Some Notes on Fires in Compartments

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P.H. Thomas

Some Notes on Fires in Compartments

Lund 1988
SOME NOTES ON FIRES IN COMPARTMENTS

Research project financed by the
Swedish Fire Research Board (BRANDFORSK)
CONTENTS

| Page |
|-----------------|---|
| 1   | THE BEHAVIOUR OF POLYURETHANE MATTRESSES AS AN INPUT TO THE HARVARD CODE | 2 |
| 2   | THE RADIATION TO THE FLOOR OF A COMPARTMENT AND THE FLAME HEIGHT FROM BURNING CONTENTS | 8 |
| 3   | A NOTE ON THE McCAFFREY-QUINTIERE REGRESSION AND OTHER STATISTICALLY BASED FORMULAE | 17 |
| 4   | ON FULLY DEVELOPED FIRES IN LARGE COMPARTMENTS | 27 |
Summary

In the course of an examination of some data on the burning of furnishings and bedding in compartments, the measured rates of fire development in polyurethane mattresses have been compared with one of the standard inputs used in fire modelling with the Harvard Code.

An apparent discrepancy is discussed and an explanation offered in physical terms. The explanation is germane to a comparison between the exponential and square law models of fire growth.

Introduction

Andersson (1) has reported several well documented furniture and bedding fire tests and, as part of an examination of the data, a comparison is made here with the burning of polyurethane mattresses as recorded and as described in the Harvard Code (2). The data of interest are presented in Figure (27) of Reference (1). The results of 4 tests are shown, two made-up beds and two mattresses (standard polyurethane), one in the open [Test (11)] and one in a room [Test (1)]. Table (1) gives data from the record of visual observations for Test (11). Some of them are plotted in Fig. (1). Apart from the last few minutes, i.e. after 11 minutes, flame spread on the two mattresses was about 1.5 to 2 mm/s. The record of observations for Test (1), also with a cotton cover on the mattress, and ignition by a wood crib is not specific regar-
ending spread rate. The data for Test (3) for a made-up bed with a quilt and sheet are shown in Fig. (2). The rates of spread reach 5-6 mm/s at about 9 min.

Discussion

There are two important points of difference between these data and the data (3) (4) which were used as the basis for the model of spread on a polyurethane mattress in the Harvard Code. The first is that the Lund fires lasted much longer, typically 500 seconds and over whereas F.M.R.C. data cover about 1/3 of this; Mitler himself refers to 170 seconds up to which time the equation given by Land for the radial distance of spread at time "t" in seconds

\[ R = 0.042 \ e^{0.01t} \text{metres} \]  

(1)

from which

\[ \frac{dR}{dt} = 0.42 \ e^{0.01t} \text{mm/s} \]  

(2)

is a good description of the spread. However, it is quite apparent that the spread does not continue exponentially: at 13 minutes the flame front had reached 1.1 metre from the point of ignition, whereas equation (1) predicts about 10 metres.

There are simple physical reasons for this difference which is difficult to account for by the fact that the Lund mattresses were covered by bedding. The experiments Land made were on pieces of polyurethane 5ft. x 5ft. which permit radial spread of 0.75 metre only. This simulates spread across the mattresses used by Andersson but not spread along them and the physical processes change when the burning penetrates the 100 mm thick mattress and the spread along the length of the mattress corresponds more nearly to a spread rate constant in time. Babbrauskas and Krasny (5) show that pyrolysis will penetrate a polyurethane cushion 100 mm thick in about 100 to 180 secs. The major part of the thermal energy in the mattress is released after the exponential
model ceases to apply! Calculations employing Mitler's equation for mass loss rate in Orloff's experiments,

\[ m' = 8.95 \times 10^{-6} \frac{e^{t/30.7}}{t} \text{ kg/s} \]

give a mass loss in 170 seconds of 30.7 x 8.95 x 10^{-6} (e^{170/30.7} - 1) i.e. about 70 gm. which is less than 3% of the mass of the 0.9m x 2m x 0.1m mattress of 35 kg/m^3 density. Similar numbers arise using the correlation of Mizuno et al (6).

Clearly, if the mattress fire is not extinguished, the energy is mainly released after the time when the standard polyurethane input to the Harvard Code has ceased to be expressed validly.

Spread of fire through a fuel bed with a combustion zone of constant thickness along a line front is acceptably steady-state once the fuel at the rear of the propagating zone is no longer contributing to the fire and then one can adopt a simple description of spread (7).

\[ I = \rho \Delta H R \]  

(3)

where \( R \) is the spread rate
\( \Delta H \) is the enthalpy rise required for ignition
\( \rho \) is the density of the material heated to ignition
and \( I \) the forward heat flux.

Equation (3) contains two unknown quantities, \( R \) & \( \rho \). For our purpose it is sufficient to write

\[ \Delta H = c \theta_i \]

where \( \theta_i \) is the temperature rise necessary in the fuel before it is capable of sustaining flaming combustion i.e. the temperature of the flame front isotherm, the effective ignition temperature rise. It does not include the heat of pyrolysis if this is regarded as feedback from the flame.

It is important to note that \( \rho \) is not the density of the fuel
as it is sometimes stated but in this burning of polyurethane we shall so regard it. This leads to a maximum estimate for $I$.

For $\rho = 35 \text{ kg/m}^3$, $c \approx 1 \text{ kJ/kg}$, $\theta \approx 300^\circ$ and the measured mean rate of spread of 2.0 mm/s for the unmade up mattress, a forward heat flux of $210 \text{ kW/m}^2$ has to be presumed.

Although there are many qualifications to this simple estimate, the front has been assumed vertical, the spread assumed along a line front and so on, the estimate is of a plausible magnitude for the radiation flux close to a flame and to hot solids and gives a more realistic picture of the spread than does an exponential model. Account must be taken of the real thickness of furniture fuel if it can be penetrated.

Conclusion

If spread does occur in the way postulated a radial spread gives a square law for the mass consumption rate and linear spread gives a proportionality law with respect to time. One is tempted to suggest that exponential growth laws are appropriate for fuels which are not burnt through in the process of spread and square laws where they are. For bedding, and exceptionally for other fuel systems, when they can be presumed to spread in one direction a linear law obtains.

One might hope that detection is speedy enough for an exponential growth law and flashover slow enough for the square law to be the basis of modelling.
References


[4] Land, R., Private Communication to H Mitler (see Reference (2)).


### TABLE 1

<table>
<thead>
<tr>
<th>Time (min - sec)</th>
<th>Diameter of Burning Area '2R' (metres)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 - 10</td>
<td>0.2</td>
</tr>
<tr>
<td>2 - 0</td>
<td>0.3</td>
</tr>
<tr>
<td>3 - 0</td>
<td>0.4</td>
</tr>
<tr>
<td>3 - 40</td>
<td>0.5</td>
</tr>
<tr>
<td>4 - 0</td>
<td>0.6</td>
</tr>
</tbody>
</table>

---

Flame front reaches a distance from head of mattress metre (Linear spread)

<table>
<thead>
<tr>
<th>Time (min - sec)</th>
<th>Distance from head of mattress</th>
</tr>
</thead>
<tbody>
<tr>
<td>9 - 25</td>
<td>1.1</td>
</tr>
<tr>
<td>10 - 15</td>
<td>1.2</td>
</tr>
<tr>
<td>10 - 20</td>
<td>1.3</td>
</tr>
<tr>
<td>11 - 30</td>
<td>Flame under mattress</td>
</tr>
<tr>
<td>12</td>
<td>1.4</td>
</tr>
<tr>
<td>12 - 30</td>
<td>1.5</td>
</tr>
<tr>
<td>13</td>
<td>1.6</td>
</tr>
</tbody>
</table>

Between 4 and 9 minutes the burning area reaches the sides of the mattress and reestablishes itself as a spread along the mattress.
Fig (1). Comparison of some fire spread data and exponential rate (Andersson).

\[ R = 0.042 e^{0.01t} \]

Test (II) of reference ①
Test (3) of reference

Mean rate $\approx 4 \text{mm/sec}$

Fig (2). Fire spread along bed
(Andersson)
2 THE RADIATION TO THE FLOOR OF A COMPARTMENT AND THE FLAME HEIGHT FROM BURNING CONTENTS

Introduction

Andersson has recently (1) reported measurements of radiation to the floor when items of furniture were burning in a compartment.

We shall examine these data and compare them with those of Quintiere and McCaffrey (2) who earlier reported similar data for crib fires.

Results

Quintiere and McCaffrey (2) used a room 2.18 m x 2.18 m x 2.41 m high but the radiometer in the floor was not central. They calculated the view factor and the emissivity of the hot gas layer using data for flame absorption allowing for dilution of the combustion products. Results in the range 0.1 - 0.9 m\(^{-1}\) were obtained in good agreement with Modak's (3) model.

Quintiere and McCaffrey got excellent agreement between experimental radiant and calculated values for the lower fluxes but the higher experimental fluxes were low (See Fig 5-19 of references (2)) because, wrote Quintiere and McCaffrey, the mean layer temperature overestimated the effective radiating temperature which was at the cooler lower boundary of the gas layer.

It should also be noted that although Quintiere and McCaffrey
wrote of radiation "from a layer" the temperatures were over 600°C indicating flashover was imminent. This suggests that there might have been flames, if only transient, in the layer. These differences between the conditions recognized by Quintiere and McCaffrey appear however not to effect the comparable correlation by Andersson (1) who burnt chairs, sofas, mattresses and made up beds in a compartment 2.4 m x 3.6 m x 2.4 m high in which the radiation from above was measured in the centre of the floor.

Fig 1 shows data from the two reports.

Although there are only three results for temperatures over 600°C, two of the three tests produced fluxes to the floor over twice that to be expected from Quintiere and McCaffrey's correlation. One distinction between the two correlations is that the correlation of crib fires by Quintiere and McCaffrey is with mean upper gas layer temperature. The Andersson data are here correlated with maximum temperatures. This tends to bring the results closer than they perhaps are. Radiation is perhaps more likely to be better correlated by the maximum than with mean temperature but no examination in detail has been made.

For a simple gas layer - neglecting contributions from the lower walls and treating upper surfaces as at Tg and the effective radiator as at the mid-height plane we obtain for Andersson's data a view factor of

\[ \psi \approx 0.8 \]

A curve based on an emissivity of 1 and \( \psi = 0.8 \) is shown in figure 1 and is a good first approximation to the two sets of data. We shall, extend the approximation in order to exploit further the correlation between temperature rise and energy release.
Analysis of Radiation Data

We assume a power law correlation of heat flux to the floor "E" and "Q" the energy release rate. A satisfactory approximation to $T^4 - T_0^4$ over the ranges $0.7 < \frac{T}{T_0} < 3.0$ viz approx 200°C to 600°C (the limit of preflashover fires) is

$$T^4 - T_0^4 = 15 T_0^4 \left( \frac{T-T_0}{T_0} \right)^{2.5}$$

(1)

Using McCaffrey and Quintiere's correlation (4) viz

$$T-T_0 = \Delta T = 6.85 \frac{Q^{2/3}}{(h_K A_T A V H)^{1/3}}$$

(2)

where

- $A_T$ is the total internal surface area of the compartment
- $A$ is the opening area
- $H$ is the opening height
- $h_K$ is the effective heat transfer coefficient

we obtain from equation (1) and (2)

$$E = 15 \times 0.80 \times 57 \times 10^{-12} \times 293^4 \times \left[ \frac{6.85}{2.93} \right]^{2.5} \frac{Q^{1.67}}{(h_K A_T A V H)^{0.835}}$$

$$= 420 \times 10^{-6} Q^{1.67} (h_K A_T A V H)^{-0.835}$$

(3)

The mean best value of $(h_K A_T A V H)^{1/3}$ is 1.265 as recorded by Andersson and we insert this value into equations (2) and (3). Figure (2) shows Andersson's data compared to equation (2) and equation (3) becomes
The data and calculated values are shown in TABLE 1 and the combination of the regression formula for temperature rise and an approximation for $T^4$ in terms of temperature rise seems an adequate predictor of these radiation measurements.

Table 2 shows data, taken from reference (2) (p. 28/29).

Although we have developed a relationship of the form

$$E \sim Q^{1.67}$$  \hspace{1cm} (5)

for radiation from the upper layer there may be an additional term from the flame from the fire itself.

<table>
<thead>
<tr>
<th>Test No</th>
<th>Measured Q kW</th>
<th>Measured $E = kW/m^2$</th>
<th>Calculated E</th>
<th>Measured $100E/Q$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>280</td>
<td>3</td>
<td>2.9</td>
<td>1.07</td>
</tr>
<tr>
<td>3</td>
<td>600</td>
<td>11</td>
<td>10.6</td>
<td>1.82</td>
</tr>
<tr>
<td>4</td>
<td>400</td>
<td>10</td>
<td>5.3</td>
<td>(2.50)</td>
</tr>
<tr>
<td>5</td>
<td>1800</td>
<td>69</td>
<td>65</td>
<td>3.82</td>
</tr>
<tr>
<td>6</td>
<td>1600</td>
<td>60</td>
<td>54</td>
<td>3.75</td>
</tr>
<tr>
<td>7</td>
<td>800</td>
<td>15</td>
<td>17.0</td>
<td>1.875</td>
</tr>
<tr>
<td>8</td>
<td>350</td>
<td>5</td>
<td>4.3</td>
<td>1.43</td>
</tr>
<tr>
<td>9</td>
<td>1000</td>
<td>13</td>
<td>24.6</td>
<td>(1.3)</td>
</tr>
<tr>
<td>10</td>
<td>1100</td>
<td>25</td>
<td>28</td>
<td>2.27</td>
</tr>
</tbody>
</table>

The data and calculated values are shown in TABLE 1 and the combination of the regression formula for temperature rise and an approximation for $T^4$ in terms of temperature rise seems an adequate predictor of these radiation measurements.

Although we have developed a relationship of the form

$$E = 230 \times 10^{-6} \cdot Q^{1.67} = 53 \times 10^{-2} \cdot \frac{Q}{100}^{1.67}$$  \hspace{1cm} (4)
TABLE 2 Continuing

| 6.98 | 161 | 3.81 | 2.37 | 212 |
| 20.19 | k465 | 10.4 | 2.31 | 366 |
| 33.02 | 760 | 23.9 | 3.14 | 682 |
| 35.29 | 813 | 28.6 | 3.51 | 794 |
| 11.94 | 179 | 4.2 | 2.35 | 288 |
| 18.73 | 282 | 5.8 | 2.06 | 356 |
| 28.28 | 425 | 10.1 | 2.36 | 424 |
| 15.42 | 355 | 10 | 2.82 | 386 |
| 25.02 | 577 | 23.9 | 4.15 | 680 |
| 11.27 | 169 | 4.3 | 2.54 | 319 |
| 24.28 | 364 | 14.5 | 4.00 | 488 |
| 26.41 | 396 | 14 | 3.55 | 478 |
| 5.9 | 135 | 3.9 | 2.9 | 238 |
| 14.55 | 335 | 9.8 | 2.74 | 403 |
| 21.97 | 505 | 17.7 | 3.5 | 632 |
| 22.93 | 527 | 17.9 | 3.4 | 642 |

Radiation from a flame is typically a fraction of about 20-40% of the energy release and 1/2 of this will be distributed over the surrounding floor and other low surfaces. We can therefore expect a flux of order

\[
F_{\text{flame}} = \frac{fQH}{4\pi(R^2 + H^2)^{3/2}} \tag{6i}
\]

where \( f \) is 0.2 - 0.4, \( H \) is the perpendicular distance from the centre of the flame to the floor and \( R \) is the horizontal distance to the receiver.

i.e.

\[
E_{\text{total}} = bQ + aQ^{1.67} \tag{6ii}
\]

Hence \( E/Q = b + aQ^{0.67} \)

We therefore expect \( E/Q \to f/4\pi H^2 \) as \( Q \to 0 \)
For \( H \approx 1 \text{ m} \) and \( R = 0 \), \( f \approx 0.3 \) we have \( 100 \frac{E}{Q} \approx 5 \text{ m}^{-2} \), and for \( R = H \), \( 100 \frac{E}{Q} \approx 1 \).

The data are shown in figure (3) and Andersson's data have been replotted in terms of \( Q^{0.67} \) in figure (4): there is no justification for including any additional component of radiation from the flame near floor level. The scatter in the Quintiere-McCaffrey data would also preclude any additional term \( bQ \).

The radiation to the floor from the hot layer can thus be correlated by a formula based on the well known regression formula for temperature rise and an "ad hoc" relationship between it and radiation. Layers with low emissivity will allow the radiation from the ceiling to reach the floor so partially compensating for the low gas layer emissivity. Detailed calculations have been made by several workers: here we are examining the very simplest of correlations which might well profit from further amplification. But the results suggests that more data could usefully be examined.

**Flame Height**

In the descriptive records of the various tests in Andersson's report there are comments regarding flame height. There are records for tests 1, 3 and 7 when "flames reach the ceiling". Taking the base of the flame as the seat level or the mattress level (noting each case is about 0.4 m above the floor where drips can burn) the flame heights have been plotted in Fig (5) for the value of the heat release rate at the time.

Flame heights \( Z_f \) based on McCaffrey's two equations

\[
Z_f = 0.08 \, Q^{2/5} \tag{7}
\]

for the "solid" lowest zone of flame and
For the middle, intermediate zone are shown.

Thomas's more general correlation requires an estimate of the characteristic base dimension and is therefore less useful in this application.

The upper limit to the observations corresponds roughly to the boundary of the "intermittent" zone but some data lie below it.

Conclusions

Relatively simple and well established methods of estimating flame height and radiation are able to interpret data on the burning of furniture expressed in terms of heat release. The predictability of flame height in terms of this rate needs emphasis because for higher heat release flames are deflected and other correlations would need to be adopted.

There are therefore some simple first approximation methods of characterizing the thermal hazard of burning furniture in relation to room geometry and the propensity to "flashover" and to spread fire along the floor; the data examined here are not the only data available and a further examination is needed to incorporate these.

One of the consequences of this type of analysis - if confirmed - is that for any piece of furniture with a measured maximum burning rate $Q_{\text{max}}$ one could in principle estimate readily its propensity to assist floor spread in a given compartment by-passing calculations of ceiling temperature and one could estimate whether or not its flames would reach the ceiling as well as of course the mean ceiling temperature.
References


Fig 1. Upper gas layer temperature rise, $\Delta T_{max}$ for Andersson and $\Delta T$ for Quintiere-McCaffrey data

Fig 2. Andersson and Magnusson's data for furniture

Fig 3. Measured $E$ and measured $Q$

Fig 4. Andersson's data replotted

Fig 5. Flame heights above seat or 0.4 m above floor
\[ \frac{\Delta T}{100} = \left( \frac{Q}{1000} \right)^{2/3} \times 5.4 \]
• and (x) Anderssens data

○ Quintiere-McCaffrey data

Fig. 3

$\frac{100E}{Q}$

Measured $Q$ kw
The numbers at each data points e.g. refer to the test nr. in reference ①.

Flame heights above seat (c 0.4 m above flow)
3 A NOTE ON THE McCAFFREY–QUINTIERE REGRESSION AND OTHER STATISTICALLY BASED FORMULAE

Introduction

McCaffrey, Quintiere and Harkleroad (1) have succeeded in correlating temperatures in the upper gas layer of compartment fires with the heat release rate, effective heat loss coefficients to the walls, etc., and various geometric properties of the compartments. They correlated their own and other data.

The purpose of this note is to explore the correlation of the temperature rise "θ" with a view to generalizing it and extending earlier discussions of its physical basis (1) (2).

The correlation is widely known in the form

\[ \frac{\theta}{T_0} = 1.6 \times 10^{2/3} \times 10^{-1/3} \]

(1)

where \( T_0 \) is the absolute ambient temperature

\[ X_1 = \frac{Q}{A_0 \sqrt{gH_0}} \rho c T_0 \]

(2)

\[ X_2 = h_K A_T / A_0 \sqrt{gH_0} \rho c \]

(3)

\( Q \) is the rate of energy (heat) release
\( h_K \) is the effective heat transfer with respect to ambient temperature.
\( A_0 \) is the area of opening
\( g \) is the acceleration due to gravity
\( \rho \) is the gas density, taken as constant
\( c \) is the gas specific heat, taken as constant
\( A_T \) is the internal surface area over which heat is lost
and \( H_0 \) is the opening height.
It is dimensionless but not obviously complete.

On inserting conventional values for the constants equation (1) may be written as

\[ \theta = 6.85 \times 10^2 \frac{Q^{2/3}}{A_o \sqrt{H_o} A_T} \cdot \frac{h_r}{K}^{-1/3} \]  

(4)

There are remarks in the discussion of the regression that the 2/3 power law of heat release is connected to the well known plume relationship and an early report (2) in fact correlates some data in terms of the variable appropriate to plumes. \( Q^{2/3}/h^{5/3} \) where "h" is a height characteristic of the position on the vertical axis of the plume.

Also in the background of the development of the correlation is the flow through the opening, the maximum of which is proportional to \( A_o \sqrt{H_o} \) and the simplified energy balance

\[(m_a c + h_r A_T) \theta = \dot{Q}\]  

(5)

where \( m_a \) is the actual air flow (fuel flow being normally negligible in comparison).

In an early report (2) experimental data for \( m_a \) were correlated by

\[ m_a \propto m_v^{1/4} \left( A_o \sqrt{H_o} \right)^{1/2} \]  

(6)

where \( m_v \) is the pyrolysis rate to which we presume \( Q \) is proportional.

In that report reference was made to dimensional analysis. Here this aspect of the problem is explored further.

However before proceeding we recall that reference (2) refers
to two correlations for temperature, one close to that of equation (1) with $-1/2$ instead of $-1/3$ as the second index and a correlation which we write here as

$$\theta \sim \frac{Q^{2/3}}{H_0^{5/3}} \left( \frac{H_0^2}{A_0} \right)^{1/5}$$

(7)

where we have chosen to remove $H$ the room height and replace it by $H_0$ in the first term, on the grounds that the plume cannot extend above the doorway opening in a steady state.

Hence $\theta \sim \left( \frac{Q}{A_0 \sqrt{H_0}} \right)^{2/3} \left( \frac{A_0}{H_0^2} \right)^{7/15}$

(8)

which to avoid attaching undue importance to trivial difference, we might write as

$$\theta \sim \left( \frac{Q}{A_0 \sqrt{H_0}} \right)^{2/3} \left( \frac{A_0}{H_0^2} \right)^{1/2}$$

(9)

The fact that both these correlations "fit" the data implies a correlation between the experimentaly chosen values of

$$\left( \frac{A_0}{H_0^2} \right)^{1/2} \quad \text{and} \quad \left( \frac{h_K A_T}{A_0 \sqrt{H_0}} \right)^{-1/2}$$

i.e. between $H_0$ and $\frac{h_K A_T}{H_0^{1/4}}$.

If $A_0$ varies more than other variables such a correlation is difficult to avoid: it necessitates a choice of compartments of considerable difference in shape and in the materials of their construction.
Dimensional analysis

Air flow

The experimental correlation above equation (6) is written here as

\[ m_a \sim Q^{1/4} (A_o \sqrt{gH_o})^{1/2} \] (10)

where \( m_a \) has been regarded as proportional to \( Q \). Neither equation (7) nor (6) appears to be part of a dimensionless form and it is that we first explore.

From the theory of axi-symmetric plumes the velocity at height "h" appears as proportional to

\[ \left( \frac{gQ}{\rho cT_o h} \right)^{1/3} \]

and, because we expect the mean flow in the compartment to be relevant, we assume that the relevant dimensionless ratio is the ratio of \( (gQ/\rho cT_o h)^{1/3} \) to \( A_o \sqrt{gH_o}/hW \) characteristic of the mean velocity in the compartment where \( W \) is the breadth of the compartment.

We therefore write the functional equation to express the induced air flow in relation to other flows,

\[ \frac{m_a}{\rho A_o \sqrt{gH_o}} = F\left( \left( \frac{gQ}{\rho cT_o h} \right)^{1/3} / (A_o \sqrt{gH_o}/hW) \right) \] (11)

A formal derivation would lead to the inclusion of all other geometric ratios, and \( h \) would be itself a function of these and the above variables. For geometrically similar compartments we replace \( h \) by \( H \) where \( H \) is the compartment height. And for these, equation (11) is generalized to
\[
m_a / \rho A_o \sqrt{g H_o} = F \left\{ Q / \rho c T_o A_o \sqrt{g H_o} \cdot \frac{A_o}{2 H_o} \cdot \frac{H_o}{H} \right\} \\
\]

We represent this as a power law, retaining only the variable quantities

\[
viz. m_a \propto A_o \sqrt{H_o} (Q/A_o \sqrt{g H_o})^\alpha \left( \frac{H_o}{A_o} \right)^\beta \left( \frac{H}{H_o} \right)^\gamma
\]

Comparing the indices of \( Q \) in equations (10) and (13) gives \( \alpha = 1/4 \) and comparing those of \( A \sqrt{H} \) gives \( \alpha = 1/2 \).

A simple consideration of plume theory would suggest an index of 1/3.

In reference (2) the airflow \( m_a \) is calculated in terms of temperature of the hot gas layer; a procedure which would allow for any "wall loss", but if the correlation is in terms of \( Q \) (as in equation (10)) then a wall loss term must be included, as must the factor \( W/W_o \) where \( W_o \) is the open width of the doorway.

The discrepancy between the indices however is unlikely to be associated with the variable \( X_2 \) since to get equation (10) would necessitate assuming \( m_a \) increased with \( h K \) i.e. with cooling and lower temperature which seems implausible.

We postulate that perhaps equation (6) is derived from

\[
\rho \frac{m_a}{A_o \sqrt{g H_o}} \sim (\frac{Q}{A_o \sqrt{g H_o}})^{1/4} \left( \frac{W^{5/2}}{A_o \sqrt{H_o}} \right)^{1/4} \]

where one cannot for one room confirm that the second term
has W or H in the numerator. A term involving $h_K$ should in principle, also be present. It is perhaps of relevance that a term $(W/W_0)^{1/4}$ appears in the equations used in reference (2) for calculating the internal exchange between the lower and upper gas layers in the compartment. The regression co-variances between the dependent terms would need study to resolve this question: a high co-variance between the experimental conditions would reduce the statistical significance of any real effect. We now turn to explore this in greater detail.

**Energy_balance_and_temperature**

Equation (5) is the simplest starting point for an estimate of trends in temperature but it is expressed as a linear sum and we must therefore make a diversion to consider the relation between power laws and linear sums in these correlations of data. If one writes the approximation

$$z = A.x + B.y + D.x^m.y^n$$

(15)

where A, B, D, m and n are constants, we have on writing

$$z = \bar{z} + z' = A\bar{x} + Ax' + B\bar{y} + By'$$

where $\bar{z} = A\bar{x} + B\bar{y}$

$$\ln(\bar{z}) + z'/\bar{z} = \ln D + m.\ln \bar{x} + n.\ln \bar{y} + m.x'/\bar{x} + n.y'/\bar{y}$$

for small departures $x'$, $y'$, $z'$ from the means $\bar{x}$, $\bar{y}$ and $\bar{z}$ respectively. Comparing coefficients of $x'$ and $y'$ gives

$$A/\bar{z} = m/\bar{x}$$

$$B/\bar{z} = n/\bar{y}$$
and

\[ m + n = 1 \quad (16) \]

The relative values of \( m \) and \( n \) reflect the relative importance of the contributions of the two terms \( Ax \) and \( By \).

We write equation (5) as

\[ \dot{Q} \propto (m_0 \theta)^p (h_KA_T\theta)^q \quad (17) \]

where \( p + q \neq 1 \). If we replace \( m_0 \) as in equation (14) we obtain

\[ \dot{Q} \propto \left( \frac{Q}{\sqrt{Q/G}} \right)^{1-p/4} \left( \frac{h_KA_T}{\sqrt{Q/G}} \right)^{(1-p)/4} \left( \frac{A\sqrt{H}}{W} \right)^{p/4} \quad (18) \]

where we now drop the suffix \( o \).

We cannot exactly match the indices actually obtained. The dependence of \( m_0 \) on \( Q \) is weaker than is implied by \( \theta \propto Q^{2/3} \). Even so, it may be noted that for \( p \) equal to \( 2/3 \) the indices of \( A\sqrt{H} \) and of \( (h_KA_T/A\sqrt{H}) \) are as in equation (1) but the index of \( Q \) would be \( 5/6 \) not \( 2/3 \). The range of \( Q \) in the data is \( 7:1 \) so this difference amounts to \( \pm 17\% \) only.

**Conclusion**

One could continue with such numerical exercises but enough has been done to show the plausibility if not the complete consistancy between a simple heat balance and two observed experimental correlations.
It has also been argued that there must be at least three independent variables, not just \( X_1 \) and \( X_2 \), the third variable involving room geometry, the variations of which in these experiments appear not to be large enough in relation to their effects on temperature to produce a significant effect in the regression. The presence of such a third variable would have to be justified statistically in experiments over an appropriate range of condition. There are clearly good reasons for numerically modelling these compartment flows and developing empirical correlations on the basis of a full treatment which should include shapes of compartment (and perhaps opening geometries) beyond the range usually used in experiments, the theory being used to generate "data" for the regression analysis. Preflashover fires are important for domestic and sleeping accommodation. They are also important for industrial and other large spaces and designers must either ignore the advice of the developers of the regression that there are possible limitations to them or further work needs to be done to deal with pressing practical problems.

Appendix

Statistical analysis of dimensionless groups

If we have a power law, for example

\[
Y = x_1^m x_2^n x_3^p
\]  

(1)

and form the hypothesis from physical arguments that the variables \( Y, X_1, X_2, X_3 \) can be arranged in dimensionless groups

e.g. \( Y/x_1^\alpha \), \( X_2/x_1^\beta \) and \( X_3/x_1^\gamma \) then the rearranged equation becomes
from which it follows that

\[ \alpha - n\beta - \gamma p - m = 0 \]  

This null hypothesis can be tested in the statistical analysis: the co-variances between m, n and p are required for this as well as the variances of the separate regression coefficients themselves.

If we extend the argument to consider that Y and some powers of \(X_1\), \(X_2\) and \(X_3\) depend on one dimensionless group only,

\[ Y/\left(X_1^\alpha X_2^\gamma / X_1^\beta \right) = (X_2 X_3^k / X_1^\beta)^\ell \]  

Then \[ Y = X_1^{\alpha - \ell \beta} X_2^{\gamma + \ell} X_3^{k \ell} \]

i.e. \[ m = \alpha - \ell \beta \]  
[6i] \[ n = \gamma + \ell \]  
[6ii] \[ p = k \ell \]  
[6iii]

Eliminating the undefined and undetermined "\(\ell\)" gives two null hypotheses

\[ m - (\alpha - \beta p/k) = 0 \]  
\[ n - (\gamma + p/k) = 0 \]

\(\alpha, \beta, \gamma, k\) and \(\ell\) are part of two separate hypotheses and m, n and p are determined by statistical analysis. Provided only power laws are involved simple physically based dimensionless formulae can be tested easily. Only in a satisfactory outcome should, ideally, the correlation in terms of m, n and p be recast (and re-evaluated).
Reference


It has been generally accepted for a long time that in a conventional ventilation controlled compartment fire the mean fuel consumption rate \( R \) after flash-over is given by /1, 2/

\[
R = k \cdot A \sqrt{H}
\]  

(1)

where

\( A \) is the area of the window or door opening assumed fully open and rectilinear,

and

\( H \) is the height of the opening,

with \( k \) conventionally given by \( 5-6 \text{ kg} \cdot \text{m}^{-5/2} \cdot \text{min}^{-1} \), or, say, \( 0.09 \text{ kg} \cdot \text{m}^{-5/2} \cdot \text{sec}^{-1} \).

There are, however, data that suggest that significantly larger values of \( k \) can be obtained /3, 4, 5, 6/ in some circumstances.

"Ad-hoc" correlations between \( k \) and compartment geometry have been proposed by various authors /7, 8, 9/. These are here briefly reviewed in the light of some recently reported experiments /10/.

Figure (1) reproduces some results obtained in the well known C.I.B. international programme of experiments /5/. The coefficient \( k \) is not constant: the appearance of constancy in equation (1) may be a reflection of the limitations imposed by the practical conditions of laboratory experiments or of
ordinary building design, i.e. a low variance of $A_T/A\sqrt{H}$, where $A_T$ is the total internal surface area of the compartment. This is however, a speculation.

The curve drawn here in Fig. (1) is

$$\frac{R}{A\sqrt{H}} (D/W)^{1/2} = 0.02 \left(\frac{A_T}{A\sqrt{H}}\right)^{1/2}$$  \hspace{1cm} (2)

i.e.

$$R = 0.02 \left(\frac{A_T W}{D \cdot A\sqrt{H}}\right)^{1/2}$$  \hspace{1cm} (3)

where

$W$ is the width of the compartment, parallel to the opening,

and

$D$ is the depth of the compartment, normal to the opening.

The square-root form of equation (3) has become familiar in its inverse form as a well-known relationship for fire resistance /11, 12, 13/. Law herself employs a relationship different from equation (2),

$$k = 0.18(1-\exp(-0.036A_T/A\sqrt{H}))$$  \hspace{1cm} (4)

also shown in Fig. (1), with an upper limit of 0.18 for $k$, well above the range of the data so far discussed. Her relationship and equation (2) are hardly distinguishable in the range of the data.

Saito /7/ has for other data obtained in kg.m.sec.units

$$\frac{R}{A\sqrt{H}} = 0.05 \left(\frac{A_T}{A\sqrt{H}}\right)^{0.2}$$  \hspace{1cm} (5)
Where the floor is, in effect, wholly covered by fuel as in the C.I.B. experiments /5/ the floor area may sometimes be justifiably omitted in evaluating $A_T$. Law did this as did the original report of the C.I.B. work and we here will follow this practice for consistancy.

Correlations by Thomas and Nilsson show a similar trend i.e. indices of $(A_T/A\sqrt{H})$ lie in the range 0.1 to 0.3. Reichel /9/, commenting on equation (5) has quoted a formula in use in Czechoslovakia

$$k = 2.92 \log_{10} (4 \cdot A_T/A\sqrt{H}) \text{ kg} \cdot \text{m}^{-5/2} \cdot \text{min}^{-1}$$

where

$$8.47 > k > 4.25,$$

and has noted the close numerical agreement between the two equations, see Table I.

It is clear that $R/A\sqrt{H}$ is not constant even in ventilation controlled fires.

The recent experiments by Hagen et al were made in two large compartments, one possibly the largest ever built for a room fire experiment, 20.4 m x 7.2 m x 3.6 m high internal dimensions. The smaller compartment was 7.8 m x 7.2 m x 3.6 m.

<table>
<thead>
<tr>
<th>$A_T/A\sqrt{H}$</th>
<th>Equ. (3)</th>
<th>Equ. (6)</th>
<th>Equ. (5)</th>
<th>Equ. (4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C.I.B.</td>
<td>REICHEL</td>
<td>SAITO</td>
<td>LAW</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>0.044</td>
<td>0.06</td>
<td>0.069</td>
<td>0.029</td>
</tr>
<tr>
<td>10</td>
<td>0.063</td>
<td>0.079</td>
<td>0.079</td>
<td>0.054</td>
</tr>
<tr>
<td>20</td>
<td>0.089</td>
<td>0.092</td>
<td>0.091</td>
<td>0.092</td>
</tr>
<tr>
<td>40</td>
<td>0.126</td>
<td>0.107</td>
<td>0.105</td>
<td>0.137</td>
</tr>
</tbody>
</table>
TABLE I  Continuing

<table>
<thead>
<tr>
<th>Value</th>
<th>k</th>
<th>C.I.B. data (equ. (2))</th>
<th>Saito's equation (equ. (5))</th>
<th>Reichel's equation (equ. (6))</th>
<th>Experiments by Hagen et al /9/</th>
<th>Conventional value</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>0.141</td>
<td>0.13---0.22</td>
<td>0.14---0.17</td>
<td>0.11---0.15</td>
<td>0.47</td>
<td>0.09---0.10</td>
</tr>
<tr>
<td>100</td>
<td>0.200</td>
<td>0.112---0.15</td>
<td>0.14---0.17</td>
<td>0.11---0.15</td>
<td>0.10</td>
<td>0.09---0.10</td>
</tr>
<tr>
<td>200</td>
<td>0.28</td>
<td>0.143---0.17</td>
<td>0.11---0.15</td>
<td>0.10</td>
<td>0.10</td>
<td></td>
</tr>
<tr>
<td>400</td>
<td>0.40</td>
<td>0.155---0.17</td>
<td>0.10---0.13</td>
<td>0.10---0.13</td>
<td>0.10---0.13</td>
<td></td>
</tr>
</tbody>
</table>

In view of the differences between maximum burning rates and mean rates, secondary effects of fuel surface area, amounts of fuel etc, the results of Hagen et al for the larger compartment tend to support the extrapolation of the C.I.B. data.
but their results for the smaller one show a lesser effect of \( \frac{A_T}{A\sqrt{H}} \) than implied by the C.I.B. data or by the correlations of Saito and Reichel.

Hagen et al draw attention to a feature of the \( R-A\sqrt{H} \) relationship. In their experiments \( R \) reaches a peak value which is followed by a decrease of about \( 1/4 \) to \( 1/3 \). Conventionally the peak value is the transition between the ventilation and fuel controlled regimes but conventionally the rate remains at the peak value in the fuel controlled regime. However a decrease in the rate of mass loss has been reported for both cellulosic /8/ and non-cellulosic fuels /14, 15/, as has the tentative explanation offered by Hagen et al, viz. "radiation enhancement".

They rightly emphasize that this feedback enhancement produces excess fuel which can only burn outside the compartment and which necessarily cools the fire!

The conventional value of 0.1 for \( k \) implies a fuel/air ratio of 0.2 but the experimental value of 0.47 implies that unburnt fuel is a major term in the energy balance and in the mass balance. One would expect some "choking" of the air inlet by the extra outflow and hence a reduction in the production of energy by combustion inside the compartment. This offsets the effects of radiation enhancement.

Clearly there may be need for further discussion of fully-developed fires in compartments with values of \( \frac{A_T}{A\sqrt{H}} \) higher than have been the basis for the conventional view if this is to be applied in design.
REFERENCES


[9] Reichel, V., Personal communication. See also Czech National Standard No 73 0804


\[
\frac{\Delta T}{100} = \left( \frac{Q}{1000} \right)^{2/3} \times 5.4
\]
• and (x) Anderssons data

○ Quintiere-McCaffrey data
The numbers at each data point e.g. refer to the test nr. in reference 1.

Flame heights above seat (c.0.4m above flow)

Q_{kw}

Fig. 5
Fig (2). Fire spread along bed (Andersson)

Test (3) of reference (1)

Mean rate $\approx 4$mm/sec
Fig (1). Comparison of some fire spread data and exponential rate (Andersson)

\[ R = 0.042 \ e^{0.01t} \]