$$\left.\begin{array}{l} R \propto M_o\, \phi\, b^{-1.6} \quad (\phi \text{ small}) \\ \text{i.e. } m'' \propto h_c^{\frac{1}{2}}\, A_v/A_s \end{array}\right\} \qquad (4B)$$

A single correlation can be obtained in which

$$\frac{R\, b^{1.6}}{M_o} \propto \phi \quad (\text{small } \phi \text{ - 'densely packed' regime})$$
$$= \text{constant} \quad (\text{large } \phi \text{ - 'open' regime})$$

This type of approach has been extended by Block who developed a theoretical basis for a more complex dependence of R on A_v/A_s in the 'densely packed' regime* which may be expressed as a particular form of

$$\frac{m''}{\rho_o (g\, h_c)^{\frac{1}{2}}} = F(A_v/A_s) \qquad (5)$$

where ρ_c is a gas density, taken as that of ambient air for free burning cribs

and the function F depends on the friction factor 'f' for a vertical shaft in the crib and on the thermodynamic properties of the fuel.

Smith and Thomas[16], however, have found that the data of O'Dogherty and Young[17] and Webster[18] et al followed a result closely given by

$$m'' = 7 \times 10^{-2}\, (A_v\, h_c/A_s)^{\frac{1}{2}} \text{ kg.m.s. units} \qquad (6)$$

but were not fully consistant with Block's theory.

The above formulations and Block's theory presume no scale effect though both Block and Smith and Thomas reported some weak scale effects.

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*Block in fact used 'a_v' and 'a_s' which refer to one shaft rather than A_v and A_s and are more appropriate to a theoretical discussion. He took a nominal value for 'a_s' as $4\, h_c \sqrt{a_v}$ and a_v as s^2 where s is the distance between sticks (= $A_v/(n-1)$)

Thomas[19] has suggested that equation (6) is related to the dimensionless form in equation (5)

$$\frac{m''}{\rho_o (g\ h_c)^{\frac{1}{2}}} \propto (A_v/A_s)^{\frac{1}{2}} \qquad (7A)$$

or approximately $$m'' \propto (h_c\ \ a_v/a_s)^{\frac{1}{2}} \propto s^{\frac{1}{2}} \qquad (7B)$$

which involves the same geometric dimensionless variables as does Block's particular form of $F(^{A}V/_{A_S})$ although they differ in detail. Equation (6) has a significance which is relevant to what follows and which we briefly outline.

2.1.1. Approximate theory for densely packed cribs

Dimensionless mass transfer correlations for pipes are given in terms of a ratio

$$\frac{m''}{\rho U} = j_m\ \ln(1 + B) \qquad (8)$$

where j_m is a mass transfer number (the Schmidt No. is assumed to be unity and is a weak function of the flow Reynolds No. $(\frac{U\ l}{\nu})$)

U is the flow velocity

l is the pipe dimeter

ν is the kinematic viscosity

ρ is the local density

and B is Spalding's transfer number which depends on various properties of the fuel and heat loss. We assume that the fuel flow is small compared with the total flow.

If U in the vertical shaft of a crib is produced by a buoyancy head $g\ h_c\ \theta/T_o$ arising from gases at temperatures θ above ambient, we can write from the definition of the friction factor

$$f = \frac{g\ h_c\ \theta/T_o\ \ a}{\frac{U^2}{2}\ h_c}$$

where a is the hydraulic mean depth, (= $\frac{\sqrt{a_v}}{4}$ for a square duct)

and a_v is the cross section of the crib duct.

$$\therefore\ f = \frac{2\ g\ h_c\ \theta/T_o\ \ a_v}{U^2\ \ a_s} \qquad (9)$$

where a_s is the peripheral area (= $4\ h_c \sqrt{a_v}$)

Block in fact allows for acceleration within the duct but neglecting this we can write a simplified version of Block's flow equation, suitable for large $^{a}s/a_v$, as follows

From equation (9)

$$U = \left\{ \frac{2\ \theta/T_o \quad a_v \quad g \quad h_c}{f \quad a_s} \right\}^{\frac{1}{2}} = \left\{ \frac{\theta}{T_o}\ g \sqrt{} a_v \right\}^{\frac{1}{2}} \qquad (10)$$

$$U = (\theta\ g\ h_c/T_o \Psi)^{\frac{1}{2}}$$

where Ψ is, as defined by Block, $f\ ^{a}s/2\ av$

The mass transfer factor j_m allowing for the variation of with temperature can now be estimated from

$$j_m = \frac{m''\ \Psi^{\frac{1}{2}}}{\rho_o\ h_c^{\frac{1}{2}}} \quad \frac{T_2}{(g\ \theta\ T_o)^{\frac{1}{2}}} \quad \frac{1}{\ln(1 + B)} \qquad (11)$$

where $T_2 = T_o + \theta$

Block includes energy equations so allowing θ to be evaluated in terms of the independent variables. f and j_m are both in principle functions of Reynolds number albeit weak ones in turbulent flow and can usually be taken as constant over a limited range of conditions.

Irrespective of the determination of T_2 and θ in terms of the basic independent variables the variation of $T_2/\sqrt{\theta}$ is small over the range of θ of interest.

If then we take constant values for θ, j_m and f equation (7) follows. Block used $f = 0.13$. θ may be taken as about 1000°C and ρ_o as 1.3 kg/m^3

$$\text{so} \quad j_m = \frac{1}{1.3} \quad \left(\frac{0.13 \times 1300 \times 1300}{2 \times 9.81 \times 300 \times 1000} \right)^{\frac{1}{2}} \quad \frac{R}{\sqrt{h_c\ A_v\ A_s}} \quad \frac{1}{\ln\ (1 + B)}$$

Disregarding the difference between A_v/A_s and a_v/a_s this and equation (7) give

$$j_m = 0.01 / \ln(1 + B)$$

Block uses 1.29 for $\ln(1 + B)$ so giving 0.008 for j_m which is in the range of typical values for turbulent flow. Block's theory determines θ as well and considers details omitted here but the above is given to show some of the concepts to be used in extending crib studies to compartment studies. A more detailed analysis of crib behaviour appears elsewhere[20] which results in estimates of j_m about 50 - 100 per cent larger.

It should be noted that $\dot{m}''$ for densely packed cribs depends on h_c, A_v and A_s but does not otherwise depend on 'b'.

2.1.2. Correlation of crib behaviour

Gross and Block both normalised their correlation to the form

$$\frac{R}{R_o} = \frac{\dot{m}''}{\dot{m}''_o} = F_2(P) \qquad (12)$$

where P is a porosity variable which in Gross's correlation is ϕ, and Block's is $\frac{A_v}{A_s} s^{\frac{1}{2}} \ b^{\frac{1}{2}}$

$$F_2(P) \propto P \qquad P < P_c$$

$$F_2(P) = 1 \qquad P > P_c$$

where $\dot{m}_o''$ and R_o are appropriate to the 'open regime'. $\dot{m}''$ and R do not depend on b (other than via other parameters) and $\dot{m}_o''$ and R_o do, so P has to depend on it. P and ϕ involve terms appropriate to 'densely packed' behaviour and 'open' behaviour together. Heskestad[9] used the general form of equation (12) with Block's P.

Thus if we attempt to examine cribs in enclosures in terms of the same geometric variables, we have to remember there is only a pragmatic basis for using a variable for P based on the validity and relevance of equation (4) which itself is empirically based on the behaviour of single sticks in the 'open' regime. Block has himself pointed out the theoretical limitations of this for assemblies of sticks. In those of Nilsson's experiments discussed here b was constant and the use of ϕ then presents no problem, but we seek a form of correlation for densely packed cribs for which there is better general justification and we shall therefore examine $\dot{m}''/\rho_o (g\, h_c)^{\frac{1}{2}}$ as a function of A_v/A_s only.

There is no 'a priori' reason why in enclosures the correlation should be unique because in enclosures there are other factors whose variation might alter the temperature and oxygen concentration[9,19] which in Gross's and Block's study of free-burning cribs were constant though Block's theory could accommodate such variation in 'B'. We can surmise that one of these other factors is derived from the heat balance (see below) and is a dimensionless ratio of which the geometrically variable part is the wellknown 'opening factor'

$$A_w H_w^{\frac{1}{2}}/A_T$$

The above arguments, based on the work of Gross and Block, and extended to include a possible effect of changing the temperature of the crib environment leads us pragmatically to consider a correlation for densely packed cribs in compartments of the form

$$\frac{m''}{\rho_o (g\, h_c)^{\frac{1}{2}}} = F_3 \left[\frac{A_v}{A_s} , \frac{A_w H_w^{\frac{1}{2}}}{A_T} \right] \qquad (13)$$

Because of the difference between A_v/A_s and a_v/a_s and because even the mean temperature (and certainly not the local temperature in the neighbourhood of the fuel bed), cannot be given uniquely by $A_w H_w^{\frac{1}{2}}/A_T$, equation (13) can be proposed only as a first approximation. Later in this paper we shall see that data can be usefully correlated by it, though of course there can be other physical explanations for the influence of the opening factor here.

2.2. <u>Fuel porosity regime - Nilsson's data</u>

In Fig.1 we have plotted Nilsson's data for the mean burning rate per unit surface m" for the lowest and highest opening factors. The data are better correlated for $h_c A_v/A_s < 0.005$ whilst for $h_c A_v/A_s > 0.008$, $h_c A_v/A_s$ has little relevance. Figure 2 shows all the data for $h_c A_v/A_s < 0.005$. There is a variation of about 50 per cent for the 5 to 1 variation in $A_w H_w^{\frac{1}{2}}/A_T$

We have thus identified a regime for low values of $h_c A_v/A_s$ in which m" is largely determined by that parameter* and we have superimposed the

*Strictly it is better to refer to dimensionless variables where these have been physically identified and justified so that it is also possible to regard these data as corresponding to $A_v/A_s < 0.04$ approximately.

correlation obtained by Smith and Thomas (equation (6)). According to McCarter and Broido[21] about half of the difference can be attributed to the difference between a crib on a perforate base which may burn 50 per cent faster than one on an imperforate base. In accordance with the arguments leading to equation (13) we examined a regression equation for $m''/\sqrt{h_c}$ as a power of A_v/A_s and $A_w H_w^{\frac{1}{2}}/A_T$ and with ρ_o taken as 1.3 kg/m^3 have obtained (for $N < 8$)

$$\frac{m''}{\rho_i (g\, h_c\, A_v/A_s)^{\frac{1}{2}}} = 0.04\left(\frac{A_w H_w^{\frac{1}{2}}}{A_T}\right)^{0.158} S^{-0.26} \qquad (14)$$

$$\left(0.02 < \frac{A_w H_w^{\frac{1}{2}}}{A_T} < 0.114\ m^{\frac{1}{2}}\right)$$

where S is the scale size in metres

There is no significant effect of A_v/A_s on the right-hand side. The term $S^{-0.26}$ represents a systematic reduction of about 20 per cent between the $\frac{1}{2}$ m and the 1 m scale.

Smith and Thomas and Block both refer to scale effects in free burning cribs. Block states the effect is approximately $S^{-\frac{1}{8}}$ and Smith and Thomas give a result implying $S^{-0.26*}$ for a given stick size.

For cribs in the open it is possible that the effect is associated with departures from the ideal of vertical flow as the base area increases and similar considerations could also apply to cribs inside a compartment with a window on one side.

After allowing for this scale effect, the value of δ^2 on the logarithm of R was 0.0086, giving a coefficient of variation of approximately $\pm$ 9 per cent. Over the narrow range of 5 to 7 for N the variation of m'' with N (i.e. h_c) is consistent with the square root law but cribs with N 8, 9 and 10 behave differently and m'' tends to be less dependent on N. Clearly, a crib tall enough for its top to be above the neutral axis of the flow would not have a wholly vertical flow within, and such cribs presumably behave as if having a lesser buoyancy. Pyrolysis will still occur in the top part of the crib so m'' will remain of the same order neglecting differences in temperature, i.e. the extra height contributes to A_s and to fuel generation but not to crib buoyancy.

*They give $(A_v\ A_s)^{-0.052}$ i.e. $S^{-0.26}$ for a given stick size and given crib porosity.

2.3. <u>The fuel surface regime - Nilsson's data</u>

The data in Fig 1 for $A_v/A_s > 0.04$ ($h_c\ A_v/A_s > 0.005$ approx) is replotted in Fig.3. At high $A_w H_w^{\frac{1}{2}}/A_T$ (and high $h_c\ A_v/A_s$) the burning rate reaches an almost constant limiting value appropriate to the surface area and stick size. A suitable regression equation for this limit (based on data for $\frac{A_w H_w^{\frac{1}{2}}}{A_T}$ equal to 0.07 or 0.114 $m^{\frac{1}{2}}$) is

$$m'' = 0.45 \times 10^{-3} \left\{\frac{A_v}{A_w H_w^{\frac{1}{2}}}\right\}^{0.13} \rho_w^{\ 0.49} \qquad (15)$$

and the coefficient of variations is $\pm$ 7.3 per cent. These data are replotted in Fig.4. We have assumed that all the variations in the measured weights is due to a variation of about $\pm$ 4 per cent in density. An alternate but unsatisfactory view is that the variation lies in the dimensions of the sticks but a $\pm$ 2 per cent error on, say, a crib of 30 sticks each 25 mm square is more than is realistic; also it would imply an increase of m" with increase in b, contrary to equation (4). m" was found to be independent of crib height and so not primarily dependent on convective transfer arising from the buoyancy of the whole crib acting as one stack. This it seems that the convection that does affect m" (there is little net radiation loss within large cribs) will be locally determined by boundary layers formed on each stick. The values of m" lie in the region 0.006 - 0.010 kg/m^2s and are higher than Harmathy's estimate of 0.006 kg/m^2s for a best value, presumably because 25 mm sticks are thinner than those typical of his correlation. The 'conventional wisdom' of a charring rate for extended surfaces of $^1/40$" per min gives, for a wood density of 500 kg/m^3, a value of m" of 0.005 kg/m^2s.

The decrease of m" with increasing $A_w H_w^{\frac{1}{2}}$ may reflect a higher value of m" in compartments than in free burning. This would not be surprising as m" must depend on the heat flux onto the surface and a little confinement may have more effect on conserving heat than on restricting the air flow. The suggestion of a density effect provokes questions particularly since m" is not proportional to ρ_w i.e. the pyrolysis takes place systematically neither on a mass basis nor on a volumetric basis.

Whilst the variations in W (and so in ρ_w) are not highly correlated with the variation in any other factor, the same cannot be said for A_v which in these experiments is highly correlated with A_s and L, properties of the cribs which could well be significant in their own right.

Analysis based on these terms does in fact show them to be significant, but equation (15) has only one geometric variable and more complex power laws are not significantly better nor do they appear to have any better a physical significance. However, arguments from simplicity and lack of statistical significance cannot be taken too far. The values of m" must be presumed to vary with the stick size, higher for thinner sticks and visa versa.

2.4. The window controlled regime - Nilsson's data

We now return to the window controlled regime where it will be recalled that $\dfrac{R}{A_W H_W^{\frac{1}{2}}}$ has been regarded as a constant to a first approximation over a wide range of data. In this set of data which are summarized in Tables 2 and 3 there is, as in the data reported in ref.4 considerable variation. There is also a significant scale effect (see Fig.3) which does not have a systematic trend, though Table 2 shows that the variation of $R/A_W H_W^{\frac{1}{2}}$ with increasing $\dfrac{A_W H_W^{\frac{1}{2}}}{A_T}$ is less on larger scale.

To analyse this regime we shall exclude all data where $A_V/A_s < 0.04$ (excluding some data which might be in a transitional regime) and all data for the two highest values of $\dfrac{A_W H_W^{\frac{1}{2}}}{A_T}$ (discussed above) where the fuel surface is likely to be controlling for these experiments. We cannot argue that these are properly the parameters which separate one regime from another; they serve for the time being partly because of internal correlation in the data between A_T and A_s.

This leaves us with data for $\dfrac{A_W H_W^{\frac{1}{2}}}{A_T}$ equal to 0.02, 0.032 and 0.04 $m^{\frac{1}{2}}$ and even this last set may need exclusion in some discussions because it is possibly on the borderline with the surface controlled regime: the coefficient of variation of m" is less than that of $\dfrac{R}{A_W H_W^{\frac{1}{2}}}$ for the opening factor of 0.04 $m^{\frac{1}{2}}$.

Firstly, we note that there is as yet no theoretical justification for the use of A_T to normalize $A_W H_W^{\frac{1}{2}}$ except that this ratio - the opening factor - appears in the energy equation and affects the temperature (see below). That m" is an increasing function of temperature is in principle plausible. Gross and Robertson[22] normalized $A_W H_W^{\frac{1}{2}}$ and R by dividing both by the area scale A_T. The use of wood surface area A_s which gives a correlation of m" in term of $A_W H_W^{\frac{1}{2}}/A_s$ has pragmatic merit but $A_W H_W^{\frac{1}{2}}/A_s$ has yet to be given any physical status.

On any one scale in the window controlled regime A_s in Nilsson's data varies by about 10 per cent at most and it increases with scale in proportion. We can therefore probably interchange A_s and A_T in the above and regard m" as being independent of A_v/A_s and primarily dependent on $A_w H_w^{\frac{1}{2}}/A_T$ but statistical analysis suggests it is preferable to normalize R by A_s and $A_w H_w^{\frac{1}{2}}$ by A_T rather than both by the same one of these two possibilities. (See Appendix I)

Table 2
Mean values of $R/A_w H_w^{\frac{1}{2}}$ kg/m$^{5/2}$s
$(0.04 < A_v/A_s < 0.12)$

$A_w H_w^{\frac{1}{2}}/A_T (= 1/x)$ $m^{\frac{1}{2}}$	SCALE 0.50 m	0.75 m	1.0 m
0.02	0.154	0.12	0.118
0.032	0.123	0.12	0.115
0.04	0.105	0.095	0.10
Ratio of $\dfrac{(R/A_w H_w^{\frac{1}{2}})_{0.02}}{(R/A_w H_w^{\frac{1}{2}})_{0.04}}$	1.47	1.27	1.07

Table 3
Mean values of m" kg/m^{2}s
$(0.04 < A_v/A_s < 0.12)$

$A_w H_w^{\frac{1}{2}}/A_T$ $m^{\frac{1}{2}}$	SCALE 0.50 m	0.75 m	1.0 m
0.02	0.0055	0.0038	0.0043
0.032	0.0073	0.0060	0.0065
0.04	0.0078	0.0068	0.0075

However, if m" were solely a function of $A_w H_w^{\frac{1}{2}}/A_T$ one would expect R to increase in proportion to A_s for a given opening factor but this does not in general happen.

Clearly, more detailed analysis is required and we now discuss some statistical and theoretical aspects of window controlled fires.

2.4.1. Analysis of data

The data for $A_w H_w^{\frac{1}{2}}/A_T$ equal to 0.02 and 0.03 $m^{\frac{1}{2}}$ on all three scales have been examined statistically. They all refer to one stick size and one volumetric fire loading* defined by

$$v = \frac{n\ N\ b^2\ L}{A_T} \qquad (16)$$

thickness 'b' and length 'L' so that these crib designs have only two degrees of freedom in addition to scale and stick size 'b'.

In the analysis we do not have to use only n and N but we should not describe cribs for a given A_T by more than two parameters, independent in principle even if partly correlated in the actual designs used. Amongst various regression analyses employing two crib parameters additionally to scale we have

$$\frac{R}{A_w H_w^{\frac{1}{2}}} = 3.3 \times 10^{-6} \left[\frac{A_w H_w^{\frac{1}{2}}}{A_T}\right]^{-0.13} \left(\frac{L}{S}\right)^{-0.31} \left(\frac{hc}{S}\right)^{-0.01} \rho_w^{1.57} \ S^{-0.25} \quad (\mathrm{kg\ m\ s}) \qquad (17A)$$

The above regression shows - as do variations of it - that there is a real scale effect. The h_c (i.e. N) term alone is not significant.

Here only overall crib dimensions have been used on the argument that in this regime the internal crib structure is not a major influence, but one could, of course, quite properly have included instead of L or h_c the fuel surface area A_s or the horizontal spacing between the sticks "s" ($= \frac{\sqrt{A_v}}{n-1}$) etc.

If one dies use a property of the internal crib structure as one of two nominally independent crib properties, one finds R is correlated negatively with A_v e.g.

$$\frac{R}{A_w H_w^{\frac{1}{2}}} \propto \left[\frac{A_w H_w^{\frac{1}{2}}}{A_T}\right]^{-0.15} \left[\frac{A_v}{A_T}\right]^{-0.36} \rho_w^{1.27} \qquad (17B)$$

i.e. R increases as A_v decreases as opposed to the trend in the other two regimes. The same trend is present in some variations of this regression, it adds credence to a distinction between the regimes as described in Table 4.

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* Here fire load is related volumetrically to the total nominal bounding surface of the compartment. This is for convenience; strictly A_T should exclude the window area.

Table 4

Distinction between regimes

Controlling feature of regime	Effect of increasing A_V on R	Effect of increasing $A_W H_W^{\frac{1}{2}}$ on R
Fuel porosity	Increases R strongly	Increases R weakly
Fuel surface	Increases R weakly	Decreases R weakly
Compartment opening	None or decreases R weakly	Increases R strongly

The decrease in $A_W H_W^{\frac{1}{2}}/A_T$ was of course apparent in Table 1 whilst the significance of the effect of ρ_w is due to a strong effect at the lower opening factor and a negligible effect at the opening factor of 0.04 $m^{\frac{1}{2}}$. This may be associated with an influence of the lower temperatures at the lower opening factor and clearly requires further study. The data for the lower opening factor are correlated significantly with scale and density whereas those of the higher opening factor are not (Table 5).

After removing the non-significant term, equation (17A) gives a standard derivation for the logarithm (to base e) of 0.115, i.e. a coefficient of variation of about 12 per cent. This is large because a power law cannot represent the reversing scale effect if it is not associated with some pther parameter. Consequently separate analyses have been made for each scale as well as for each opening factor. The results are summarised in Tables 5 and 6.

Table 5

Analysis for each opening factor (kg ms s units)

$A_W H_W^{\frac{1}{2}}/A_T$	
0.02 $m^{\frac{1}{2}}$	$\frac{R}{A_W H_W^{\frac{1}{2}}} = 1.48 \times 10^{-9} \left(\frac{L}{S}\right)^{-0.38} \left(\frac{hc}{S}\right)^{-0.115} \rho_w^{2.85} S^{-0.44}$ $\sigma = 0.086$ All indices significant except that of $\left(\frac{hc}{S}\right)$.
0.032 $m^{\frac{1}{2}}$	$\frac{R}{A_W H_W^{\frac{1}{2}}} = 0.167 \left(\frac{L}{S}\right)^{-0.172} \left(\frac{hc}{S}\right)^{0.15} \rho_w^{-0.04} S^{0.019}$ $\sigma = 0.12$ No index significant.
0.04 $m^{\frac{1}{2}}$	$\frac{R}{A_W H_W^{\frac{1}{2}}} = 4.3 \times 10^{-4} \left(\frac{L}{S}\right)^{0.05} \left(\frac{hc}{S}\right)^{0.184} \rho_w^{0.93} S^{0.12}$ $\sigma = 0.11$ No index significant.

The influence of scale and density are absent at higher opening factors

Table 6

Analysis for each scale (kg m, s units)

$\frac{A_W H_W^{\frac{1}{2}}}{A_T}$ equal to 0.02 and 0.032 $m^{\frac{1}{2}}$

S = Scale	
0.50 m	$\frac{R}{A_W H_W^{\frac{1}{2}}} = 26 \times 10^{-6} \left(\frac{A_W H_W^{\frac{1}{2}}}{A_T}\right)^{-0.29} \left(\frac{L}{S}\right)^{-1.0} \left(\frac{hc}{S}\right)^{0.11} \rho_w^{1.15}$ (21) The ratio $^h c/S$ is not significant but the other items shown are. $\sigma = 0.078$
0.75 m	$\frac{R}{A_W H_W^{\frac{1}{2}}} = 52 \times 10^{-6} \left(\frac{A_W H_W}{A_T}\right)^{\frac{1}{2}\,-0.1} \left(\frac{L}{S}\right)^{-0.23} \left(\frac{hc}{S}\right)^{0.08} \rho_\omega^{1.18}$ (22) $\sigma = 0.093$ None of the terms is significant.
1.0 m	$\frac{R}{A_W H_W^{\frac{1}{2}}} = 88 \times 10^{-3} \left(\frac{A_W H_W^{\frac{1}{2}}}{A_T}\right)^{-0.14} \left(\frac{L}{S}\right)^{0.41} \times \left(\frac{hc}{S}\right)^{-0.02} \rho_\omega^{-0.014}$ (23) $\sigma = 0.078$ None of the terms is significant.

The data for the two larger scales, taken together, give

$$\frac{R}{A_W H_W^{\frac{1}{2}}} = 0.0056 \left[\frac{A_W H_W^{\frac{1}{2}}}{A_T}\right]^{-0.14} \left(\frac{L}{S}\right)^{0.2} \rho_W^{0.42} S^{0.33} \quad (24)$$

$\sigma = 0.074$

The regression on $A_W H_W^{\frac{1}{2}}/A_T$, as already seen, is significant when all data are taken together. The index of $\frac{L}{S}$ appears to change systematically with scale and the relatively small increase in $R/A_W H_W^{\frac{1}{2}}$ with scale between the two scales is significant: the combination of the $\frac{L}{S}$ and S terms might suggest that the effect is associated with L.

The conclusions we have argued by statistical analysis are that the effects on $R/A_W H_W^{\frac{1}{2}}$ of $A_W H_W^{\frac{1}{2}}/A_T$ are real, those of ρ_w are marked only for the lowest opening factors, and that there are some unattributable scale effects in the data which may be possibly associated with L rather than S.

3. THEORY OF WINDOW-CONTROLLED FIRES

We have not pursued any further the analysis of the data by statistical means because we have so far considered data for only one value of v and one value of b which necessarily leaves some ambiguities arising from the correlation between such quantities as h_c, A_s, A_v and $\frac{\sqrt{A_v}}{n - 1}$ (the distance between sticks) all having different physical significance.

Instead we shall develop a theoretical model as follows. This, too will leave some uncertainties because the physical properties of wood, for example, are not well enough defined.

Although Thomas and Heselden[23] have discussed theoretical aspects of fully developed fires on the basis of two separate physical relations between burning rate and thermal conditions, no quantitative conclusions were drawn. Other theoretical discussions have been mainly, if not exclusively, concerned with the energy balance and although this permits estimates of the temperature to be made, it helps little to estimate theoretically the rate of consumption of the fuel and hence the fire duration.

Moreover, this energy balance is invariably stated in a form which implicity assumes that $R/A_w H_w^{\frac{1}{2}}$ is constant and is therefore inappropriate to a discussion which does not. We shall assume that the temperature in the compartment is uniform, though Thomas and Heselden[23] have argued that variation does occur and could be an important feature in the control of burning rate. We shall assume that wood pyrolyses ar a temperature T_p and that the gaseous fuel emerges from the surface at T^*, which may be below the temperature T_s of the surface itself. If internal heat exchange in the fuel is good then $T^* \rightarrow T_s$. We shall assume, too, that only a fraction 'w' of the original wood pyrolyses to gases and that for 1 kg of such substance to change state at T_p requires Q joules: we neglect for the time being consumption of the residue. All oxygen entering the compartment is assumed to be consumed. Assumptions in the literature that there is a significant surplus of air are disregarded since measurements of oxygen in burning compartments show negligible amounts except near the floors and windows where some local recirculation may be occurring, though this does imply that one can expect some differences between a compartment with two windows and one having one window.

We shall neglect kinetic limitations to reaction rates and transient behaviour[14]

3.1 Energy balance

The steady state and energy balance is now written

$$M_1 \, m_{ox} \Delta H/r = (M_1+R) \, Cg\Theta + q_T + I_W A_W + R\left[Q + \left(\frac{1}{W} + 1\right) \times \right.$$
$$\left. \times \left(C_C \, (T_S - T_P) + C_W (T_p - T_1)\right)\right] \qquad (25)$$

where M_1 is the mass inflow of air

m_{ox} is the ambient concentration of oxygen

ΔH is the heat released by 1 kg of fuel

r is the stoichiometric ratio $\frac{\text{kg of oxygen}}{\text{kg of fuel}}$

R is the rate of burning of fuel

Cg is mean specific heat of the exit gases

Θ is their temperature rise

	q_T	is the heat loss to the walls etc
	I_w	is the radiation flue at the window
	A_w	is the area of window opening
	Q	is the enthalpy change from T_1 for unit mass of gaseous products
	w	is fraction of solid becoming gaseous
	c_c	is the mean specific heat of the char
	c_w	is the specific heat of wood
	T_s	is surface temperature of solids
	T_o	is the ambient temperature taken as a reference for H etc
	T_1	is the initial temperature of wood
and	T^*	is the temperature at which volatiles emerge from the wood

Such energy equations have been employed previously[24,25,26], but usually with one essential difference (other than the inclusion of transient terms). The last term is not normally included, though clearly if the fuel were liquid, one would identify Q with the latent heat.

However, if R is assumed proportional to M_1, the omission is in effect a redefinition of a 'net' heat release $\Delta H'$

$$\frac{m_{ox}\Delta H'}{r} = \frac{m_{ox}\Delta H}{r} - \left(\frac{R}{M_1}\right)\left[Q + \left(\frac{1}{W} - 1\right)\left(C_c(T_s - T_p) + C_w(T_p - T_1)\right)\right] \quad (26)$$

The use of an endothermicity Q for wood is not without its opponents and values derived (by fitting data to theories of pyrolysis and fire spread) have varied from say, - 400 kJ/kg to over 5 MJ/kg. At worst we can regard Q as a disposable 'constant'.

The empirical results of Kawagoe[11] and others leading to $R/A_w H_w^{\frac{1}{2}} \approx 0.09$ kg/m $^{5/2}$ s, the choice of an effective calorific value of wood[11] of 10.8 MJ/kg (2575 cal/gm) and the theoretical result[10]

$$M_1 = \alpha \quad A_w H_w^{\frac{1}{2}} \quad (27)$$

where α is customarily taken as 0.5 kg/m$^{5/2}$ s, may be assumed to be consistent with an energy equation using $\Delta H'$ giving

$$m_{ox}\frac{\Delta H'}{r} = \frac{10.8 \times 0.09}{0.5} \approx 2.0 \text{ MJ/kg}$$

compared with value (see Appendix I) of about 3 $\pm$ 0.35 MJ/kg for $m_{ox}\frac{\Delta H}{r}$ based on the data of Roberts[27].

The value of Δ H depends on the initial moisture content of the wood. We then have, from equation (26)

$$2.0 = 3.0 - \frac{0.09}{0.5}\left[Q + \left(\frac{1}{w} - 1\right)\left[c_c(T_s - T_p) + c_w\ (T_p - T_1)\right]\right]$$

With $w \approx 0.8$, $T_s - T_o \approx 500°C$ and $c_c \approx c_s \approx 1.25$ KJ/kg °C $c_c\ (\frac{1}{w} - 1)\ \ (T_s - T_o)$ is about 0.16 MJ/kg and Q in this formulation would therefore need to be about 5.4 MJ/kg ($\approx$ 1300 cal/g) to 'explain' the difference between experimental and theoretical values.

The estimate of 5.4 MJ/kg (1300 cal/gm) is clearly very sensitive to certain of our approximations. Thus, if the actual air flow is less than the theoretical the estimate of Q falls as in Table 7.

The assumed value of $^R/A_wH_w^{\frac{1}{2}}$ has a slight effect on the estimate of Q.

Table 7
Estimates of Q (with $^R/A_wH_w^{\frac{1}{2}}$ = 0.09 kg/m$^{5/2}$s)

Actual air flow / theoretical flow	Estimate of Q
1	3.5 → 7.0 MJ/kg
0.9	2.3 → 5.2 MJ/kg
0.8	0.9 → 3.5 MJ/kg

Without substantially more accurate data on actual air flows and rates of burning, we cannot realistically estimate Q from this argument. However, it would seem that any plausible Q of the order 1 MJ/kg (250 cal/g) to 7 MJ/kg (1700 cal/gm), say, can be adopted and made to appear consistent with data if it is assumed that actual air flows may be somewhat less than calculated theoretically. This may have some justification because no account of internal acceleration or fuel bed friction has previously been allowed for in theoretically estimating air flows. Because heat balances based on the above effective property values have been studied by several authors[24,25,26] & generally found acceptable. We shall therefore deal here only with the rate of burning.

The term q_T is more properly a series of separate terms for walls, ceilings, and floors of differing thermal properties and is the term with the greatest thermal inertia[24,25,26]. Here we simplify it to concentrate on other aspects of the heat balance and write

$$q_T = \bar{h}\quad A_T\theta$$

where $\bar{h}$ is an effective mean transfer coefficient

The term $I_w A_w$ is small and for a fully emissive flame of uniform temperature

$$I_w = \sigma \left(T_g^4 - T_o^4\right) \qquad (29)$$

where σ is the Stefan-Boltzman constant,

and T_g is the flame temperature* taken as equal to the temperature of the exit gases T_2 $(= T_o + \Theta)$

We now introduce a second relation expressing the surface transfer conditions.

3.2. The surface transfer relation

The energy balance across the fuel surface is written as

$$I_f + h_c\,(\Theta + T_o - T_s)\,A_s' = R\,\left(Q + C_c\left(\frac{1}{W} - 1\right)(T_s - T_p) + \frac{C_w}{w}\,(T_p - T_1) + C_g(T^* - T_p)\right) \qquad (31)$$

where I_f is the net radiant flux onto the fuel surface.

A_s' is an effective area of fuel surface exposed to heating

h_c is the convection transfer coefficient

If we write as approximations

$$T_w - T_o \approx \gamma(T_2 - T_o)$$

where γ is a transient coefficient less than unity which depends on the thermal properties of the walls and their gaseous boundary layer

and $I_f \simeq h_R \quad (1 - \epsilon)\,(T_w - T_s) + \epsilon\,(T_g - T_s)$

where for $\gamma \simeq 1$, h_R is an effective block body radiation transfer coefficient, equal for the solid surfaces and the gases. The walls etc and wood are assumed to be black and the flame gases to have an emissivity of ϵ.

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* Variations in gas temperature introduce difficulties since it is the mean of T_g^4 that is involved.

Hence

$$I_f \approx h_R\left[(1-\epsilon)\left(\gamma(T_g-T_o)+(T_o-T_s)\right)+\epsilon(T_g-T_s)\right]$$
$$\approx h_R\left(\beta\theta+(T_o-T_s)\right) \tag{32}$$

where $\beta\left(\gamma(1-\epsilon)+\epsilon\right)$ is unity for fully emissive flames but otherwise lies between unity and ϵ or γ whichever is the nearer to unity.

From equations (25) and (31) we obtain an expression independent of Q

$$M_{ox}\frac{\Delta H}{\gamma} = (1+y)C_g\theta - y\left\{C_g(T^x-T_p)+C_w(T_p-T_1)\right\} \tag{33}$$
$$+\bar{h}\frac{\theta x}{\alpha}+\frac{I_w}{\alpha H_w^{1/2}}+\frac{I_f A_s' x}{\alpha A_T}+\frac{h_c A_s'}{\alpha A_T}(\theta+T_o-T_s)x$$

where $y = \dfrac{R}{A_W H_W^{\frac{1}{2}}}$ and $x = \dfrac{A_T}{A_W H_W^{\frac{1}{2}}}$

To discuss the effects of scale would require a more detailed discussion of T_s which involves in turn a discussion of the details of the pyrolysis of wood, some of which are uncertain and which we omit from this paper.

3.3. The theoretical rate of burning and temperature

The quantity $\dfrac{h_c A_T}{C_g A_W H_W^{\frac{1}{2}}} = \dfrac{h_c x}{\alpha C_g} = \dfrac{h_c A_T}{C_g M_1}$ and has the form of a Stanton number for heat transfer which we write as j. Equation (25) then gives

$$y = \frac{M_{ox}\Delta H/\gamma - I_w/\alpha H_w^{1/2} - C_g\theta - \dfrac{\bar{h}_T\theta x}{\alpha}}{Q' + C_g\theta} \tag{34}$$

where $$Q' = Q + \left(\frac{1}{\omega}-1\right)\left(C_a(T_s-T_p)+C_w(T_p-T_1)\right) \tag{35}$$

Equations (31) and (32) give

$$y = \frac{\frac{A_s'}{A_T}\left[\frac{h_R x}{\alpha}\left(\beta\theta + T_o - T_s\right) + C_g \dot{j}\left(\theta + T_o - T_s\right)\right]}{\phi' + C_g\left(T^x - T_P\right) + C_w\left(T_P - T_1\right)} \qquad (36)$$

Eliminating y gives a quadratic for θ which for convenience we write as

$$\theta = \frac{m_{ox}\frac{\Delta H}{r} - \frac{I_w}{\alpha H_w^{1/2}} + \lambda\left(\frac{h_R x}{\alpha} + C_g \dot{j}\right)\left(T_s - T_o\right)}{C_g + \bar{h}\frac{x}{\alpha} + \lambda\left(\frac{h_R x}{\alpha}\beta + C_g \dot{j}\right)} \qquad (37A)$$

where $$\lambda = \frac{A_s'\left(\phi' + C_g\theta\right)}{A_T\left(\phi' + C_g\left(T^x - T_P\right) + C_w\left(T_P - T_o\right)\right)} \qquad (37B)$$

We similarly obtain y as

$$y = \frac{m_{ox}\frac{\Delta H}{r} - \frac{I_w}{\alpha H_w^{1/2}} - F(x)\left(T_s - T_o\right)\frac{A_s'}{A_T}\left(C_g \dot{j} + \frac{h_R x}{\alpha}\right)}{\phi' + F(x)\left[\phi' + C_g\left(T^x - T_P\right) + C_w\left(T_P - T_o\right)\right]} \qquad (38A)$$

where $$F(x) = \frac{A_T\left(C_g(1+y) + \bar{h}\frac{x}{\alpha}\right)}{A_s' \quad C_g \dot{j} + \beta\frac{h_R x}{\alpha}} \qquad (38B)$$

If the following generally acceptable approximations are made

$$\left(C_g(1+y) + \bar{h}\frac{x}{\alpha}\right)\left(T_s - T_o\right) \lll m_{ox}\frac{\Delta H}{r} - \frac{I_w}{\alpha H_w^{1/2}}$$

$$y \ll 1, \quad \beta \simeq 1, \quad \phi' \gg C_g\left(T^x - T_o\right) + C_w\left(T_P - T_o\right)$$

$$\bar{h}\frac{x}{\alpha} \lll C_g \quad \text{and} \quad \frac{I_w}{\alpha H_w^{1/2}} \lll m_{ox}\frac{\Delta H}{r}$$

then

$$y = \frac{m_{ox}\frac{\Delta H}{r}}{Q'\left[1 + \frac{A_T}{A_s'}\frac{1}{\left(j + \frac{h_R x}{\alpha C_{\varepsilon_j}}\right)}\right]} \qquad (38C)$$

and the variation of y with x is seen to be closely governed by the term

$$\frac{A_s'}{A_T}\left(j + \frac{h_R x}{\alpha C_{\varepsilon_j}}\right)$$

expressing the heat transfer coupling of the fuel.

If we write $R \propto A_s^m$, then to a first approximation equation (38C) gives, near mean values,

$$\frac{1}{m} = 1 + \frac{h_R A_s' x}{A_T C_g \alpha} + j\frac{A_s'}{A_T}$$

A_s'/A_s is the extent to which parts of the fuel surface are 'shielded' from the main combustion zone and this will be very dependent on the disposition of the fuel in cribs even when the gas flow through the crib is restricted only by the window and not by the crib porosity. Values of the coupling typical of experimental compartments can give values of m sufficient to produce the observed but weak effects of fuel quantity and surface area sometimes reported for ventilation controlled fires.

The expressions for y in equations (34), (38A) and (38C) have some similarity with the definition of B, Spaldings Transfer No.Equation (38C) separates fuel properties from other terms.

Fig 5(A) shows some y relations from eqn (38A) with values of $\overline{h}$, h_R etc as in Table 8 with Q chosen in each case to normalise y to 0.2 at $x = 25\ m^{\frac{1}{2}}$. (see Fig 5(B). These variations are comparable with those in Nilsson's data and in Ref.4.

It can be seen in Fig 5(C) that y increases faster with x the less is A_S'/A_S which will be dependent on the design of the fuel bed even in surface controlled fires. Small scale experiments, by making flame emissivity less, may slightly favour variations of $R/A_W H_W^{\frac{1}{2}}$ with x.

Table 8

Values assumed for calculations

T_1	$= T_o$
$T^x - T_1$	$= 400^\circ C$
$T_s - T_1$	$= 500^\circ C$
$Cg = Cw$	$= 1.25$ kJ/kg
w	$= 0.8$
$\bar{h}$	$= 30 \times 10^{-4}$ kW/m^2 $^\circ C$
h_R	$= 0.2$ kW/m^2 $^\circ C$
$m_{ox} \dfrac{\Delta H}{r}$	$= 3000$ kJ/kg
I_w	$= 80$ kW/m^2
H_w	$= 0.5$ m
α	$= 0.5$ kg/m$^{5/2}$ s
$\dfrac{A_S}{A_T}$	$= 0.6$
$j = \beta$	$= 1$

For $Q \gg Cg\,\theta$ and $y \ll 1$ we have the approximate expression

$$\theta = \frac{m_{ox}\frac{\Delta H}{r} - \frac{I_w}{\alpha H_w^{1/2}} + \frac{A_I^{\prime}}{A_T}(T_s - T_o)\frac{h_R x}{\alpha}}{C_g + \frac{\bar{h} x}{\alpha} + \frac{h_R}{\alpha}\frac{A_I^{\prime}}{A_T} x \beta} \qquad (39)$$

$$\frac{h_R x \beta}{\alpha} \gg C_g$$

Because $m_{ox}\frac{\Delta H}{r}$ is a large term in the determination of θ by equation (39) θ tends to decrease slightly with increasing x. These trends for y to increase and θ to decrease with increasing x are exhibited in the C.I.B. data and in Nilsson's data though to a lesser extent. One possible reason for this difference is that the feedback could be less for the larger cribs, i.e. $A_s^{\prime}/A_s$ is less in the C.I.B. experiments.

4. THE TRANSITIONS BETWEEN THE REGIMES

It is not possible to discuss properly the question of the boundaries between the regimes without allowing for the effects of fuel (stick) thickness. What follows is thus approximate and tentative. The important transition between the window and fuel surface controlled regimes has been discussed by various writers including Thomas, Heselden and Law[15], Heselden[29] and Magnusson and Thelandersson[26]. The simplest approach is to equate the established relationships for the two regimes so obtaining, for example, the simplest form based on the two 'best' values for $R/A_w H_w^{\frac{1}{2}}$ for window controlled and m" for surface controlled fires, corrected conventionally for the effect of stick size

$$m''_{s.w.} \approx 0.09 \left(\frac{A_w H_w^{\frac{1}{2}}}{A_s}\right) \approx 0.008\ (40b)^{-0.6}$$

$$\text{i.e.} \qquad \left(\frac{A_w H_w^{\frac{1}{2}}}{A_s}\right)_{s.w.} \approx \frac{0.09}{(40b)^{0.6}} \quad m^{\frac{1}{2}} \qquad (40)$$

the suffix denoting the boundary condition between the s - surface and w - window regimes.

These values which in principle depend primarily on 'b' and not on fireload, differ slightly from those discussed in more detail by Hamathy[2].

Because each of the relations describing the three regimes has to be slightly extrapolated to the transition to the neighbouring regime, the definition of the transition by the intersection of two extrapolated relationships is not too accurate. However, we shall follow this procedure to give an indication of the form of second approximations. Thus, for S = 1m and the mean values of ρ_w

and $^{L}/S$ we have from equations (15) and (24)

$$\left(\frac{A_w H_w^{\frac{1}{2}}}{A_S}\right)_{s.w.} = \frac{0.135}{(40b)^{0.6}} \left\{\frac{A_V}{A_T}\right\}^{0.13} \quad m^{\frac{1}{2}} \tag{41}$$

The coefficient 0.135 is an over-estimate since equation (15) over-estimates m" at low values of $\frac{A_w H_w^{\frac{1}{2}}}{A_T}$

For these data the mean value of A_V/A_T is of order 0.04 so equation (41) gives virtually the same as does equation (40).

$$\left(\frac{A_w H_w^{\frac{1}{2}}}{A_S}\right)_{s.w.} \approx \frac{0.09}{(40b)^{0.6}} \quad m^{\frac{1}{2}} \tag{42}$$

Since for these data the total fuel load M_f is $2\ A_T$ and $A_s/A_T \simeq 0.6$

$$\left(\frac{M_f}{A_w H_w^{\frac{1}{2}}}\right)_{s.w.} \approx \frac{2 \times (40b)^{0.6}}{0.09 \times 0.6} \approx 38(40b)^{0.6} \quad kg/m^{5/2}$$

For $b = 0.040$ m this would be 54 $kg/m^{5/2}$, somewhat less than a previous estimate by Heselden[29] based on sticks of such a size. He gave $\left(\frac{M_f}{A_w}\right)_{s.w.}$ as 150 kg/m^2 for a compartment 1.83 m high and b = 0.045 m, ie. $\left(\frac{M_f}{A_w H_w^{\frac{1}{2}}}\right)_{s.w.}$ as 110 $kg/m^{5/2}$, twice the value given here. Magnusson and Thelandersson[13] who in effect assumed m" independent of b gave $\left(M_f/A_w H_w^{\frac{1}{2}}\right)_{s.w.}$ as 175 $kg/m^{5/2}$.

Magnusson and Thelandersson[13] do, however, comment that Sjölin's[30] experiments were ventilation controlled at values of $M/A_w H_w^{\frac{1}{2}}$ as low as 54 $kg/m^{5/2}$.

If $$\frac{A_w H_w^{\frac{1}{2}}}{A_T} < \left(\frac{A_w H_w^{\frac{1}{2}}}{A_T}\right)_{s.w.}$$

we obtain from equations (14) and (24)

$$\left(\frac{A_w H_w^{\frac{1}{2}}}{A_T}\right)_{p.w.}^{0.7} = 2.4 \left(\frac{h_c A_v A_s}{A_T^2}\right)^{0.5} \tag{43}$$

The index 0.7 arises from the cumulative effect of the secondary effect of $\frac{A_w H_w^{\frac{1}{2}}}{A_T}$ in equations (14) and (24)

If these secondary effects are neglected and $\frac{A_w H_w^{\frac{1}{2}}}{A_T}$ is put equal to its median value ($0.03\ m^{\frac{1}{2}}$) in those terms, we obtain

$$\left(\frac{A_w H_w^{\frac{1}{2}}}{A_s}\right)_{p.w.} \approx 0.64 \left(h_c \frac{A_v}{A_s}\right)^{0.5} \tag{44A}$$

$$hc \frac{A_v}{A_s} \approx hc \frac{a_v}{a_s} \approx \frac{S}{4} \approx 2.5\left(\frac{Aw}{As}\right)^2 Hw \tag{44B}$$

which is simpler in form, firstly, because it excludes A_T for the inclusion of which there is little reason in a criterion which one expects to depend primarily on the relative resistance to flows of the window and the crib , and secondly, because it eliminates dimensional quantities. Based directly on equations (1) and (6) the coefficient 0.64 is replaced by 0.77.

It is probably more reasonable to use equation (43) for values of $\frac{A_w H_w^{\frac{1}{2}}}{A_T}$ outside the range 0.02 to 0.04 $m^{\frac{1}{2}}$ for which equation (44A) applies.

The transition between the porosity and the surface controlled regime necessarily has similarities to the transition for cribs in the open. Here there are secondary effects of the compartment and the window opening, so the result is modified. At its simplest the criterion is of the form obtained by putting m" proportional to $b^{-0.6}$ in equation (7B). This results in our requiring larger values of 's' with smaller 'b' to avoid porosity effects.

Proceeding instead with equation (15) (coupled with the $b^{-0.6}$ law) and equation (14) we obtain, for S = 1 m

$$h \frac{A_v}{A_s} = 4.6 \times 10^{-4} \ (40b)^{-1.6} \left(\frac{As}{A_T h_c}\right)^{0.35} \left(\frac{AwHw}{A_T}\right)^{-0.78} \tag{45}$$

though for large $\frac{A_w H_w^{\frac{1}{2}}}{A_T}$ the power law form of equation (15) and hence that of equation (41) cannot be valid.

For the data in this report $(^{As}/_{A_T}\ h_c)^{0.35}$ may be treated as constant on the right hand side of equation (45) and for $\frac{A_w H_w^{\frac{1}{2}}}{A_T}$ equal to 0.04 (the lower value for surface control in these experiments) porosity ceases to be a limiting factor for 25 mm sticks if

$$h_c \frac{A_V}{A_S} \approx h_c \frac{a_v}{a_s} \approx \frac{S}{4} \approx 0.008 \text{ m}$$

The above criteria corresponds closely to our initial choice and it implies a stick spacing of 30 mm and over: larger sticks will reduce the spacing required to avoid porisity effects and vice versa. The effect, allowing for the term $A_s/h_c A_T$ appears to be between a simple inverse law and an inverse square law.

An important application of the above criterion is to the CIB experiments where cribs of sticks, mainly 20 mm with some 10 mm and 40 mm, spaced horizontally by distance equal to the stick size (1 spacing) or three times greater (3 spacing), were burnt in a variety of compartments. We cannot expect direct application of the above criterion because the CIB cribs rested on the floor and covered a greater fraction of the floor area but according to it the CIB experiments with 40 mm sticks and those of 3 spacing with 20 mm sticks, probably satisfy the requirement for window control but those of 10 mm spaced 10 mm apart do not.

Thus, the difference found between the two types of crib in the CIB experiments[4] does not require us to extrapolate the data to greater spacings; we can regard the larger spacing (at least those for the 20 mm and 40 mm sticks) as large enough to be typical of cribs which are not influenced by their porosity.

These results are summarised in Fig.6 which of necessity is somewhat idealised and incomplete.

5. THE MODELLING CRITERIA OF HESKESTAD

Heskestad follows Block in his treatment of cribs, uses his parameter for P. (see sect.2.1.2) and combines it with equation (1) to describe rates of burning in terms of two independent parameters. If instead we combine equations (4a) and (6) with equation (1) we obtain a modification of Heskestad's formulations consistant with the treatment of cribs in this paper viz

$$\frac{m''}{m''_o} = F\left[\left(\sqrt{\frac{A_v h_c}{A_s}}\; b^n\right), \frac{A_w\sqrt{H_w}}{A_s\, m''_o}\right] \qquad (46)$$

n is here 0.6 Block and Heskestad used 0.5. We have seen how m''_o is not strictly a constant for a given 'b' nor is equation (1) strictly correct, so Heskestad's formulation (and the above varient of it) are first approximations.

Equation (46) can readily be shown to give the forms of the first approximations of equations(40)and (44) for the transitions between the regimes.

In this paper we have chosen to identify the regimes separately so as to examine certain second order effects.

6. CONCLUSIONS

6.1. Nilsson's data show unsystematic scale effects which are not fully understood.

6.2. $R/A_w H_w^{\frac{1}{2}}$ is not a constant in the window controlled regime nor is m" strictly constant in the fuel surface controlled regime though they are nearly so for the given stick size.

6.3. The combination of the energy balance for the fire as a whole and for the fuel surface can account for certain experimental features of compartment fires.

6.4. Theory indicates that the primary geometric variable in window controlled fires is the opening factor $\frac{A_w H_w^{\frac{1}{2}}}{A_T}$ but there are several factors including the radiation transfer to the fuel from the emissive flames, whose influence on the rate of burning lies in their effect on heat transfer. The theory suggests that the variation of $R/A_w H_w^{\frac{1}{2}}$ and θ with $A_w H_w^{\frac{1}{2}}/A_T$ can be affected by the extent to which the fuel is exposed to its surroundings, ie the value of A_s'/A_s and by flame emissivity.

6.5. We have distinguished between three regimes; the data for the two dependent on the porosity and surface area of cribs are closely comparable in form to those reported for free burning cribs. First approximations to the limits of the porosity controlled regime have been estimated to be

(a) between the porosity and the window controlled regimes

$$\left(hc \frac{A_v}{A_s} \right)_{p.s} \simeq 2.5 \left(\frac{A_w}{A_s} \right)^2 Hw$$

(b) between the porosity and the fuel surface regimes

$$s_{p.s} \approx 4 \quad hc \frac{A_v}{A_s} \approx 30 \text{ mm}$$

for sticks 25 mm thick and it is presumed that this critical value will be less for thicker sticks.

and (c) between the window controlled and the surface controlled regimes

$$\left(\frac{AwHw^{\frac{1}{2}}}{As} \right)_{s.w.} \quad 0.09 \ (40b)^{-0.6} \qquad m^{\frac{1}{2}}$$

We must accept that such simplified estimates will be somewhat imprecise and may need revision after considering data for other fire loads and fuel thicknesses.

6.6. We have estimated that the largest spacing used in the C.I.B. experiments was large enough for the porosity of the cribs not to be a limiting factor in the fire behaviour of compartment fires using cribs of sticks of 20 mm, that cribs of 10 mm sticks were probably porosity controlled and cribs of 40 mm sticks probably were not.

6.7. The theoretical arguments suggest that the radiation shielding of the internal fuel surfaces may have an influence on the behaviour of compartment fires using cribs.

6.8. Implications of the theory will be discussed elsewhere but one immediate consequence of the assumption of a ventilation controlled fire is that the calorific value of the fuel is not the primary calorific property of the fuel. It is the calorific value per unit mass of oxygen (or air) that controls R & θ

APPENDIX I

If the simple relation

$$R \propto A_w H_w^{\frac{1}{2}}$$

is valid then one cannot distinguish between

$$m'' \ (= R/A_s) \propto \frac{A_w H_w^{\frac{1}{2}}}{A_s}$$

and

$$\frac{R}{A_T} \propto \frac{A_w H_w^{\frac{1}{2}}}{A_T}$$

as devices for reducing data on different scales to the same order. However, if

$$R \propto (A_w H_w^{\frac{1}{2}})^n$$

where $n < 1$

then we can statistically examine

$$m'' \propto \left(\frac{A_w H_w^{\frac{1}{2}}}{A_T} \right)^q \left(\frac{A_s}{A_T} \right)^v$$

(i) If normalising by dividing by A_s is preferable then $r \approx q \approx 0$

(ii) If normalising by A_T is preferable $v \simeq -1$

(iii) If normalising R by A_s and $A_w H_w^{\frac{1}{2}}$ by A_T is preferable $v = 0$

The statistical analysis for $\frac{A_w H_w^{\frac{1}{2}}}{A_T} = 0.02, 0.032$ and $0.04 \ m^{\frac{1}{2}}$

gives $q = 0.80$ (significantly different from unity as well as from zero) and $v \approx 0.5$ with a standard error of 0.5.

Clearly the data are more consistent with (iii) than with either (i) or (ii).

APPENDIX II

The heat release

Roberts[27] gives the heat release of the volatiles from dry wood as 16.4 MJ/kg of volatiles. He also gives an effective composition of $(CH_2O)_n$ so that 1 gm of volatiles requires 1.067 gm of oxygen for complete combustion. Hence the heat release is 15.4 MJ/kg of oxygen or 3.5 MJ/kg of air. If we assume that combustion is incomplete and the only difference is that carbon monoxide is produced in place of carbon dioxide, the heat release is then calculated as 9.3 MJ/kg which is 7.1 MJ/kg 13.3 MJ/kg of oxygen reacted or 3.05 MJ/kg of air.

Let the moisture content of wood by V_m and z the fraction of wood remaining. We shall need to assume that the moisture leaves the wood at a uniform rate. All the free moisture appears in the volatiles and the gross calorific value of the volatiles is $\left(\frac{1 - z - V_m}{1 - z} \right) \Delta H'_{vap}$

where $\Delta H'_{vap}$ is the calorific value of the volatiles products from dry wood.

The net calorific value for complete combustion

$$\frac{3.93\ (1 - z - V_m) - \left[V_m + \frac{18}{62}\ (1 - z - V_m) \right] L}{1 - z}$$

where L the latent heat is 2.25 MJ/kg. For combustion to CO it is

$$\frac{1.69\ (1 - z - V_m) - \left[V + \frac{18}{46}\ (1 - z - V_m) \right] L}{1 - z}$$

We shall take z as 0.2

The ratio of oxygen required per unit mass of volatiles is $\frac{32}{30} \left(\frac{1 - z - V_m}{1 - z} \right)$, or $\frac{16}{30} \left(\frac{1 - z - V_m}{1 - z} \right)$ for conversion to CO_2 and CO respectively.

Table A

Net calorific value per kg of volatiles

V_m	Complete combustion to CO_2 Heat release MJ/kg of fuel	Complete combustion to CO_2 Heat release MJ/kg of air	Incomplete combustion to CO Heat release MJ/kg of fuel	Incomplete combustion to CO Heat release MJ/kg of air
0	16.5	3.5	7.1	3.1
0.05	15.1	3.45	6.3	2.9
0.10	13.8	3.4	5.6	2.75
0.15	12.5	3.3	4.7	2.55

Uncertainties in the CO/CO_2 ratio produce greater errors with high moisture contents. A "best" value for $m_{ox} \frac{\Delta H}{r}$ is 3 ± 0.35 MJ/kg (730 ± 80 cal/g).

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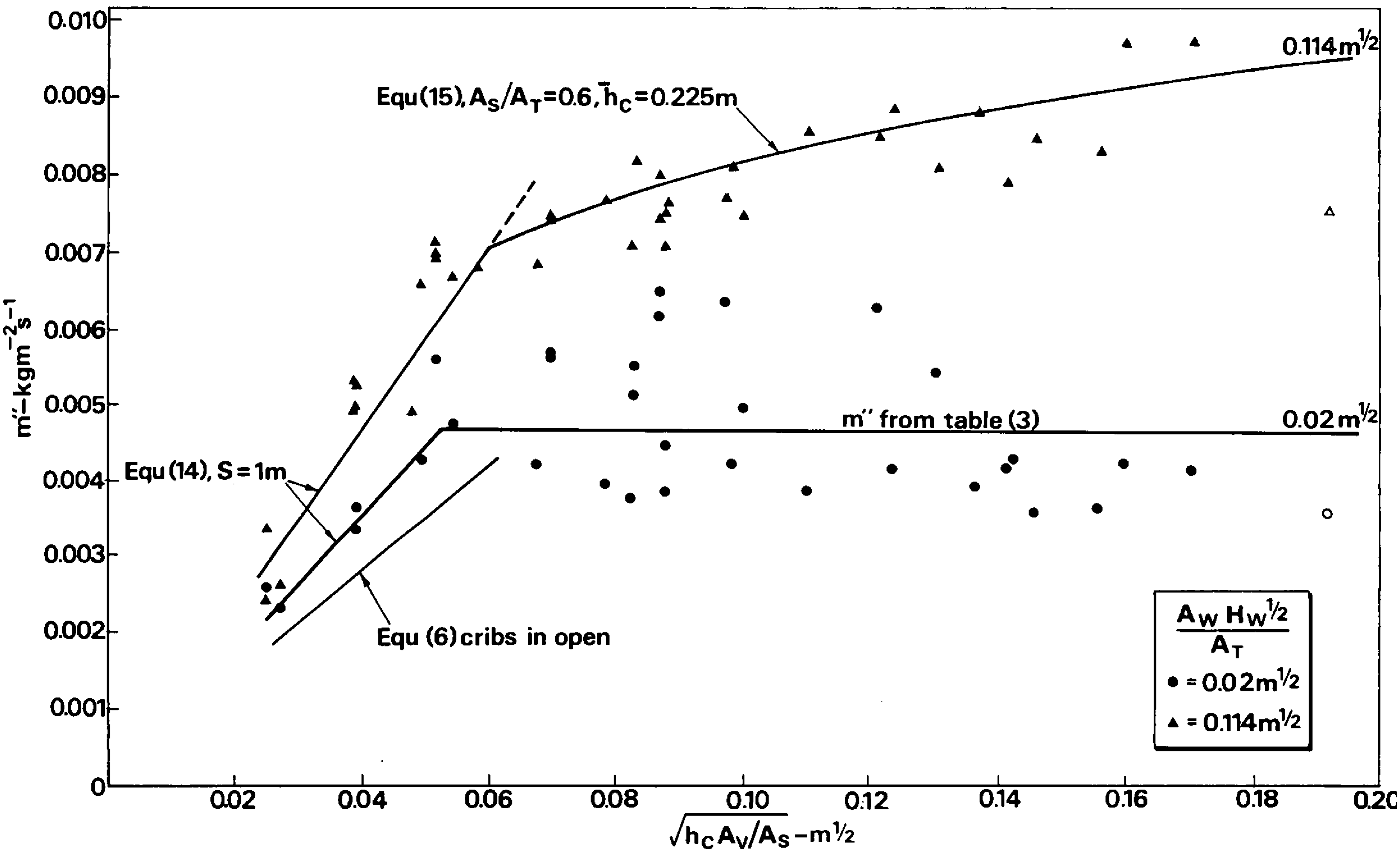

Figure 1 Nilsson's data (b=0.025m, fire load 2kg per square metre of total surface)

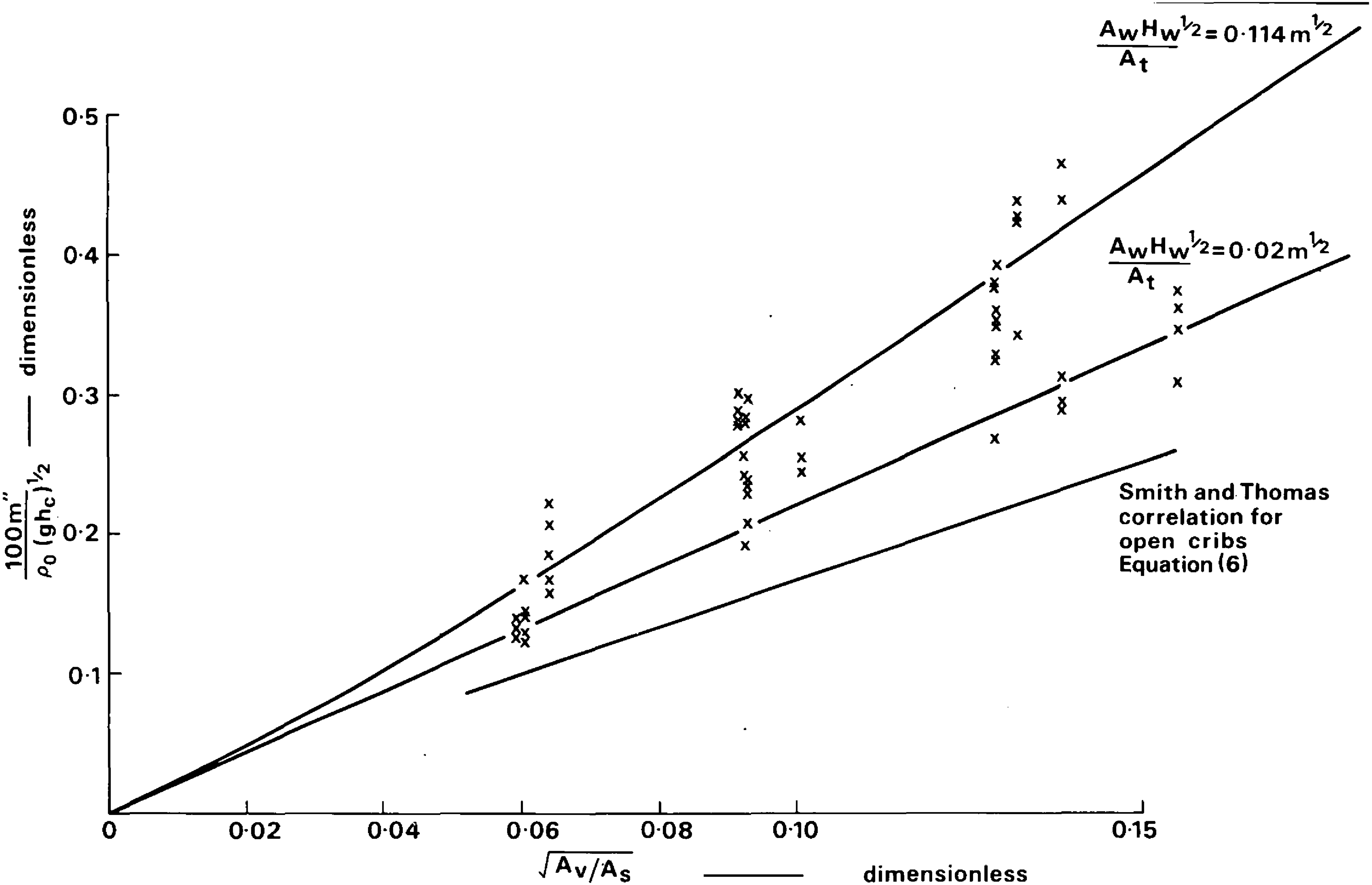

Figure 2 Fuel porosity regime

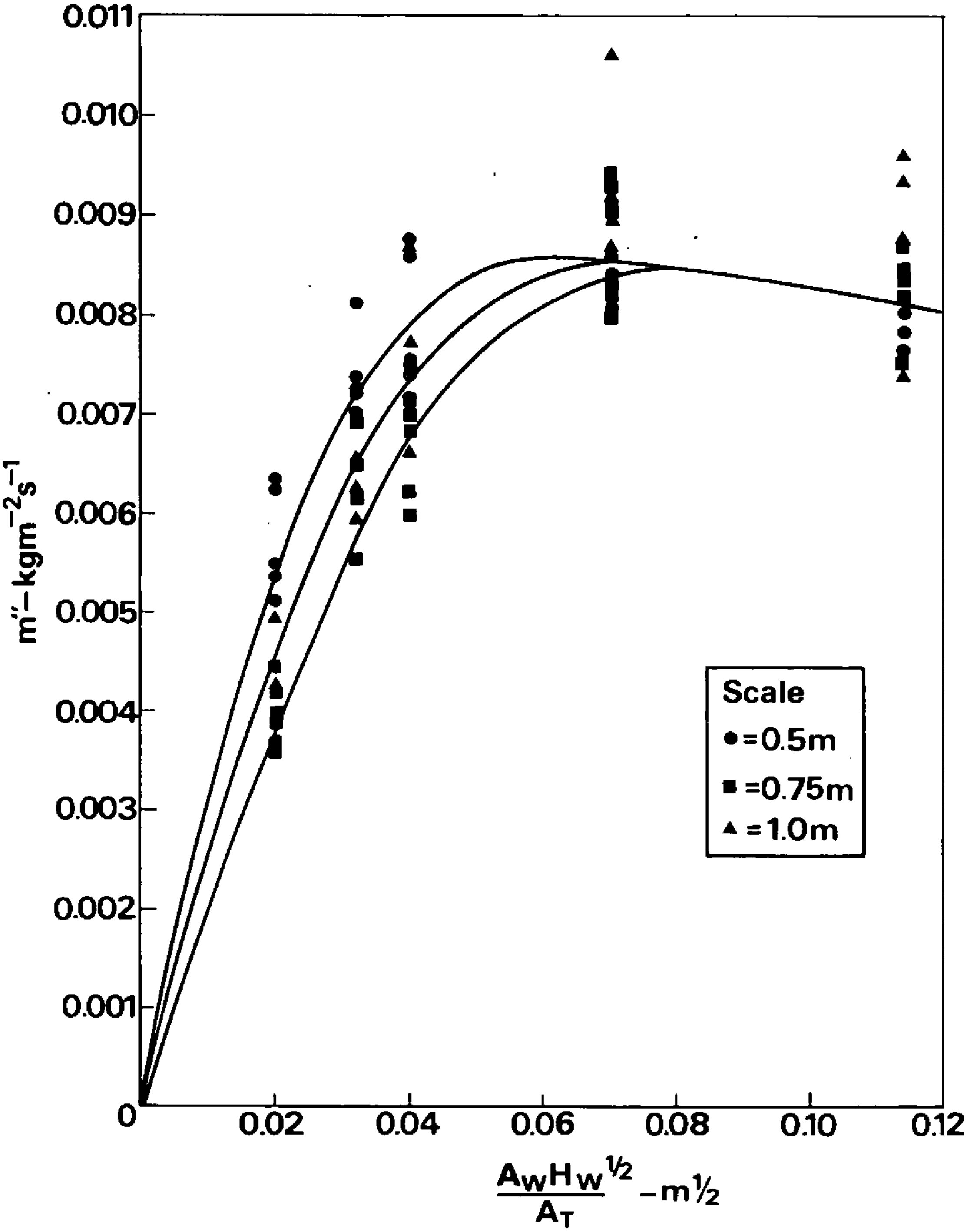

Figure 3 Data for $A_V/A_S > 0.04$

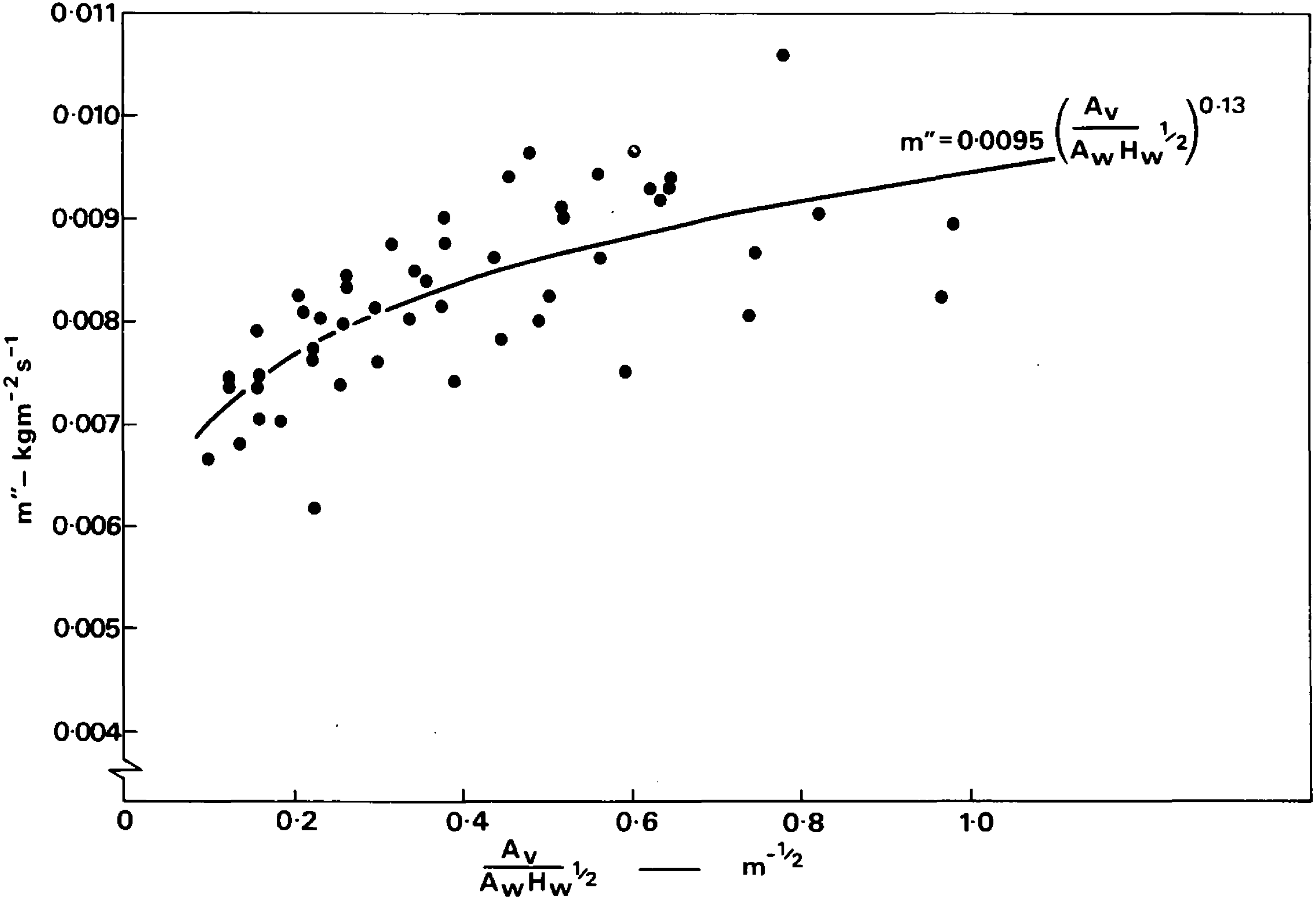

Figure 4 Fuel surface controlled regime

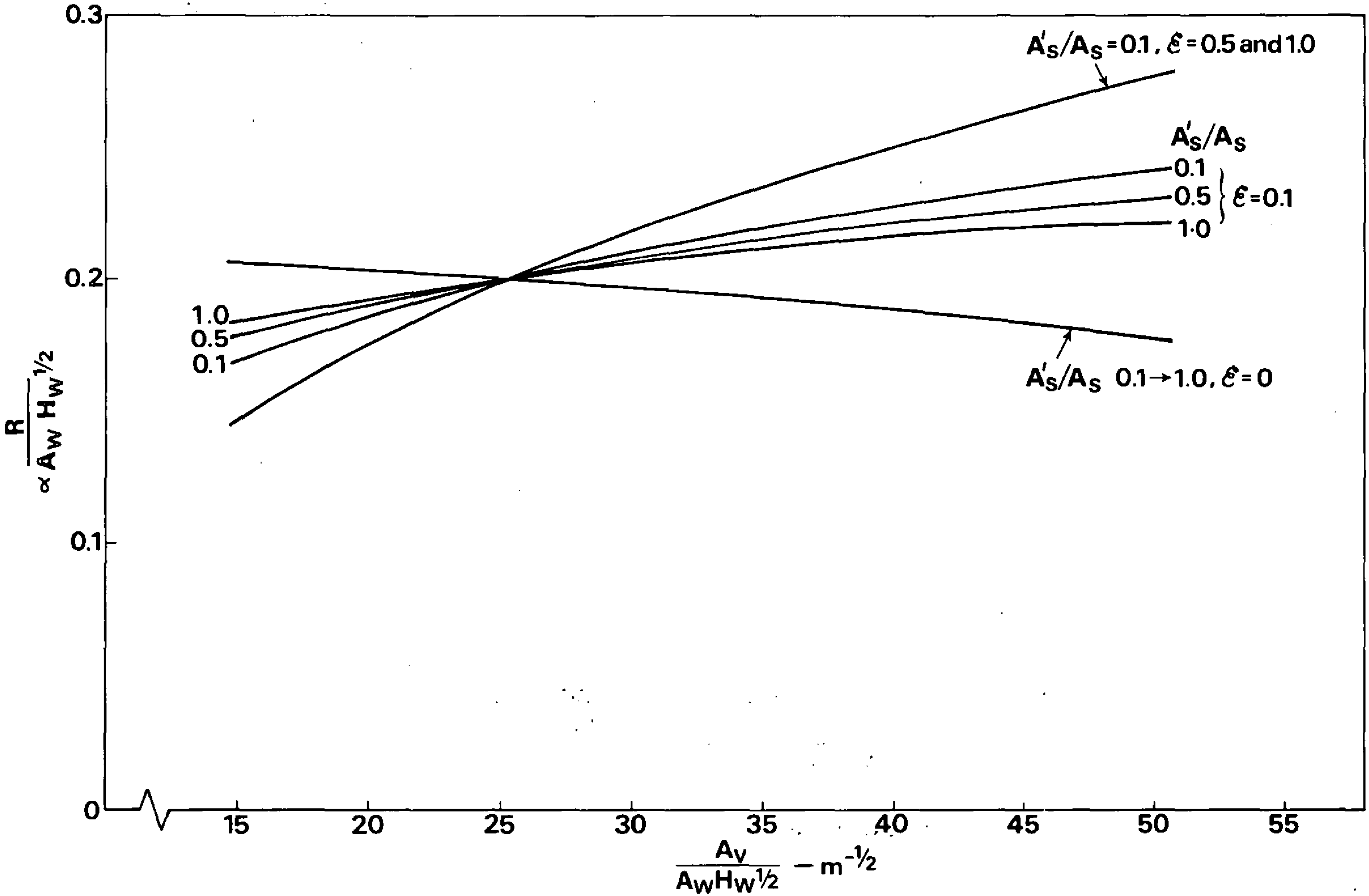

Figure 5a Some y(x) characteristics (Equ 38a)

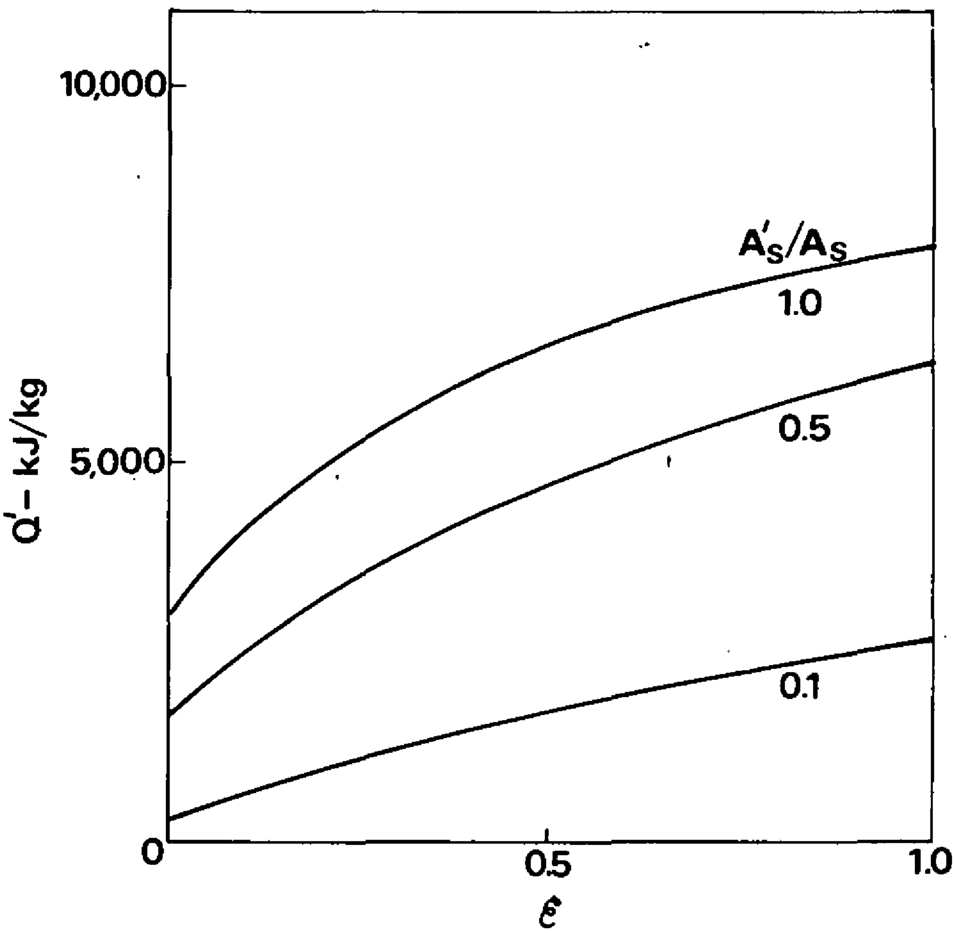

Figure 5b Values of Q' required to normalise y(25)=0.2

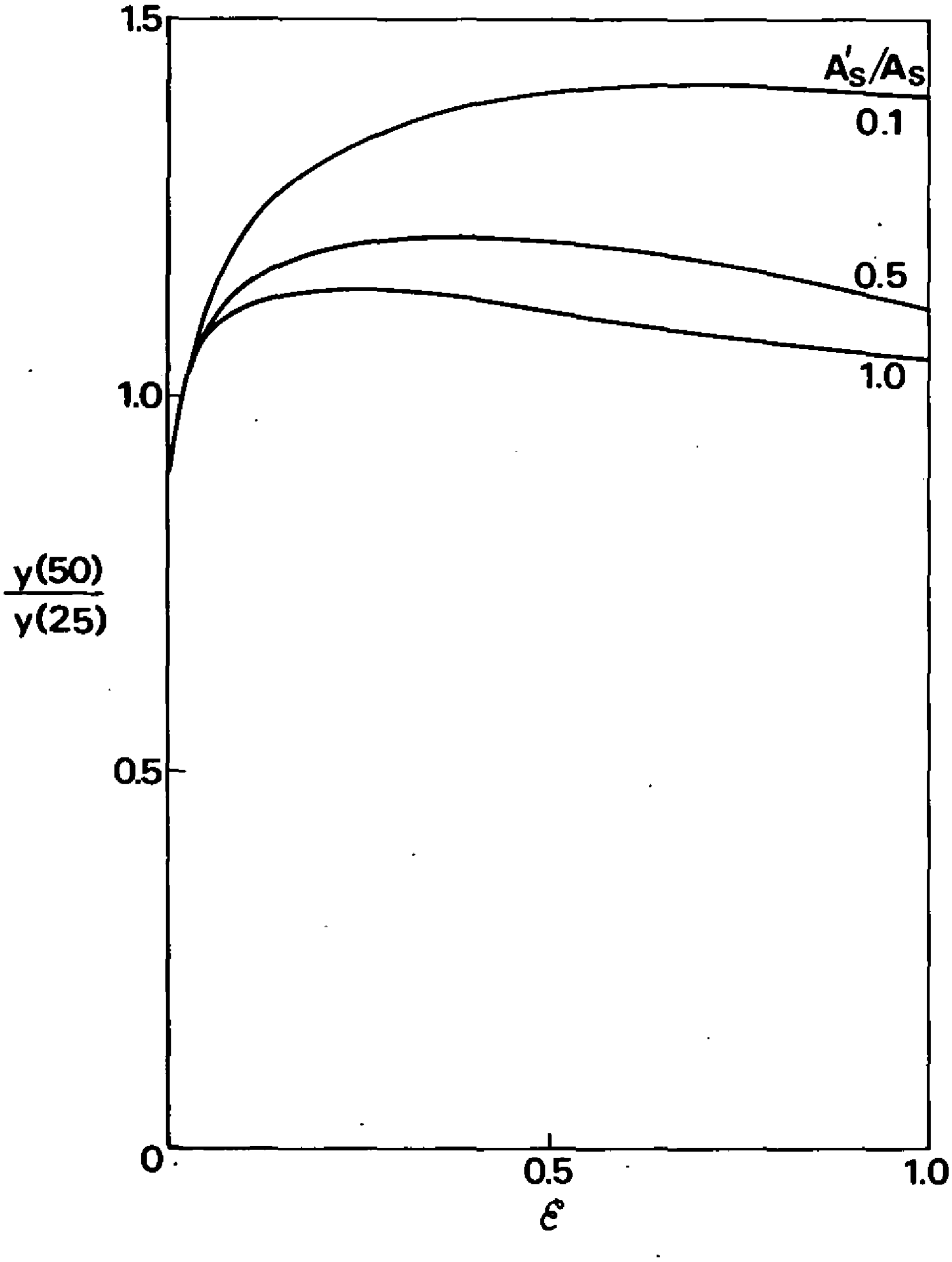

Figure 5c Variation of y(x)

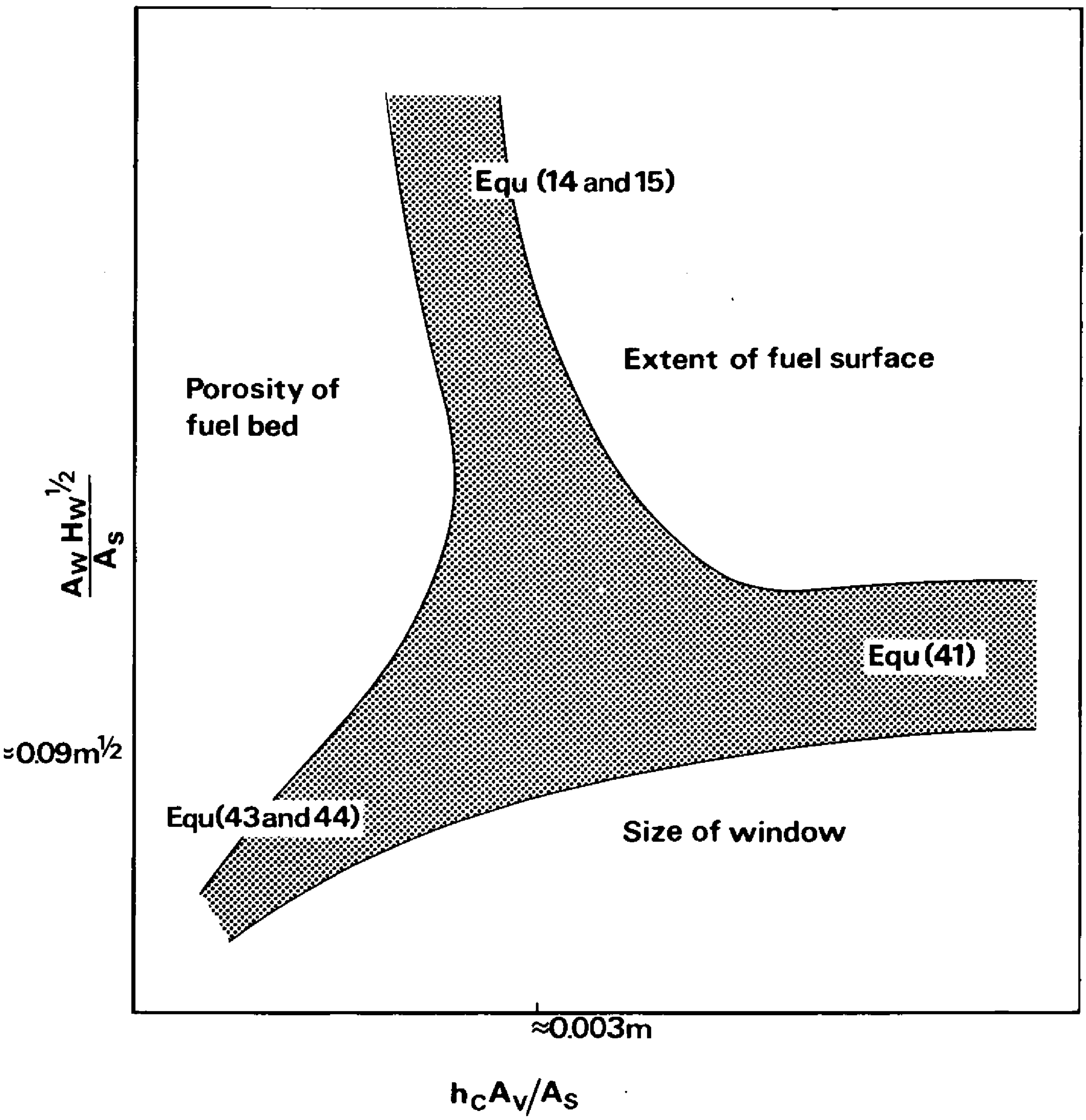

Figure 6 Regimes in Nilsson's data:
main factors affecting burning rate (b=0.025m)