Some Notes on Fires in Compartments

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1 THE BEHAVIOUR OF POLYURETHANE MATTRESSES AS AN INPUT TO THE HARVARD CODE

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 apparant 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 (I) 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 regarding 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

viz $$R = 0.042\ e^{0.01t} \text{ metres} \qquad (1)$$

from which $$dR/dt = 0.42\ e^{0.01t} \text{ mm/s} \qquad (2)$$

is a good description of the spread. However, it is quite apparant 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. Babrauskas 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,

viz, $$m' = 8.95 \times 10^{-6}\, e^{t/30.7}\ \text{kg/s}$$

give a mass loss in 170 seconds of $30.7 \times 8.95 \times 10^{-6}$ $(e^{170/30.7}-1)$ 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).

viz, $$I = \rho . \Delta H . R \qquad (3)$$

where R is the spread rate

ΔH is the enthalpy rise required for ignition

ρ is the density of the material heated to ignition

and I the forward heat flux.

Equation (3) contains <u>two</u> unknown quantites, R & ρ. For our purpose it is sufficient to write

$$\Delta H = c\, \theta_i$$

where θ_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 ρ 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 ρ = 35 kg/m^3, c approx 1 kJ/kg, θ_i say 300^o and the measured mean rate of spread of 2,0 mm/s for the unmade up mattress, a forward heat flux of 210 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

[1] Andersson, B., "Fire Behaviour of Beds & Upholstered Furniture - an Experimental Study, Pt. 1." Division of Building Fire Safety & Technology. Report LUTVGD/(TVBB-3023) Lund, Sweden 1985.

[2] Mitler, H., "The Physical Basis for the Harvard Computer Fire Code" Harvard Univ. Oct. 1978

[3] Orloff, L., "Preliminary Testing of a Polyurethane Slab", Factory Mutual Research Corporation, May 23 1977.

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

[5] Babrauskas, V. & Krasny, J., "Fire Behaviour of Upholstered Furniture" N.B.S. Monograph 173 U.S. Dept. of Commerce (1985)

[6] Mizuno, T., Sasagawa, F., Horiuchi, S. & Kawagoe, K., Fire Sci.&Tech. (1981) 1 33.

[7] Thomas, P.H., Forestry (1967) 40 (2) 139.

TABLE 1

Time (min - sec)	Diameter of Burning Area '2R' (metres)
1 - 10	0.2
2 - 0	0.3
3 - 0	0.4
3 - 40	0.5
4 - 0	0.6
	Flame front reaches a distance from head of mattress metre (Linear spread)
9 - 25	1.1
10 - 15	1.2
10 - 20	1.3
11 - 30	Flame under mattress
12	1.4
12 - 30	1.5
13	1.6

Between 4 and 9 minutes the burning area reaches the sides of the mattress and reestablishes itself as a spread along the mattress.

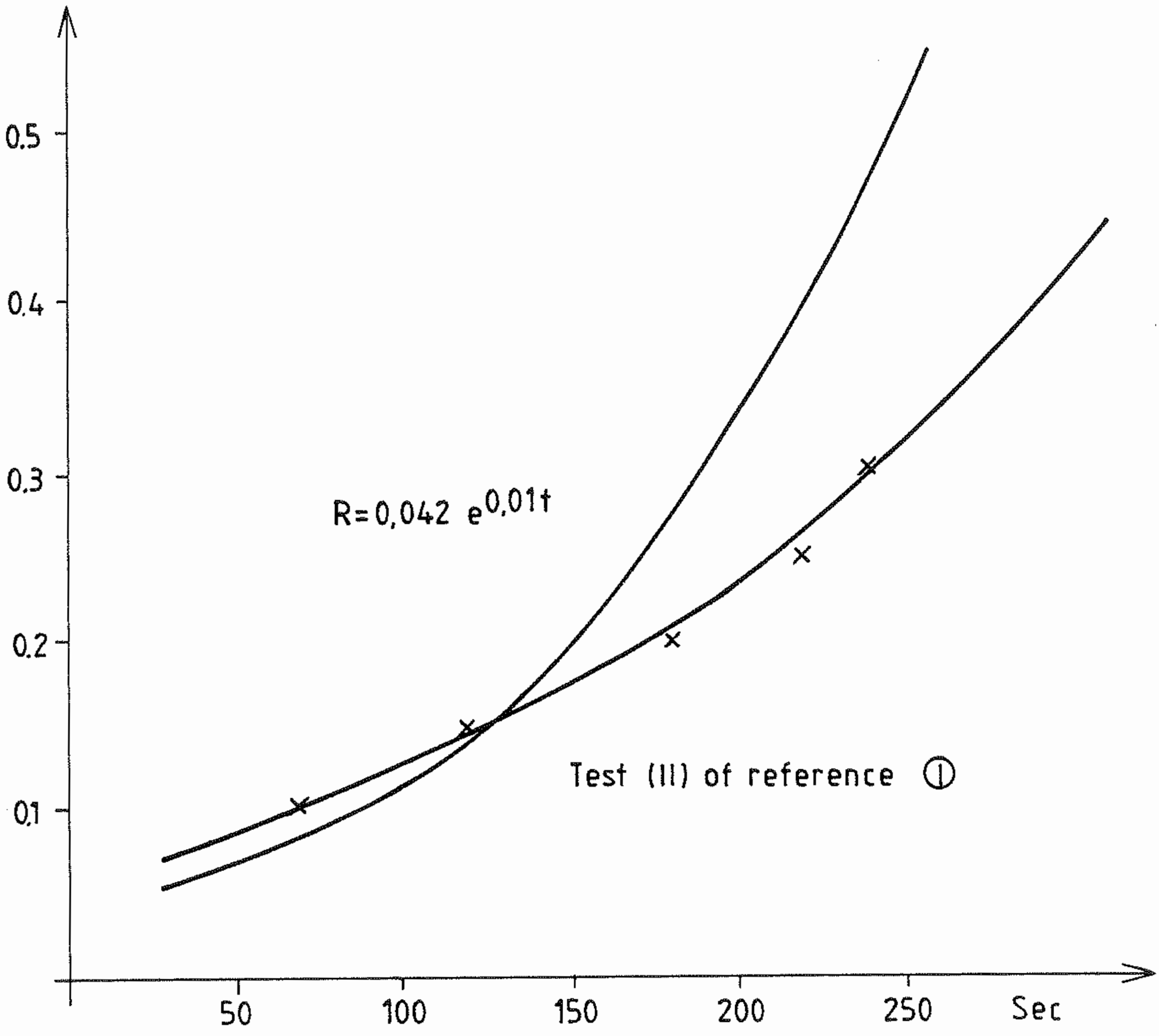


Fig (I). Comparison of some fire spread data and exponential rate (Andersson)

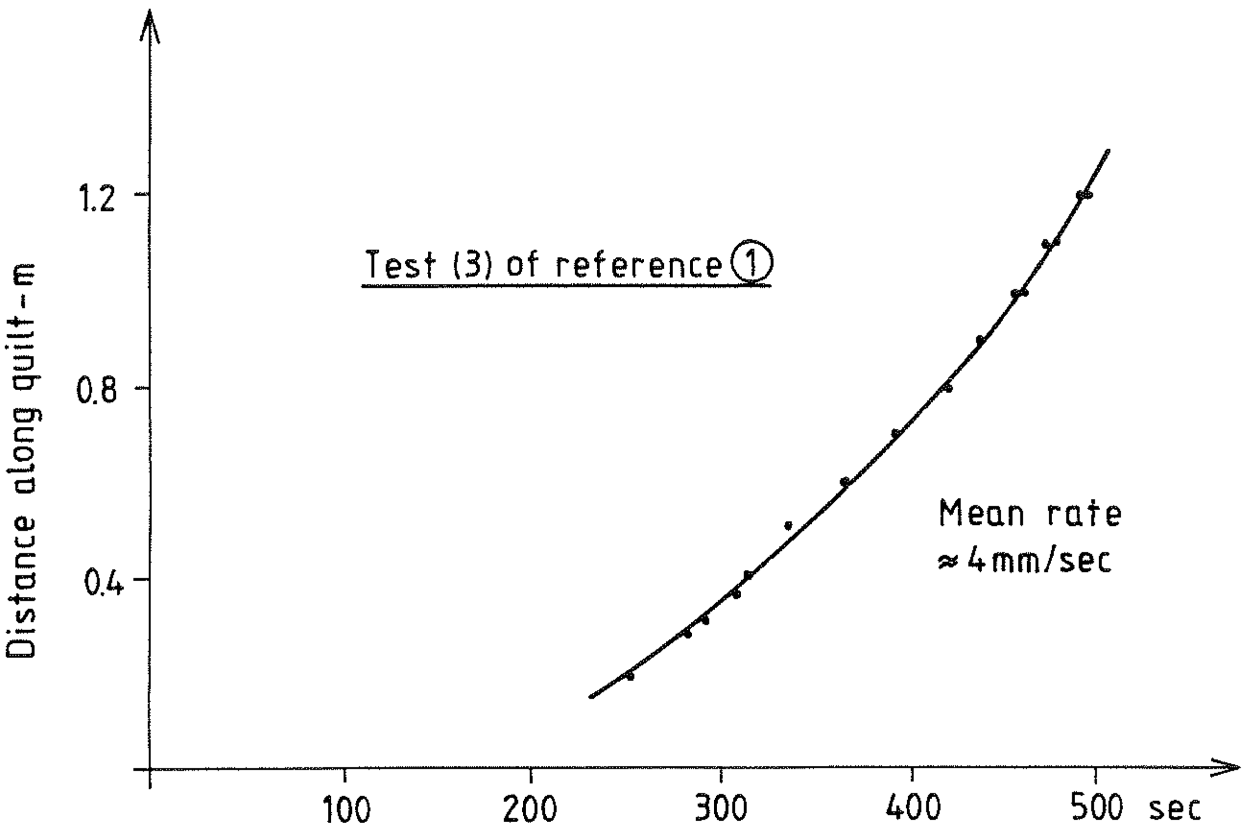


Fig (2). Fire spread along bed
(Andersson)

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^{o}C indicating flashover was immanent. 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^{o}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 <u>mean</u> 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 T_g 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 heatflux to the floor "E" and "Q" the energy release rate. A satisfactory approximation to $T^4 - T_o^4$ over the ranges $0.7 < \frac{T}{T_o} < 3.0$ viz approx 200^oC to 600^oC (the limit of preflashover fires) is

$$T^4 - T_o^4 \doteqdot 15\ T_o^4 \left(\frac{T-T_o}{T_o}\right)^{2.5} \qquad (1)$$

Using McCaffrey and Quintiere's correlation (4) viz

$$T-T_o = \Delta T = 6.85\ Q^{2/3}/(h_K A_T A\sqrt{H})^{1/3} \qquad (2)$$

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)

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

$$= 420 \times 10^{-6}\ Q^{1.67}\ (h_K A_T A\sqrt{H})^{-0.835} \qquad (3)$$

The mean best value of $(h_K A_T A\sqrt{H})^{1/3}$ 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

$$E = 230 \times 10^{-6} \cdot Q^{1.67} = 53 \times 10^{-2} \left(\frac{Q}{100}\right)^{1.67} \qquad (4)$$

TABLE I <u>Andersson's data</u>

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

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 seams 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

$$E \sim Q^{1.67} \qquad (5)$$

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

TABLE 2 Quintiere and McCaffreys data p 28/29 of ref (2).

M_v	ΔH	Q_{kW}	E_{kW/m^2}	100E/Q	ΔT
5.08		76	1.53	2.01	157
5.10		76.5	1.48	1.94	151
11.86	15.0	178	2.48	1.39	243
20.14		302	5.43	1.80	328
28.64		430	10.01	2.34	416

TABLE 2 Continuing

6.98		161	3.81	2.37	212
20.19		k465	10.4	2.31	366
33.02	23	760	23.9	3.14	682
35.29		813	28.6	3.51	794
11.94		179	4.2	2.35	288
18.73	15	282	5.8	2.06	356
28.28		425	10.1	2.36	424
15.42		355	10	2.82	386
25.02	23	577	23.9	4.15	680
11.27		169	4.3	2.54	319
24.28	15	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	23	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

$$F_{flame} \doteqdot \frac{f.Q.H}{4\pi(R^2+H^2)^{3/2}} \qquad (6i)$$

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.

$$E_{total} \doteqdot bQ + aQ^{1.67} \qquad (6ii)$$

Hence $E/Q = b + aQ^{0.67}$

We therefore expect $E/Q \longrightarrow f/4\pi H^2$ as $Q \longrightarrow 0$

For $H \approx 1$ m and $R = 0$, $f \approx 0.3$ we have $100\ E/Q \approx 5\ m^{-2}$, 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 Anderssons 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

$$Z_f = 0.08\ Q^{2/5} \qquad (7)$$

for the "solid" lowest zone of flame and

$$Z_f = 0.2\ Q^{2/5} \qquad (8)$$

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

Relativly 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 term 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 futher 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_{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

[1] Andersson, Berit, Fire Behaviour of Beds and Upholstered Furniture - An Experimental Study, Part I, Lund Institute of Technology, Lund, Sweden, Report LUTVDG/TVBB 3023 (1985)

[2] Quintiere, J.G. and McCaffrey, B.J., The Burning of Wood and Plastic Cribs in an Enclosure, Vol I, National Bureau of Standards, Washington DC, NBS IR 80-2054 (1980)

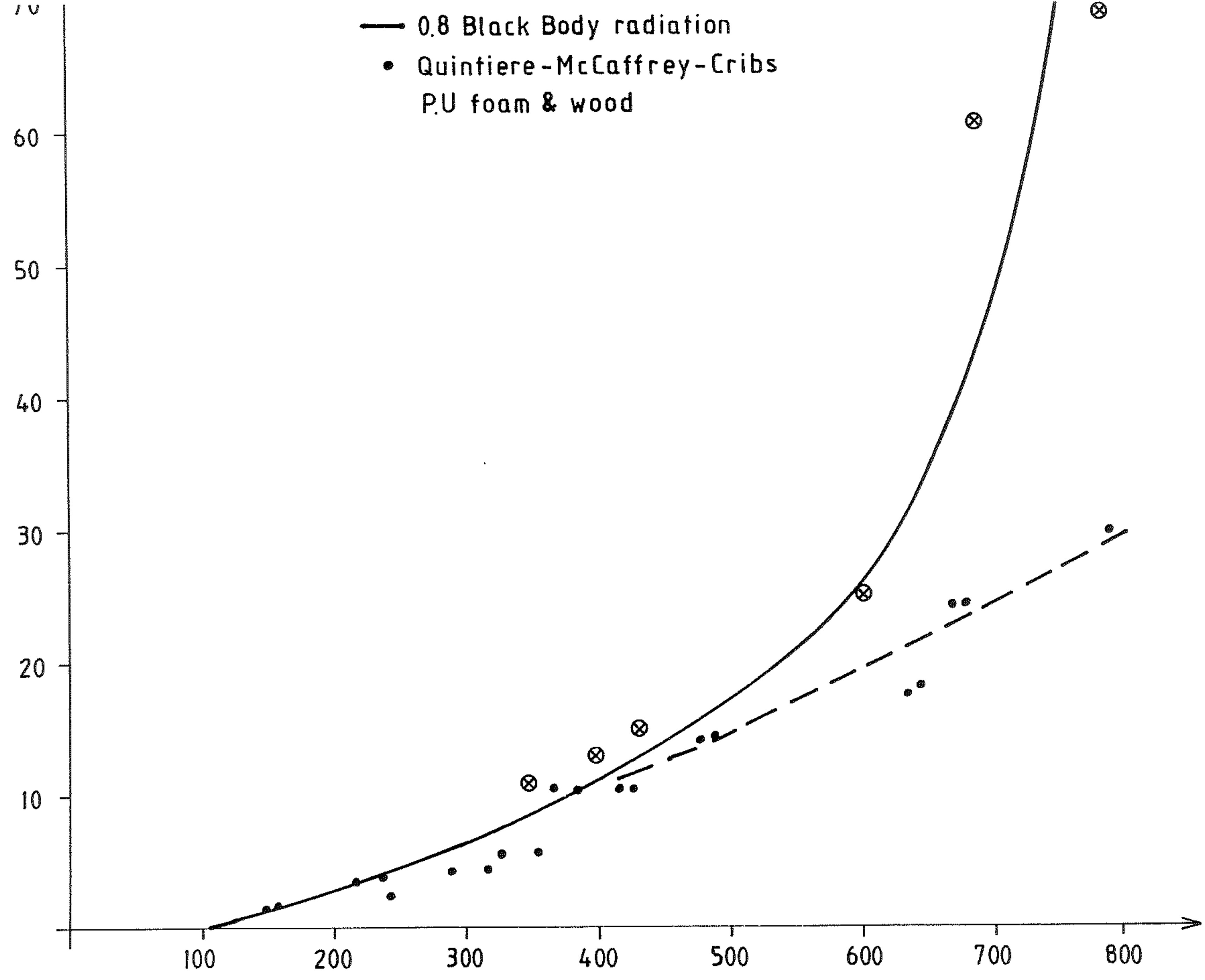
[3] Modak, A., Radiation from Products of Combustion, Factory Mutual Research Corporation, Norwood, Mass. FMRS 5I.OAOE6 BU-1, (Oct 1975)

[4] McCaffrey, B.J., Quintiere, J.G. and Harklerod, M.F., Fire Technology 17-2 (1981) p 98

[5] McCaffrey, B.J., Purely Bouyant Diffusion Flames: some experimental Results (1979), National Bureau of Standards NBSIR 79-1910

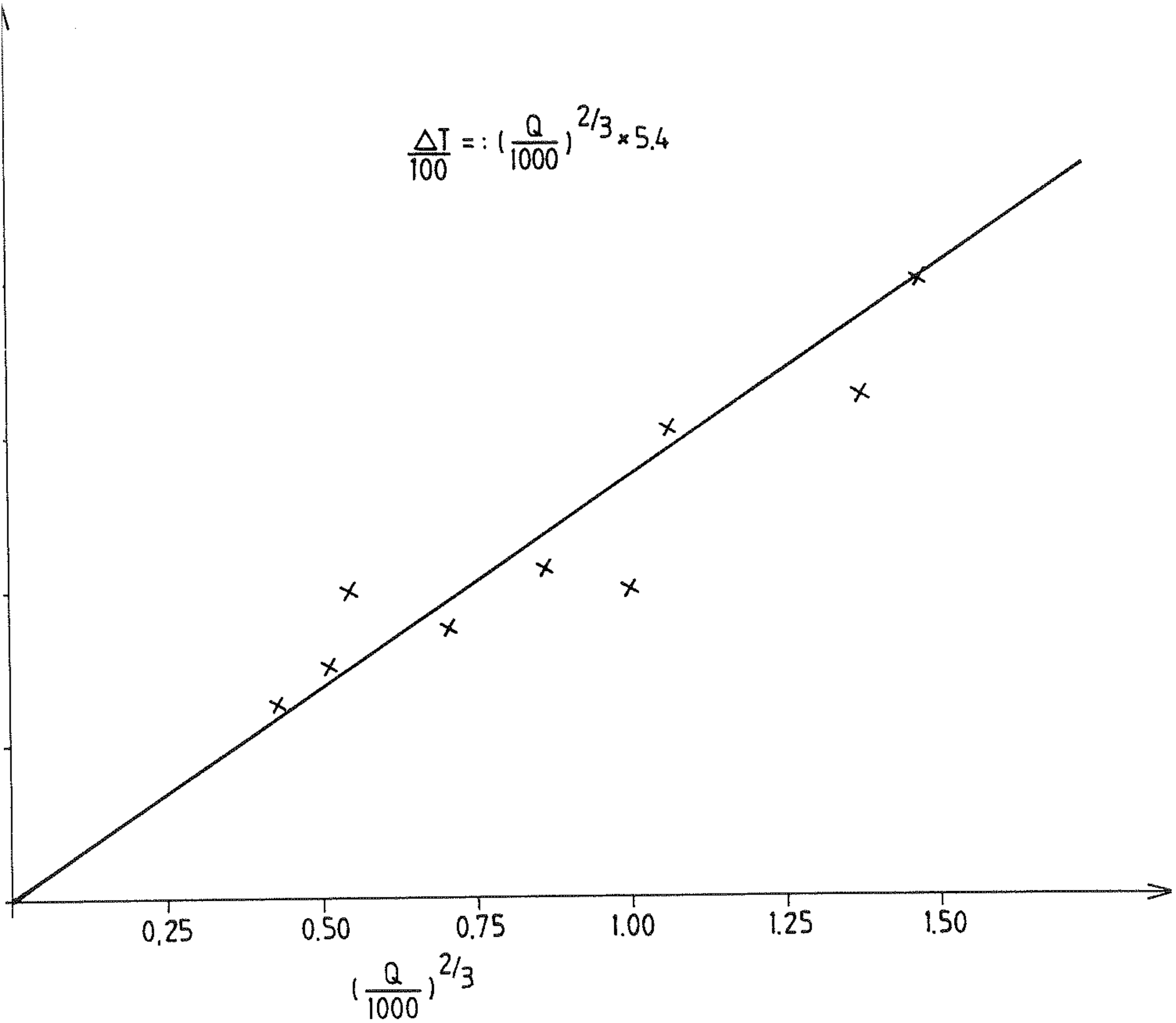
[6] Thomas, P.H., 9th Symposium (International) on Combustion, Combustion Institute

[7] Thomas, P.H., The Burning Behaviour of Mattresses etc, Lund Univeristy (1987)



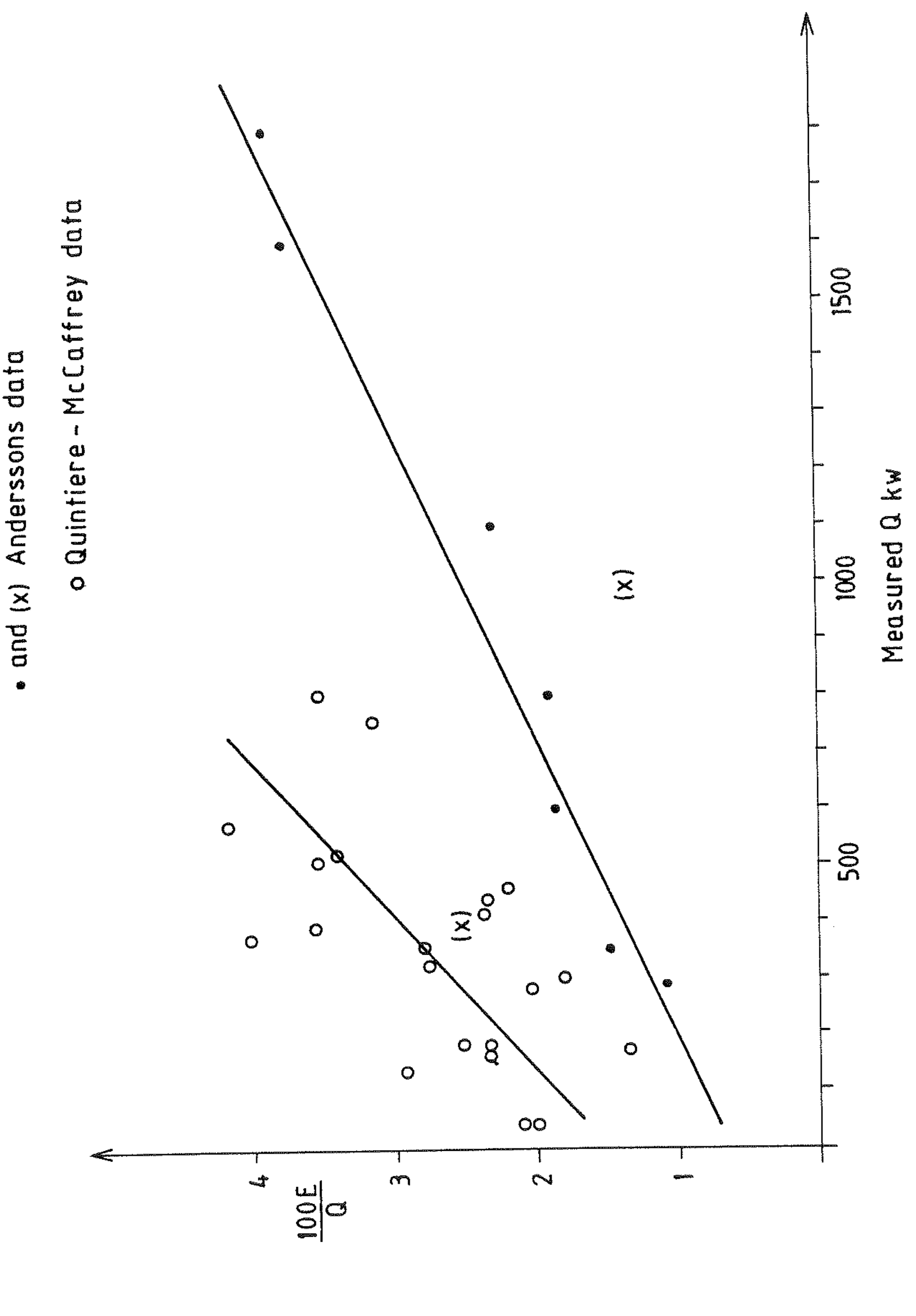
0.8 Black Body radiation
Quintiere-McCaffrey-Cribs
P.U foam & wood
60
50
40
30
20
10
100
200
300
400
500
600
700
800

Fig.1



$\frac{\Delta T}{100} =: \left(\frac{Q}{1000}\right)^{2/3} \times 5.4$
0,25
0.50
0.75
1.00
1.25
1.50
$\left(\frac{Q}{1000}\right)^{2/3}$

Fig. 2



• and (x) Anderssons data
o Quintiere - McCaffrey data
100E / Q
4
3
2
1
(x)
(x)
500
1000
1500
Measured Q kw

Fig. 3

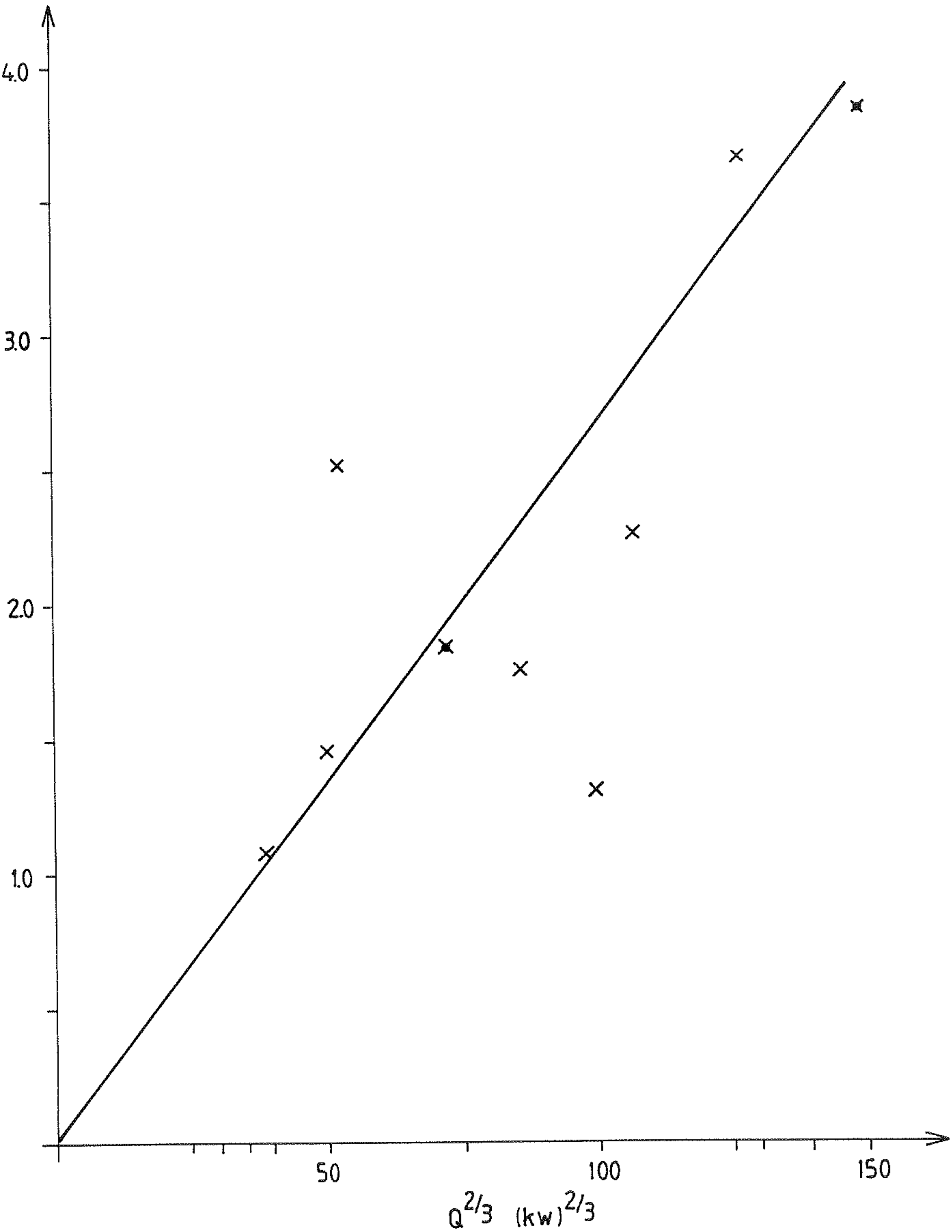
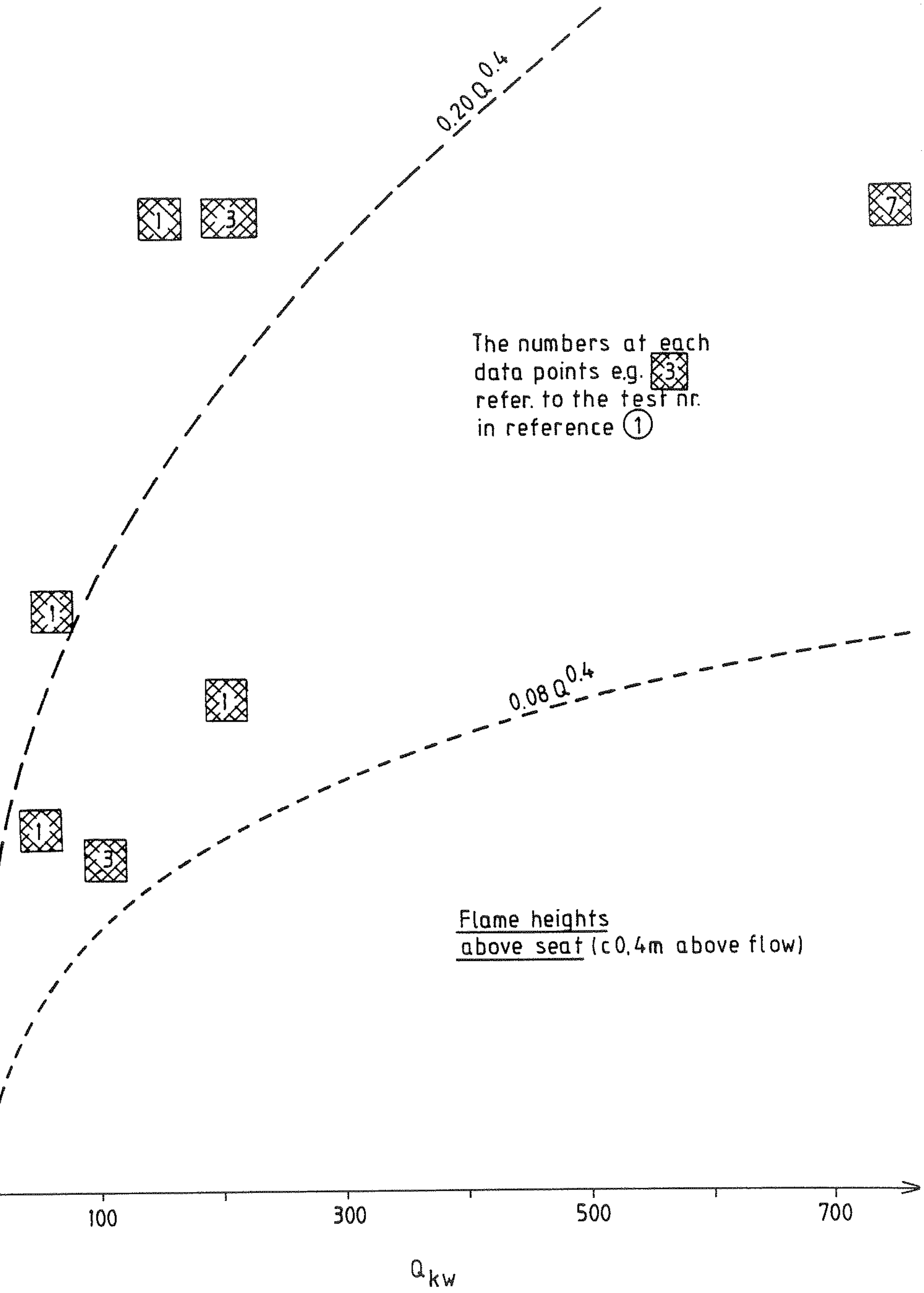


Fig. 4



0.20 Q 0.4
1
3
7
The numbers at each
data points e.g. 3
refer. to the test nr.
in reference 1
1
0.08 Q 0.4
1
1
3
Flame heights
above seat (c 0,4m above flow)
100
300
500
700
Q kW

Fig. 5

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

$$\theta/T_o = 1.6\ X_1^{2/3}\ X_2^{-1/3} \qquad (1)$$

where T_o is the absolute ambient temperature

X_1 is $\dot{Q}/A_o\sqrt{gH_o}\ \rho c\ T_o$ (2)

X_2 is $h_K A_T/A_o\sqrt{gH_o}\rho c$ (3)

Q is the rate of energy (heat) release

h_K is the effective heat transfer with respect to ambient temperature.

A_o is the area of opening

g is the acceleration due to gravity

ρ 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_o is the opening height.

It is dimensionless but not obviously complete.

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

$$\theta = 6.85\ \dot{Q}^{2/3}\ [A_o\ \sqrt{H_o}\ A_T \cdot h_K]^{-1/3} \tag{4}$$

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

$$(m_a c + h_K A_T)\ \theta = \dot{Q} \tag{5}$$

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

$$m_a\ \alpha\ m_v^{\ 1/4}\ (A_o\sqrt{gH_o})^{1/2} \tag{6}$$

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

$$\theta \sim \frac{Q^{2/3}}{H_o^{5/3}} \left[\frac{H_o^2}{A_o}\right]^{1/5} \tag{7}$$

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

$$\text{Hence } \theta \sim \left[\frac{Q}{A_o\sqrt{H_o}}\right]^{2/3} \left[\frac{A_o}{H_o^2}\right]^{7/15} \tag{8}$$

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

$$\theta \sim \left[\frac{Q}{A_o\sqrt{H_o}}\right]^{2/3} \left[\frac{A_o}{H_o^2}\right]^{1/2} \tag{9}$$

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

$$\left[\frac{A_o}{H_o^2}\right]^{1/2} \quad \text{and} \quad \left[\frac{h_K\ A_T}{A_o\sqrt{H_o}}\right]^{-1/2}$$

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

If A_o 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

$$m_a \sim Q^{1/4} \, (A_o \sqrt{gH_o})^{1/2} \qquad (10)$$

where m_v 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

$$\left[\frac{gQ}{\rho c T_o h}\right]^{1/3}$$

and, because we expect the mean flow in the compartment to be relevant, we assume that the relevant dimensionless ratio is the ratio of $(g\, Q/\rho c T_o h)^{1/3}$ 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,

$$\frac{m_a}{\rho A_o \sqrt{gH_o}} = F\{(\frac{gQ}{\rho c T_o h})^{1/3}/(A_o \; \sqrt{gH_o}/hW)\} \qquad (11)$$

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

$$m_a/\rho A_o\sqrt{gH_o} = F\ \{Q/\rho cT_oA_o\sqrt{gH_o} \cdot \frac{A_o}{H_o^2} \cdot \frac{H_o}{H}\} \qquad (12)$$

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

$$\text{viz. } m_a\ \alpha\ A_o\sqrt{H_o}\ (Q/A_o\sqrt{gH_o})^{\alpha}\ (\frac{H_o^2}{A_o})^{\beta}\ (\frac{H_o}{H})^{\gamma} \qquad (13)$$

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

$$\rho\ \frac{m_a}{A_o\sqrt{gH_o}} \sim (\frac{Q}{A_o\sqrt{H_o}})^{1/4}\ (\frac{W^{5/2}}{A_o\sqrt{H_o}})^{1/4} \qquad (14)$$

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 $(W/W_o)^{1/4}$ appears in the equations used in reference (2) for calculating the internal exchange between the lower and upper gaslayers 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

$$z = A.x + B.y \doteqdot D.x^m.y^n \qquad (15)$$

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

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

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

$$\mathrm{Ln}\ (\overline{z}) + z'/\overline{z} \doteqdot \mathrm{Ln}\ D + m.\mathrm{Ln}\ \overline{x} + n.\mathrm{Ln}\ \overline{y} + m.x'/\overline{x} + n.y'/\overline{y}$$

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

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

$$B/\overline{z} = n/\overline{y}$$

and

$$m + n = 1 \tag{16}$$

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

$$\dot{Q} \; \alpha (m_a \; \theta)^p \; (h_K A_T \theta)^q \tag{17}$$

where $p + q \doteqdot 1$. If we replace m_a as in equation (14) we obtain

$$\text{i.e. } \theta \; \alpha \left[\frac{Q}{A\sqrt{H}}\right]^{1-p/4} \left[\frac{hA_T}{A\sqrt{H}}\right]^{-(1-p)} \left[\frac{A\sqrt{H}}{W^{5/2}}\right]^{p/4} \tag{18}$$

where we now drop the suffix o.

We cannot exactly match the indices actually obtained. The dependance of m_a on Q is weaker than is implied by $\theta \; \alpha \; Q^{2/3}$. Even so, it may be noted that for p equal to 2/3 the indices of $A\sqrt{H}$ and of $(h_K A_T/A\sqrt{H})$ 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

$$Y = X_1^m . X_2^n . X_3^p \qquad (1)$$

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^α, X_2/X_1^β and X_3/X_1^γ then the rearranged equation becomes

$$Y/X_1^{\alpha} = (X_2/X_1^{\beta})^n \; (X_3/X_1^{\gamma})^p \tag{2}$$

from which it follows that

$$\alpha - n\beta - \gamma p - m = 0 \tag{3}$$

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,

$$\text{e.g. } Y/(X_1^{\alpha}.X_2^{\gamma}) = (X_2X_3^k/X_1^{\beta})^{\ell} \tag{4}$$

$$\text{Then } Y = X_1^{\alpha-\ell\beta} \; X_2^{\gamma+\ell} \; X_3^{k\ell} \tag{5}$$

$$\text{i.e. } m = \alpha-\ell\beta \tag{6i}$$
$$n = \gamma+\ell \tag{6ii}$$
$$p = k\ell \tag{6iii}$$

Eliminating the undefined and undetermined "ℓ" gives two null hypotheses

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

α, β, γ, k and ℓ are part of two separate hyptheses and m, n and p are determined by statistical analysis. Provided only power laws are involved simple physically based dimensionless formulaes 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

[1] McCaffrey, B.J., Quintiere, J.G. and Harkleroad, M.F., Fire Technology 17.2 1981 p 98

[2] Quintiere, J.G., McCaffrey, B.J., The Burning of Wood and Plastic Cribs in an Enclosure, Vol 1, National Bureau of Standards, NBSIR 80-2054, Nov 1980

4 ON FULLY DEVELOPED FIRES IN LARGE COMPARTMENTS

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/

$$R = k \cdot A\sqrt{H} \tag{1}$$

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 $kg \cdot m^{-5/2} \cdot min^{-1}$, or, say, 0.09 $kg \cdot m^{-5/2} \cdot sec^{-1}$.

There are, however, data that suggest that significally 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

$$R/A\sqrt{H}_t \ (D/W)^{1/2} = 0.02 \ (A_T/A\sqrt{H})^{1/2} \qquad (2)$$

i.e.

$$R = 0.02 \ (A_T W/D \cdot A\sqrt{H})^{1/2} \qquad (3)$$

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),

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

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

$$R/A\sqrt{H} = 0.05 \ (A_T/A\sqrt{H})^{0.2} \qquad (5)$$

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

$$k = 2.92 \; \mathrm{Log}_{10} \; (4 \cdot A_T/A\sqrt{H}) \; \mathrm{kg} \cdot \mathrm{m}^{-5/2} \cdot \mathrm{min}^{-1} \qquad (6)$$

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 I Values of k in k•m•s. A comparison of correlations between $R/A\sqrt{H}$ and $(A_T/A\sqrt{H})$ (D=W=1)

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

TABLE I Continuing

50	0.141	0.112	0.109	0.150
100	0.200	0.126	0.125	0.176
200	0.28	0.143	0.144	0.18
400	0.40	0.155	0.165	0.18

Their results for the larger compartment gave values of k far in excess of the conventional value of 6 kg $\cdot$ $m^{-5/2}$ $\cdot$ min^{-1}. For the lowest values of opening factor $A\sqrt{H}$ viz. 1.06 and 3 $m^{5.2}$ they quote 28 kg $\cdot$ $m^{5/2}$ $\cdot$ min^{-1} i.e. 0.47 kg $\cdot$ $m^{-5/2}$ $\cdot$ s^{-1}. The lower values for A_T (those excluding the floor) are respectively 370 m^2 and 162 m^2, the higher ones being 535 m^2 and 220 m^2 respectively.

TABLE II The values of k predicted from the above equations for the experiments of Hagen et al together with the experimental values themselves

Predicted values	Large compartment	Small compartment
Extrapolation of C.I.B. C.I.B. data (equ. (2))	0.37---0.82	0.13---0.22
Saito's equation (equ. (5))	0.14---0.17	0.11---0.13
Reichel's equation (equ. (6))	0.11---0.15	0.10---0.13
Experiments by Hagen et al /9/	0.47	0.10
Conventional value	0.09---0.10	0.09---0.10

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 $(A_T/A\sqrt{H})$ 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 $(A_T/A\sqrt{H})$ higher than have been the basis for the conventional view if this is to be applied in design.

REFERENCES

[1] Kawagoe, K., Fire behaviour in rooms. Japanese Ministry of Construction, Building Research Institute, Report No 27, 1958

[2] Thomas, P.H., Heselden, A.J.M. and Law, Margaret,, Fully-developed compartment fires. Two kinds of behaviour. Fire Research Technical Paper No 18 London, 1967. HM Stationery Office

[3] Gross, D. and Robertson, A.F., Experimental fires in enclosures. 10th Symposium (Internat.) on Combustion. Pittsburgh, 1965. The Combustion Institute, pp 931-42

[4] Salzburg, F. and Waterman, T.E., Fire Technology (1966)2 196

[5] Thomas, P.H. and Heselden, A.J.M., Fully-developed fires in single compartments: A co-operative research programme of the Conseil International du Batiment. (C.I.B. Report No 20) Joint Fire Research Organisation Fire Research Note 923 (1973)

[6] Magnusson, S.E. and Thelandersson, S., Comments on the Rate of Gas Flow and Rate of Burning for Fires in Enclosures. Division of Structural Mechanics and Concrete Construction, Lund Institute of Technology, Lund, Sweden. Bulletin 19, 1971

[7] Saito, F., Experimental Study of Compartment Fires using Model Boxes. Building Research Institute, Tokyo, Japan. Research Note 81, 1979

[8] Thomas, P and Nilsson, L., Fire Research Station, Borehamwood, Herts., England. Fire Research Note No 979, 1973

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

[10] Hagen, E., Kordina, K. and Haksever, A., A Contribution to the Flame Spread and the Heat Release in Compartments of Various Size. International Meeting of Fire Research and Test Centres ITSEMAP, Avila, Spain, October 1986

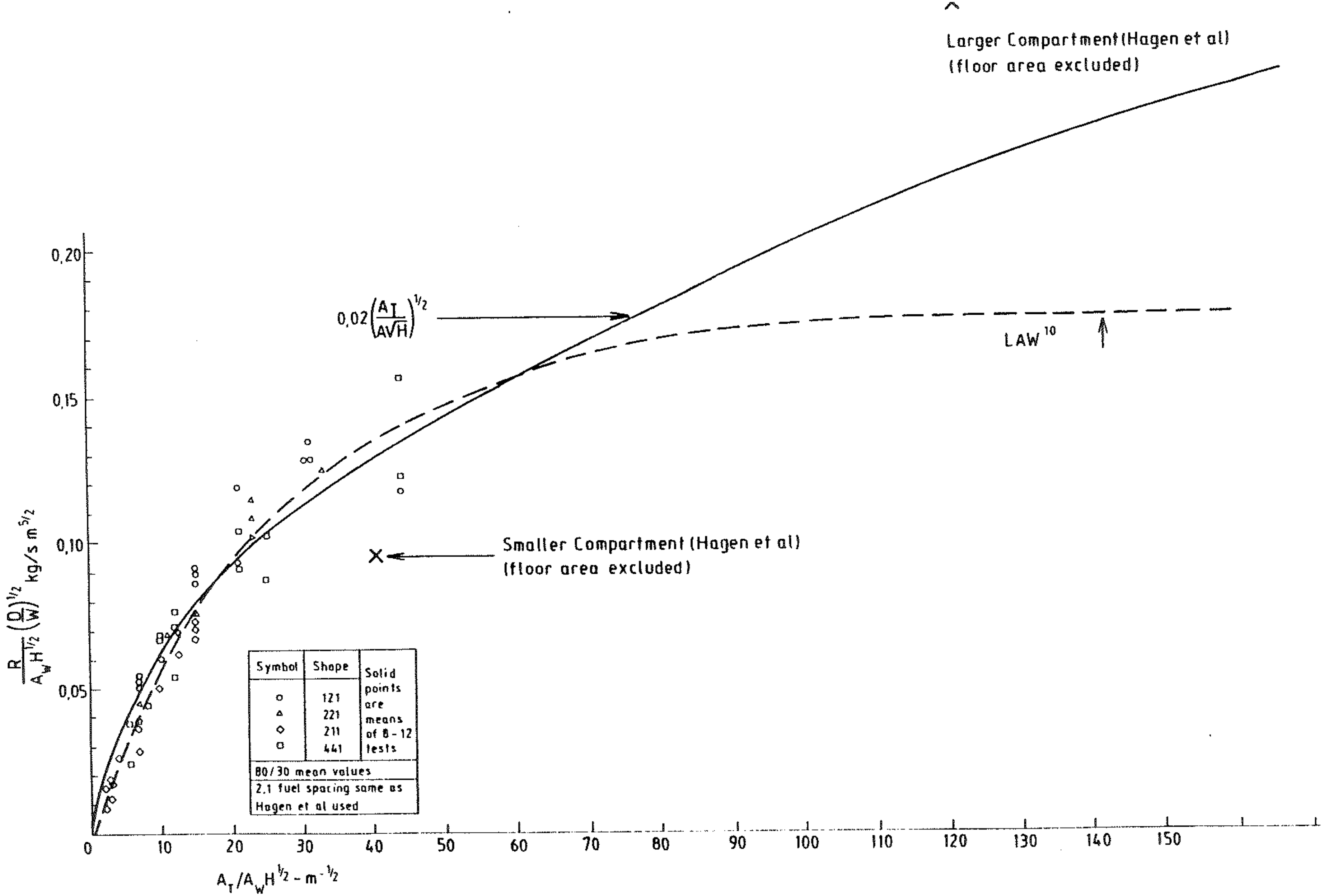
[11] Law, Margaret., A relationship between fire grading and building design and contents. Joint Fire Research Organization, Borehamwood. Fire Research Note 877/1971

[12] Thomas, P.H., The Fire Resistance Required to Survive a Burn-out idem, Fire Research Note No 901, 1970

[13] Pettersson, O., Need for and Some Remarks on Internationally Standardized Fire Test Procedures. Division of Structural Mechanics and Concrete Construction, Lund Institute of Technology, Lund, Sweden. Bulletin 41, 1974

[14] Friedman, R., Proc. Int. Symposium on the Fire Safety of Combustible Materials. Univ. of Edinburgh, October 1975, p. 100

[15] Bullen, M. and Thomas, P.H., 17th Symposium (Internat.) *on Combustion*. The Combustion Institute, Leeds, 1978, p. 1139



Larger Compartment (Hagen et al)
(floor area excluded)
$0{,}02\left(\frac{A_T}{A\sqrt{H}}\right)^{1/2}$
LAW 10
Smaller Compartment (Hagen et al)
(floor area excluded)
$\frac{R}{A_W H^{1/2}}\left(\frac{D}{W}\right)^{1/2}$ kg/s m$^{5/2}$
0,20
0,15
0,10
0,05
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
$A_T/A_W H^{1/2}$ - m$^{-1/2}$
Symbol
Shape
121
221
211
441
Solid points are means of 8 - 12 tests
80/30 mean values
2,1 fuel spacing same as Hagen et al used

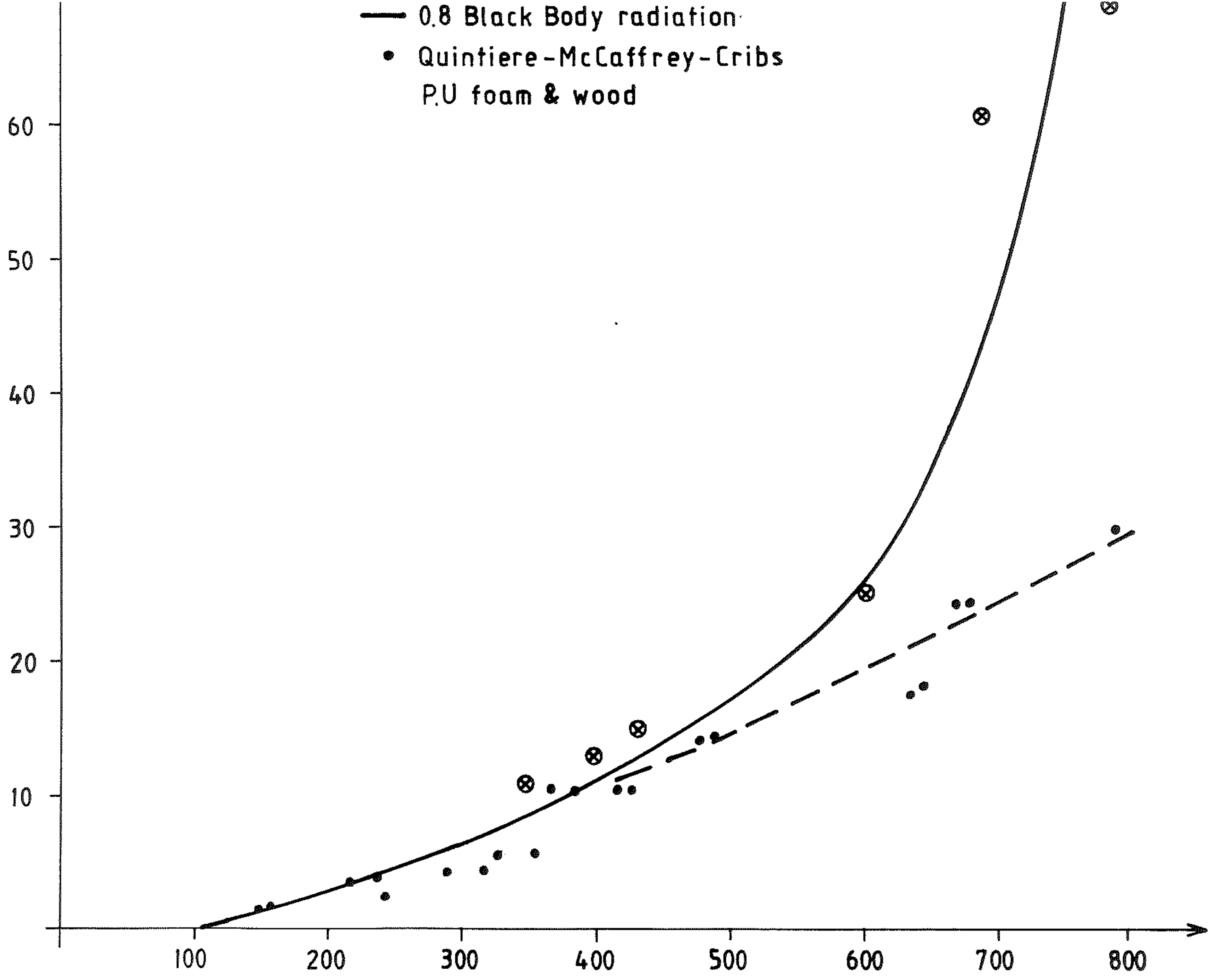
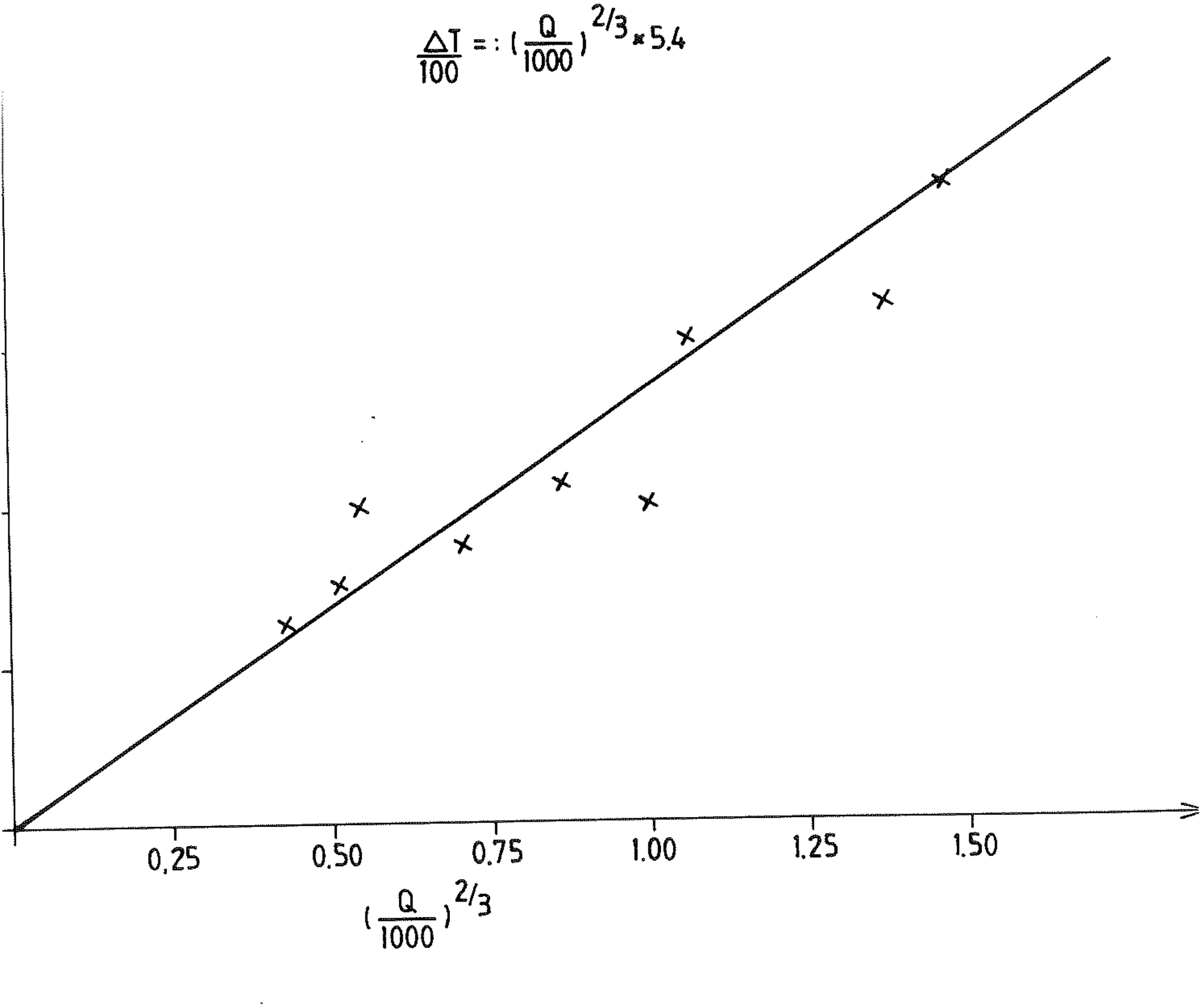
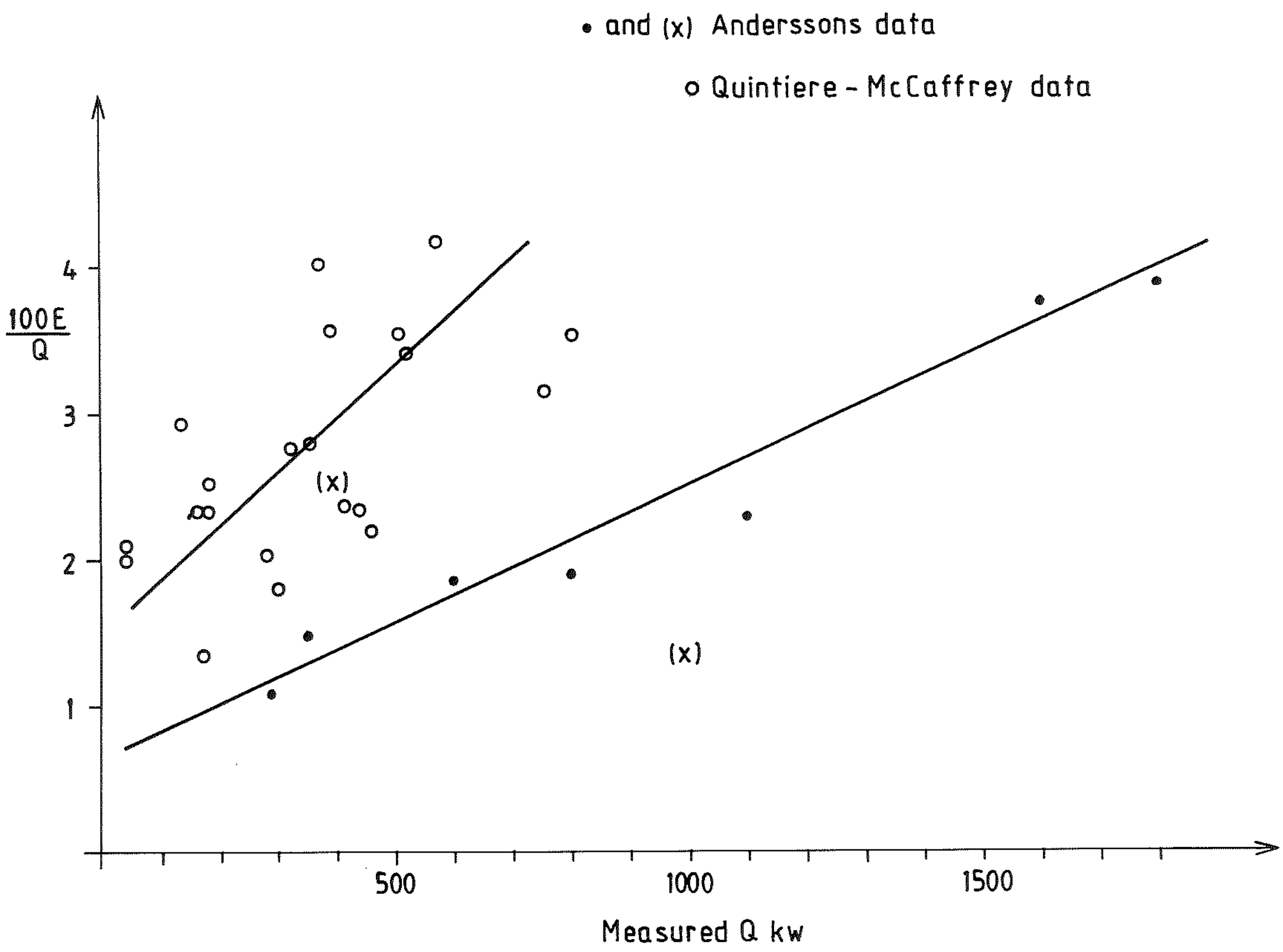

0.8 Black Body radiation
Quintiere-McCaffrey-Cribs
P.U foam & wood
60
50
40
30
20
10
100
200
300
400
500
600
700
800

Fig. 1



$\frac{\Delta T}{100} =: (\frac{Q}{1000})^{2/3} \times 5.4$
0,25
0,50
0,75
1,00
1,25
1,50
$(\frac{Q}{1000})^{2/3}$

Fig. 2



• and (x) Anderssons data
o Quintiere - McCaffrey data
100E / Q
4
3
2
1
(x)
(x)
500
1000
1500
Measured Q kw

Fig. 3

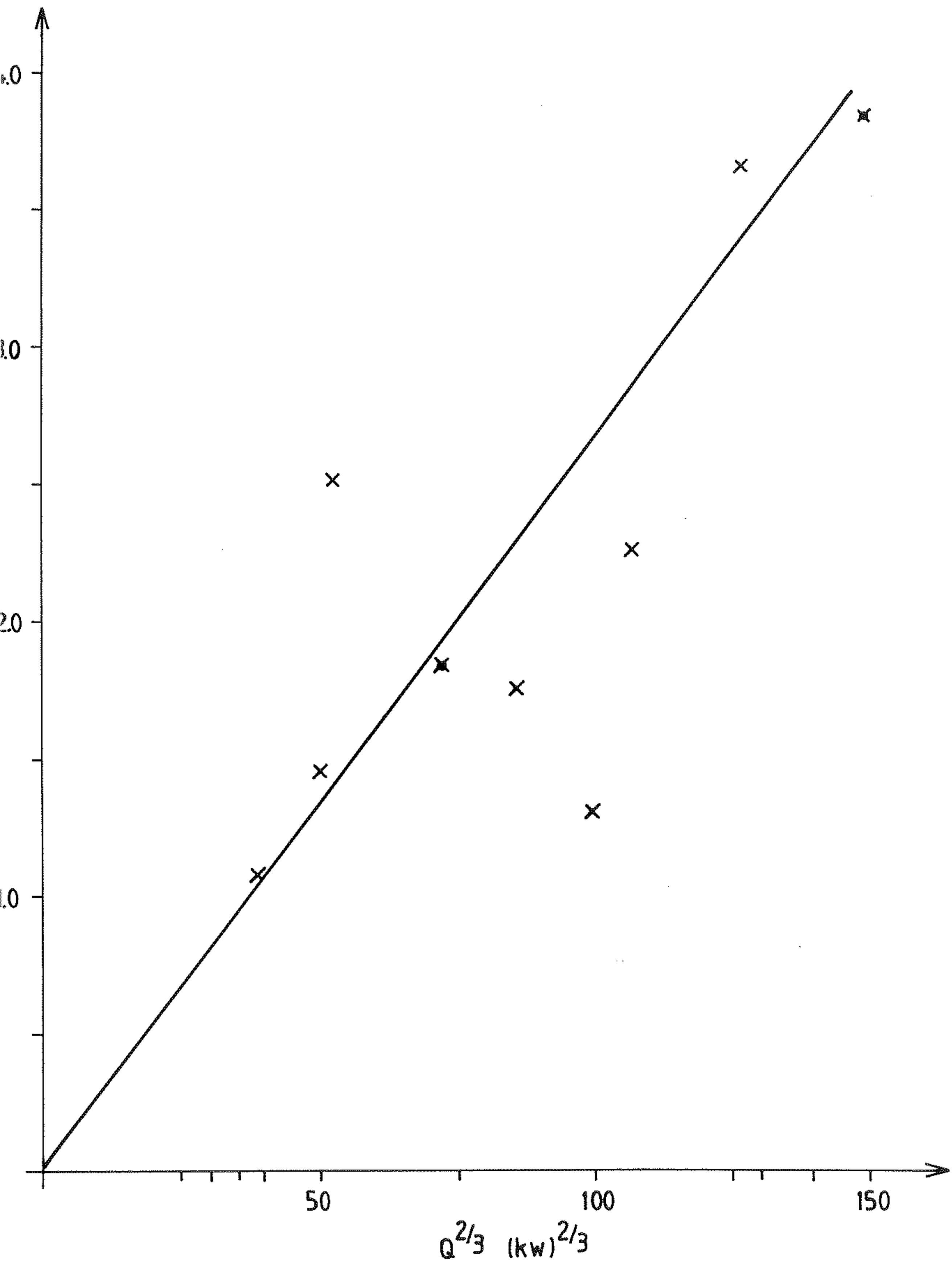
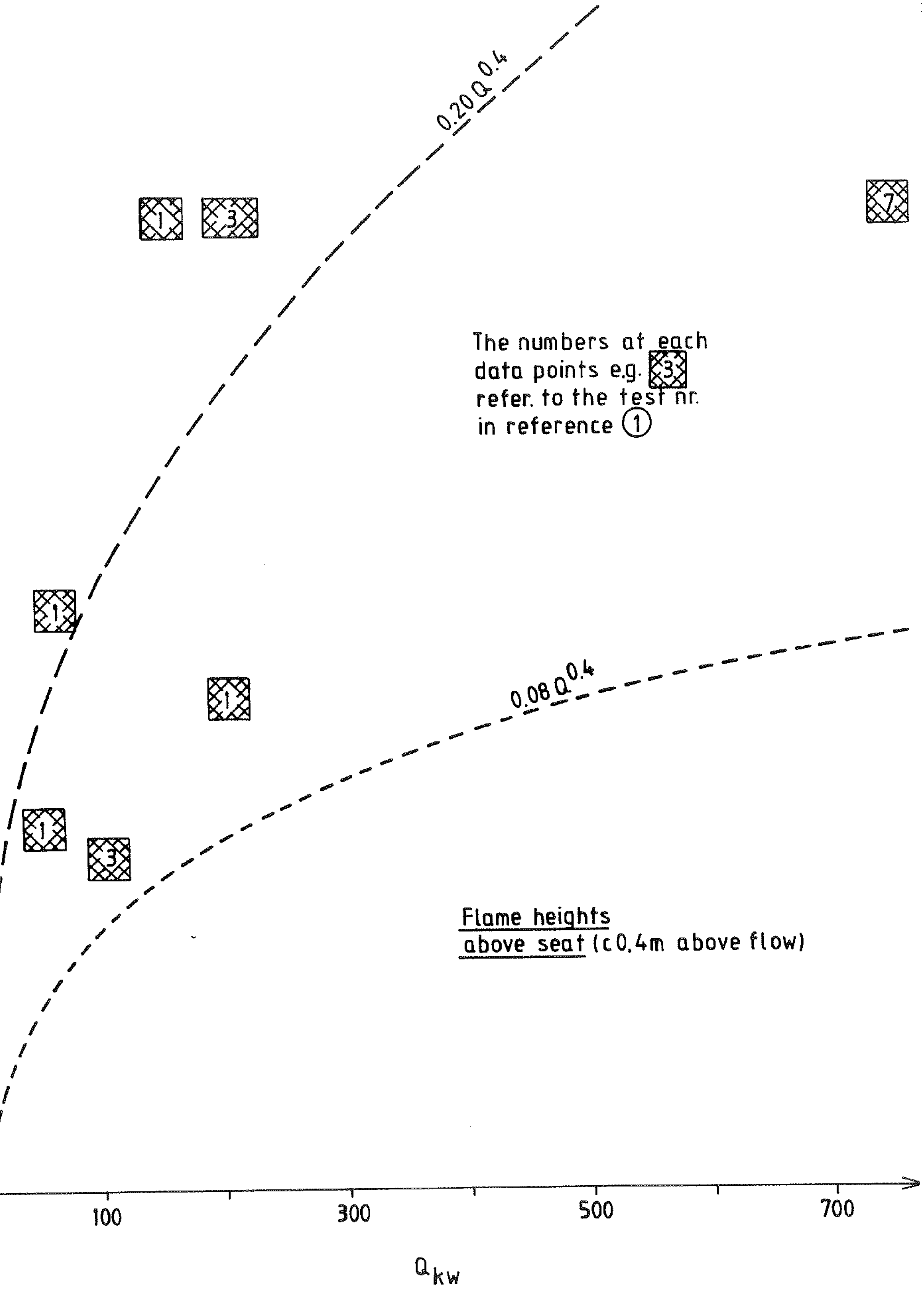


Fig. 4



0.20 Q 0.4
1
3
7
The numbers at each data points e.g. 3 refer. to the test nr. in reference 1
1
1
0.08 Q 0.4
1
3
Flame heights above seat (c 0.4m above flow)
100
300
500
700
Q kw

Fig. 5

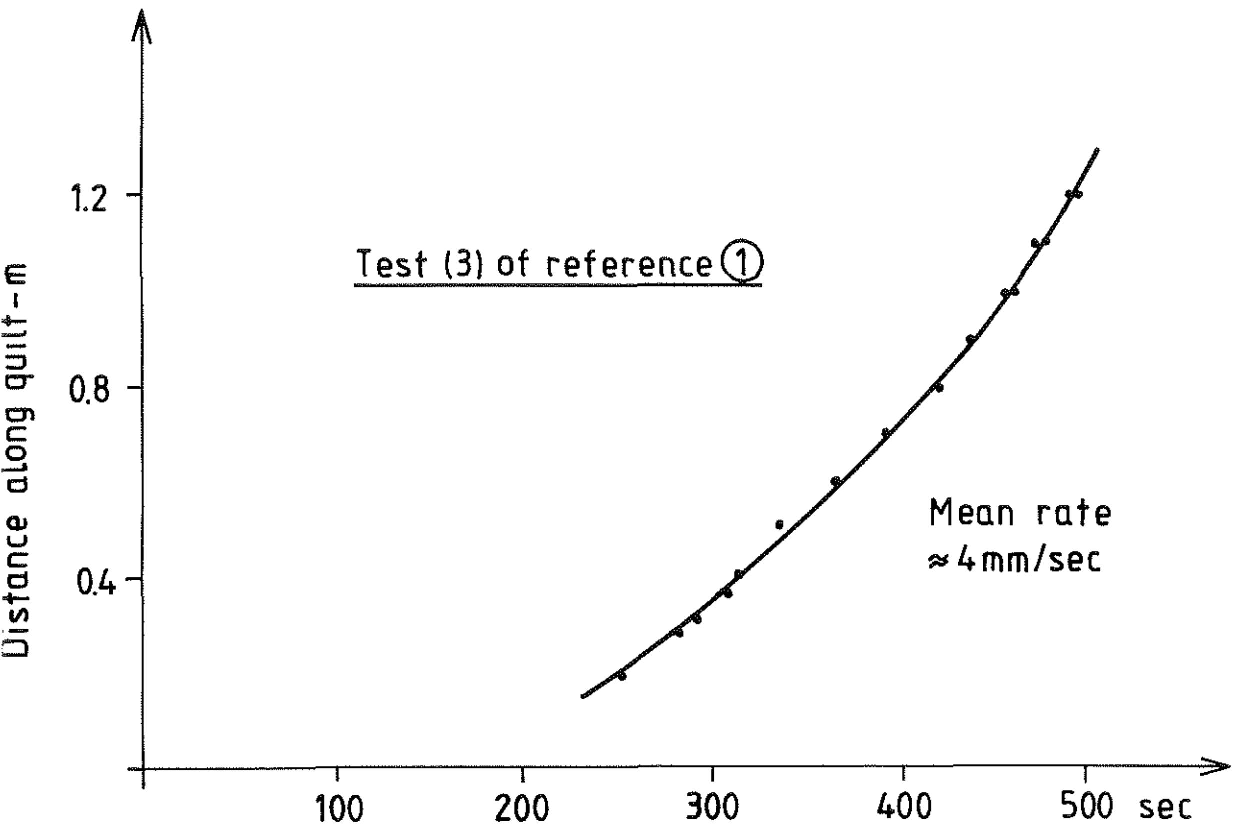


Fig (2). Fire spread along bed
(Andersson)

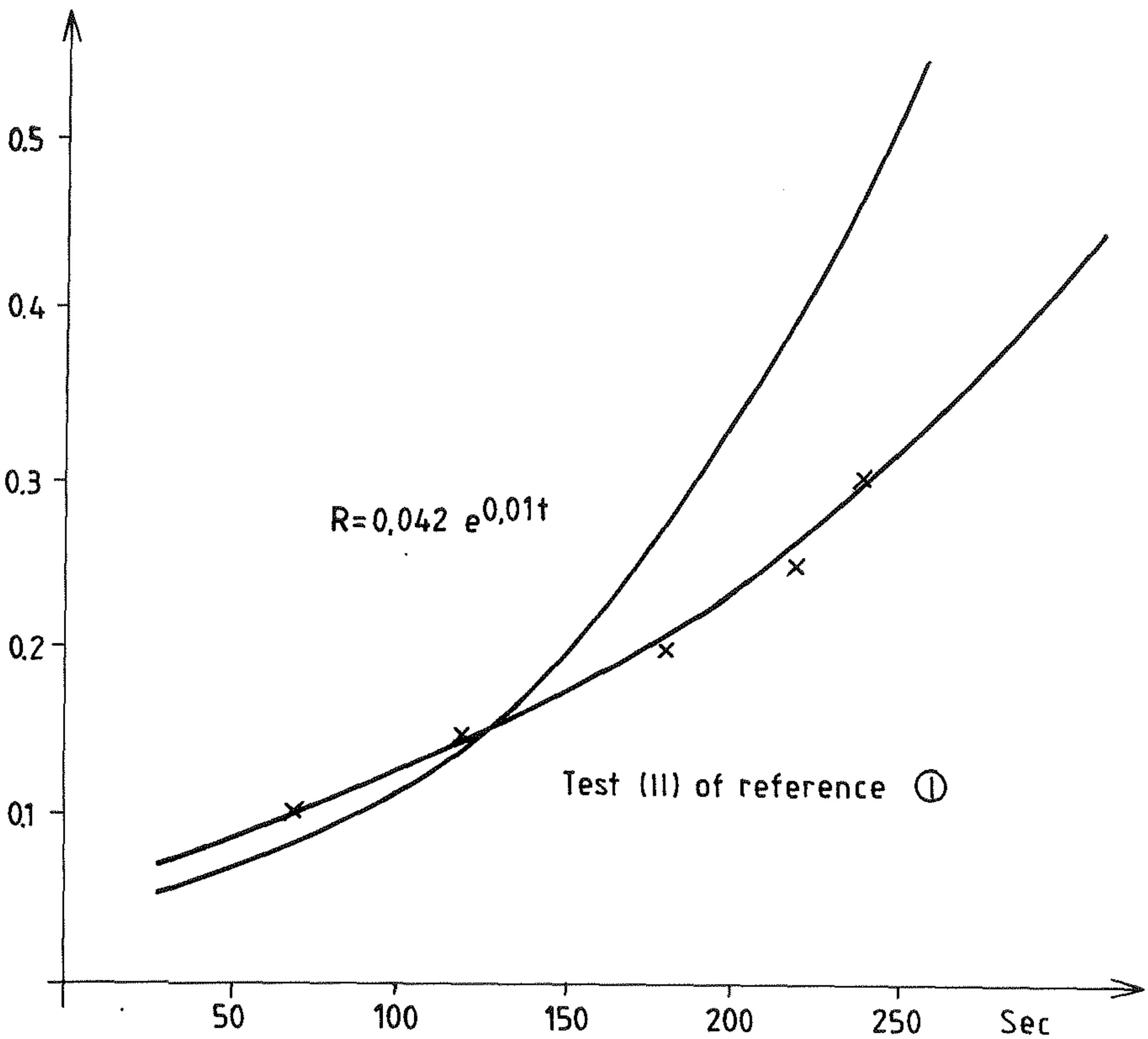


Fig (I). Comparison of some fire spread data and exponential rate (Andersson)