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List of contents

1. Background, objective of paper

In January 1990 an expert group was set up by DP2 of TC2, CEC to define the research and development work needed to be undertaken within the community to achieve a robust solution with respect to reaction–to–fire material classification. The expert group delivered in December 1990 its proposal for a 5–year research and development program. But a system of harmonised European fire test methods and classification system cannot await this period of development, so the search for an "interim solution" is on.

The objective of this paper is to inform that very recent research (during the last year) at Lund University and other places has demonstrated that there exist simplified approaches, using the test developed within ISO TC92/SC1, for an interim solution. In practical terms "the simplified approach" implies the following

- the fire hazard assessment is made on the basis of a specified scenario (to be denoted by scenario A), using DIS 9705 with a 100 kW ignition source and linings on walls and ceiling

- ignitability, and heat release rate (HRR) curves from DIS 5660 are directly used to calculate two indices dividing the products into 3 groups
  1) products where flame spread either does not start or immediately begins to decrease
  2) products where flame spread first accelerates but then stops
  3) products with experimentially increasing flamespread, generating room flashover

- for group 3 materials, ignitability data and a direct, time weighted integral of the HRR–curve from DIS 5660 are combined into a simple algebraic expression or index, giving time to flashover t_{fo} and providing a more detailed classification for that group of materials.

Extensive validation studies have been carried out in the Nordic countries. The experience available from these studies strongly suggests that the whole procedure is simple, unambiguous and reliable. In addition, it complies with the requirements of fire engineering and is scientifically based.

The same methodology has been applied to another scenario (to be denoted as scenario B): again DIS 9705 but with linings on three walls only. Again, indices giving time to flashover for those materials which cause room flashover or maximum value of heat released in the full–scale room test for material not causing flashover are directly calculated from ignitability data and the HRR–curve generated by DIS 5660. The problem with scenario B as a basis for classification is that full–scale experimental validation is severely limitied (although validation by a 1/3 scale model of DIS 9705 is extensive).

Underlying the calculation of the mentioned classification indices is a long term theoretical study of the fire growth process on internal linings and the development of various computer programs numerically simulating this process. This paper presents a summary review of these research activities and finishes by outlining explicitly the possible classification system.

2. Previous modelling work in Lund (LTH)

During the first part of the 1980's a research program was carried out on lining fires within the BRANDFORSK project "The pre–flashover fire". 13 materials (see Table 1) were tested in a number of bench scale flammability tests as well as in the full–scale room corner test and in a 1/3 scale version of the latter tests. The results, which were carried out in Borås (SP), Lund (LTH) and Stockholm (TTC), have been extensively reported and analyzed; this information will not be repeated here.

It is important to realize that two different scenarios were treated in the BRANDFORSK project:

Scenario A	with combustible linings on walls and ceiling and with materials tested in both full– and 1/3–scale
Sencario B	with linings on walls only. Only two materials tested in full–scale, all materials tested in 1/3–scale

In 1985, Magnusson and Sundström [1] developed for scenario A a simple, non–dimensional equation for the heat release rate $\dot{Q}_{rt}$ in full–scale

$$\frac{\dot{Q}_{rt} - \dot{Q}_{start}}{\dot{Q}_{cf}} = \alpha \left[e^{at} - e^{-\lambda t}\right]^{\beta} \dot{Q}''_{max} \left[\frac{a}{a+\lambda}\right] \qquad (1)$$

The quantity $\dot{Q}_{start}$ is defined as the sum of the heat release from the ignition source and the vertical wall area behind the burner, assuming complete combustion. The corresponding time t_{start} denotes the time necessary for the whole of the lining material behind the burner to be pyrolysing. t_{start} is taken directly from the experimental time – RHR curves and thus includes time delay components such as transportation time in the measurement system.

Comparison of t_{start} values with results from the ISO ignitability test can be done in various ways. It was found that the simple procedure of correlating ignition time at the 30 kw/m² impressed radiation level with t_{start} seemed to work best. For the full scale series

$$t_{start} = t_{ign} + 5$$

gave a good approximation of t_{start}. Further, $a = h^2/k\rho c$ and $\dot{Q}_{rt}$ denotes measured RHR (rt meaning room test) and $\dot{Q}_{cf}$ the non–combusted part of wall corner flame reaching the ceiling (= Q_{start} minus combustion in the vertical part of the corner flame). The time t is measured from $t = t_{start}$. A basic assumption was also that the output from the bench–scale HRR–test $\dot{Q}''(t)$ could be written as

$$\dot{Q}''(t) = \dot{Q}''_{max} \, e^{-\lambda t}$$

The parameters α and β were determined by regression analysis but only for those tests which went to flash–over. In 1989 Karlsson [2] extended the regression equation with calculation of hot gas temperatures, heat flux to floor and wall surface temperatures for both 1/3– and full–scale room tests and demonstrated the generality and robustness of Eq 1. In addition, for 1/3 scale, downward flame spread was calculated and compared with experiments.

The main achievement in reference [2] was modelling of scenario B. A computer model, which as closely as possible described the physical processes of flame spread and fire growth, was presented using material properties derived from standardized bench–scale tests as input data. These parameters are thermal inertia $k\rho c$, flamspread parameter ϕ, ignition temperature T_{ig} and RHR–parameters $\dot{Q}''_{max}$ and λ. (Time variation of RHR is as before assumed to be written $\dot{Q}''(t) = \dot{Q}''_{max}\, e^{-\lambda t}$). The computer based model simulates the fire growth in the full or 1/3 scale tests, which includes predicting the rate of heat release, gastemperatures, radiation to walls, wall surface temperatures and downward flame spread on the wall lining material. Prediction was validated against experimental room tests.

A weakness in the model was the treatment of the horizontal concurrent flame spread along the intersection wall–ceiling which was described empirically (see Eq 12 in reference 2). In two papers [3], [4] Thomas and Karlsson studied ceiling flames and general analytical solutions for concurrent flame spread velocity. These solutions were incorporated into the computer model for scenario B and experimentally validated. As of today, the numerical calculation procedure has been applied to 6 materials (insulating fibre board, medium density fibre board, particle board, wood panel, gypsum board, polyurethane board) in the 1/3 scale model of the ASTM/ISO room corner test room and for 2 materials (paper wallcover on particle board and particle board) in the full scale version of the same test method. The accuracy is generally good, see Figs 1a and b.

The studies on scenario B are summarized in a paper to the 3rd IAFSS symposium [5]. In addition, the problem of using results in a material classification procedure is discussed. We simply quote the last few pages of reference [5] (numbers of figures, equations, etc have been changed):

"A RATIONAL CLASSIFICATION PROCEDURE

Derivation of analytical expression for time to flashover, t_{fo}

If we want the validated computer model outlined above to be a basis for material classification a number of fundamental questions must be asked:

* which are the most important of the enumerated variables and what happens if we leave one out?

* how does the uncertainty or variability inherent in the determination of the material flammability characteristics affect the overall reliability of the classification procedure?

* how is classification reliability affected by computer modelling uncertainty?

To even start considering the answers to questions such as these requires extensive sensitivity testing and a prohibitive amount of calculation.

It is clear that in practice the entire classification would be greatly facilitated if the limit state could be expressed as an analytical function of design parameters.

To test the idea the following expression was written

$$t_{fo} = a_o (k\rho c)^{b_1} \phi^{b_2} T_{ig}^{b_3} (\dot{Q}''_{max})^{b_4} \lambda^{b_5} \tag{2a}$$

and the constant a_o and the exponentials $b_1 ... b_5$ determined by linear regression analysis, using the computer program to calculate several hundreds of values of t_{fo} for the 1/3 scale test series.

Disregarding the influence of T_{ig} (the range of variation is rather limited) the resultant expression was

$$t_{fo} = 3.08 \cdot 10^5 (k\rho c)^{0.75} \phi^{-0.37} \lambda^{0.11} (\dot{Q}''_{max})^{-0.52} \tag{2b}$$

with the coefficient of determination $R^2 = 0.98$. Standard error of estimate was 0.075. A comparison between the analytical expression for t_{fo} above and results from the computer model is given in Fig 2. For flashover times up to 800 s expression 2b gives a very good representation of the computer model.

A similar expression can be obtained to calculate the maximum rate of heat release in room fires when flashover does not occur. The result of a preliminary correlation is

$$\text{Max RHR} = 8.56 \times 10^{-5} \cdot (k\rho c)^{-0.3} \phi^{1.06} \lambda^{-0.93} (\dot{Q}''_{max})^{0.93} \tag{3}$$

with a coefficient of determination $R^2 = 0.92$.

Alternative representation of flammability parameters, future work

The flammability parameters $k\rho c$, $\dot{Q}''_{max}$ and λ were originally developed for the work described in [1]. Especially the use of $\dot{Q}''(t) = \dot{Q}''_{max} e^{-\lambda t}$ might create problems in routine classification work although it should be recognized that heat release curves from all the 13 materials tested (except polystyrene) could be expressed in this way with acceptable precision. On the other hand, unambiguous derivation procedure of $\dot{Q}''_{max}$ and λ may be hard to standardize and a direct use of $\dot{Q}''(t)$ would clearly be preferrable. For the computer model, this is mainly a question of making programming changes. Regarding the analytical regression equation, Thomas and Karlsson [6] very recently pointed out that in Equation 2b the combination of $\dot{Q}''_{max}$ and λ is

$$t_{fo} \sim \left[\frac{\dot{Q}''_{max}}{\lambda^{0.21}}\right]^{-0.52}$$

Since $\int_{0}^{\infty} t^{b}\, e^{-\lambda t}\, dt = \frac{\Gamma(b+1)}{\lambda^{b+1}}$

where Γ dontes the gamma–function they pointed out that the bracketed term is obtained by integrating a weighted heat release

$$I_Q = \int_{0}^{\infty} \frac{\dot{Q}''_{max}\, e^{-\lambda t}}{t^{0.79}}\, dt \tag{4a}$$

which strongly suggests [7] that an alternative form might be

$$I_Q = \int_{0}^{\infty} \left[\frac{\dot{Q}''(t)}{t^{0.79}}\right] dt \tag{4b}$$

with $\dot{Q}''(t)$ directly taken from the cone calorimeter. Replacing $k\rho c$ with time to ignition t_{ig}, also directly obtained from the bench–scale test, should be straight forward.

Work along all these lines is now (March 1991) continuing as well as efforts, in a wider context, to implement these results in a classification procedure with regard taken to uncertainty, reliability and economy."

It should be emphasized that Thomas and Karlsson derived the form of their results from a generalized dimensional study, using universally accepted principles of dimensional analysis only.

The form of the equations suggested above are very similar to those suggested to Mathez (reference to be inserted later); for the first time the fomulas have been quantified.

Since this was written, work has continued along a number of aspects

- to study the influence of neglecting the influence of flame spread parameter ϕ on time to flashover and maximum HRR for scenario B

- to derive a regression equation for time to flashover for scenario A

- to replace $\dot{Q}''_{max}$, λ and $k\rho c$ with parameters directly taken from the cone calorimeter(I_Q and t_{ig})

- to model, for *scenario* A, those room fire processes which do not go to flashover.

Much of the work is done in cooperation with our Finnish colleagues [7]. A progress report will be given below.

3. Regression equation for scenario B with and without flame spread parameter ϕ

Eq 2b is valid for 1/3 scale *scenario* B. For the full scale scenario B the corresponding equation is

$$t_{fo} = 2.88 \cdot 10^5 \; (k\rho c)^{0.78} \; \phi^{-0.25} \; \lambda^{0.11} \; (\dot{Q}''_{max})^{-0.79} \qquad (5)$$

with the main difference being a stronger dependence of t_{fo} on $\dot{Q}''_{max}$.

One of the strategic questions in designing a classification system is whether results from the surface spread of flame test must be included. The importance of the flame spread parameter ϕ is obviously greater for *scenario* B than for *scenario* A. Excluding the influence of varying ϕ the regression equation for t_{fo} for 1/3 scale, scenario B (cf Eq 2b) now looks like this:

$$t_{fo} = 0.31 \cdot 10^5 (k\rho c)^{0.70} \; \lambda^{0.04} \; (\dot{Q}''_{max})^{-0.43} \qquad (6)$$

with $R^2 = 0.79$. In other words, excluding ϕ leads to a marked increase in variability or uncertainty (assuming that the selection of material parameters corresponds to the distribution these parameters have in practical life). The final importance of the increased variability in predictive capability can be assessed only in the context of a proper and general reliability study of the classification procedure.

For linings, which do not cause flashover *in scenario* B, cf Eq 3, the exclusion of ϕ increases the variability in the prediction of maximum HRR proportionally more than for those materials where t_{fo} is the decisive parameter.

4. Regression equation on t_{fo} for scenario A

The regression equation for t_{fo} in scenario A, 1/3– and full–scale room corner tests are respectively

$$t_{fo} = 10.3 \cdot 10^3 (k\rho c)^{0.80} (\dot{Q}''_{max})^{-0.37} \lambda^{0.016}$$
$$R^2 = 0.99 \quad ; \quad (1/3\text{–scale}) \qquad (7a)$$

$$t_{fo} = 18.5 \cdot 10^3 (k\rho c)^{0.82} (\dot{Q}''_{max})^{-0.51} \lambda^{0.03}$$
$$R^2 = 0.99 \quad ; \quad (\text{full–scale}) \qquad (7b)$$

The main features of Eqs 7a and 7b is the strong dependence on $k\rho c$ and the very near independence on λ. The same tendency was observed in [1].

5. Replacing $k\rho c$, $\dot{Q}''_{max}$ and λ with parameters more directly produced from the cone

It is clear that in routine practical classification work the transformation of bench–scale test results into classification limits or indices should be as simple, unambigous and robust as possible. To remove any arbitrariness it would be preferrable to base prediction directly on output from the cone calorimeter, i.e. the values of t_{ig} and the time–HRR curve. For the computer programs developed for the numerical simulation of scenarios A and B this poses no substantial problem but still requires some re–programming work.

For the regression equations given earlier, a recalculation must be done introducing t_{ig} and I_Q as the independent variables, replacing $k\rho c$ and the combination of $\dot{Q}''_{max}$ and λ, respectively. When this is done we arrive at the following expression for 1/3 scale scenario B (cf Eq 2b)

$$t_{fo} = 11.7 \cdot 10^3 \, \phi^{-0.37} \, t_{ig}^{\,0.486} \, I_Q^{\,-0.53} \qquad (8)$$

with I_Q as before

$$I_Q = \int_0^\infty \frac{\dot{Q}''(t)}{t^{0.79}}\,dt$$

For scenario A full–scale the corresponding expression is (cf Eq 7b)

$$t_{fo} = 0.097\ 10^3 (t_{ig})^{0.93}\ I_Q^{-0.51} \tag{9}$$

with $I_Q = \int_0^\infty \frac{\dot{Q}''(t)}{t^{0.93}}\,dt$

Some care must be exhibited when calculating I_Q and t_{ig}

- the major contribution to the integral comes for very small times $t \leq 1$ s (cf $\int_0^\infty e^{-\lambda t} dt$)

  In practical terms this means the numerical integration procedure must be standardized and adjusted to measurement time frequency.

- the original $k\rho c$–values were calculated from thermocouple measurements of surface temperatures in the ISO ignitability tests. The equation transforming the $k\rho c$–values to value of t_{ig} introduced a degree of variability especially for lower values of $k\rho c$. A more consistent approach would be to derive the $k\rho c$–values necessary for the numerical simulation computer programs from measured t_{ig}–values using the procedure outlined by Janssens [8].

Fig 3a and 3b gives the relation between the regression equation 2b (using $k\rho c$, $\dot{Q}''_{max}$ and λ) and Eq 8 (using t_{ig}, I_Q) and experimental values for 1/3 scale, scenario B. Fig 4 gives the same correlation for scenario A, full–scale.

6. Scenario A, materials which do not go to flashover

Work is currently in progress calculating the maximum HRR and area burned for materials which do not sustain exponential spread. The approach will be based on first principle, evaluating the solutions for concurrent flame spread given in [4] for the boundary and starting conditions describing the full scale room corner test. It should thus be possible to obtain a regression equation, corresponding to Eq 7b, for maximum HRR and for scenario A. In the meantime, the information contained in [4] and [7] may serve as a basis for classification. Fig 5 is taken from the unpublished Finnish paper [7] and based on studies in [4]. It outlines four regions with differing fire propagation characteristics: In the region I the velocity accelerates exponentially with time and in the region IV the velocity decreases exponentially with time from the very beginning. In the region III the velocity decreases monotonously from the very beginning and stops completely after a finite time. In the region II the velocity behaves much like in region III, but the decrease of velocity is slower. Below the line $\gamma = (a-1)^2/a$ (in the parabola–figure) the velocity first increases but later begins to decrease and stops completely after a finite time; this time goes to infinity when we approach the lower branch of the parabola.

$$a = k_f \dot{Q}''_{max}$$
$$\gamma = \lambda \tau \approx \lambda t_{ig}$$

The value of k_f depends very much on the scenario in which the flame spread occurs; when flame spreads up the side of a wall k_f is larger than in the concurrent flame spread along a ceiling. For upward flame spread in the ISO Room Corner Test k_f can, conservatively, be taken to be $\simeq 0.02$ m²/kW. t_{ig} is directly obtained from ignition test and λ directly evaluated from

$$\lambda = \frac{\dot{Q}''_{max}}{\int_0^t \dot{Q}''(t')dt'} \tag{10a}$$

or

$$\lambda = -\frac{\ln(\dot{Q}''(t)/\dot{Q}''_{max})}{t} \tag{10b}$$

Both $\dot{Q}''_{max}$ and λ should be evaluated by an averaging procedure. As an example, $\dot{Q}''_{max}$ may be selected as the average of the five maximum values and λ evaluated for a 5 minute period. It should be emphasized that Eqs 7a and b for scenario A shows the extrem insensitivity on t_{fo} of the λ–value. The numbers in Figure 5 refer to materials in Table 1.

7. Summary of equations on which to base an interim classification system

Scenario A

1. Calculate $a = 0.02\ \dot{Q}''_{max}$

2. If $a < 1$ flame spread will be very limited

3. For $a \geq 1$ calculate $\gamma = \lambda\ t_{ig}$

   If $\gamma > (1-\sqrt{a})^2$ flame spread starts but stops before flashover

   If $\gamma < (1-\sqrt{a})^2$ flame spread exponentially increasing; calculate t_{fo}

4. Calculate

   $$I_Q = \int_0^t \frac{\dot{Q}''(t)}{t^{0.93}}\, dt$$

   calculate

   $$t_{fo} = 0.097 \cdot 10^3 (t_{ig})^{0.93}\ I_Q^{-0.51}$$

   I_Q–values for the 13 materials in Table 1 are found in Figure 7.

Scenario B

1. Calculate

   $$I_Q = \int_0^t \frac{\dot{Q}''(t)}{t^{0.89}}\, dt$$

2. Calculate

   $$t_{fo} = 2.4 \cdot 10^3 (t_{ig})^{0.56}\ I_Q^{-0.72}$$

   If $t_{fo} > 900$ sec flashover is considered not to occur.

   Regression equation for max HRR (similar to equation 3) is to be inserted later.

Obvious, the sets of equations derived above could have been based on HRR–curves from other constant exposure levels, for example 300 kW/m². *The only change* would be somewhat different coefficients and exponents.

8. Other validation studies and a method to compare various approaches

There are at least two other simulation studies of the full scale test series for scenario A: [9] and [10]. The calculation method described in [9] has been proposed as the basis for a classification procedure [11]. A rational method to compare the various calculation model would be to agree on a set of HRR–curves from DIS 5660 (real and/or hypothetical) and perform a regression study based on the parameters t_{ig} and I_Q. Such a study should be carried out as soon as possible to demonstrate the likely convergence of the different approaches.

9. Summary

1. Reaction–to–fire material classification can be done with a limited number of parameters directly (with the possible exception of the flame spread parameter ϕ) obtained from the cone calorimeter and the surface spread of flame test

   t_{ig} = *time to ignition at 30* kW/m²
   I_Q = HRR–curve, suitably time–weighted
   ϕ = flame spread parameter

   $\dot{Q}''_{max}$ = maximum HRR from DIS 5660
   λ = decay coefficient evaluated directly

2. For scenario A, ϕ is unnecessary. For scenario B, excluding ϕ means a decrease in classification procedure reliability. This decrease can be quantified; to determine its influence on the overall uncertainty requires a proper reliability study.

3. For scenario A, $\dot{Q}''_{max}$ and $\lambda \cdot t_{ig}$ are used to delineate areas or materials with no flame spread, limited amount of flame spread or exponentially growing flame spread (flashover) in full scale room corner test. For the latter category an index based on t_{ig} and I_Q gives time to flashover t_{fo}.

4. For scenario B maximum heat release rate or t_{fo} in the full scale room corner test is given by simple expressions involving t_{ig}, I_Q and (preferrably) ϕ.

5. By drawing a diagram with I_Q on one axis and $1/t_{ig}$ on the other a set of iso–chronous (time to flashover) curves are obtained [7] with decreasing flashover times found by increasing the distance from the origin, see Figure 6.

10. General remarks

Some conclusions of a general nature may be drawn

1. The available evidence indicates that existing ISO tests may be the basis for the robust solution.
2. The interim solution can be a truly first and integral step of the robust solution.
3. We may have some hope that the road to a robust solution may be less time–consuming and expensive than originally perceived.

Acknowledgements

Much of the work presented here has evolved during a number of discussions with prof Matti Kokkala, VTT, Finland. We also gratefully acknowledge the continuous contribution of Dr Philip Thomas to the progress of this paper.

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Table 1.

Material	Material name	$\dot{q}_o''$ (kW/m^2)	λ (s^{-1})	τ (s)	a	γ
1	Insulating fibreboard	139.8	0.0070	23	2.8	0.16
2	Medium density fiberboard	162.4	0.0027	72	3.2	0.19
3	Particle board	199.8	0.0049	87	4.0	0.43
4	Gypsum plasterboard	27.7	0.0150	100	0.6	1.50
5	PVC cover on gyps. pl. board	107.5	0.0293	30	2.2	0.88
6	Paper cover on gyps. pl. board	105.3	0.0208	100	2.1	2.08
7	Textile cover on gyps. pl. board	222.0	0.0278	106	4.4	2.95
8	Textile cover on mineral wool	246.2	0.0382	15	4.9	0.57
9	Melamine-faced particle board	40.9	-0.0032	153	0.8	-
10	Expended polysteren	-	-	-	-	-
11	Rigid polyurethane foam	130.6	0.0217	6	2.6	0.13
12	Wood panel, spruce	149.7	0.0086	56	3.0	0.48
13	Paper cover on particle board	164.1	0.0035	108	3.3	0.38

Materials tested in Sweden for the project "The pre–flashover fire"

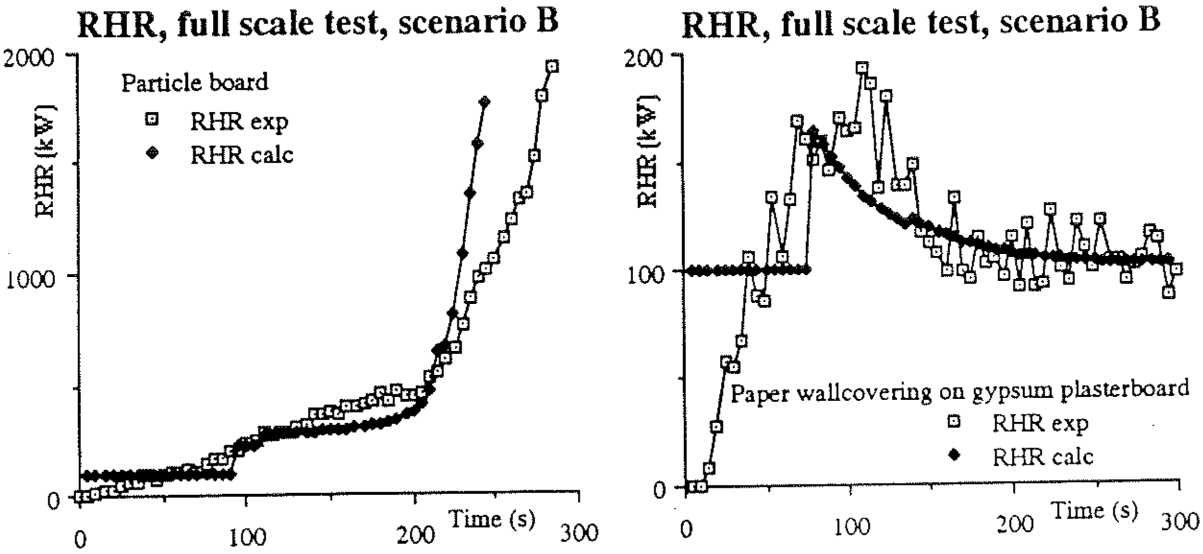

Figure 1 a and b.

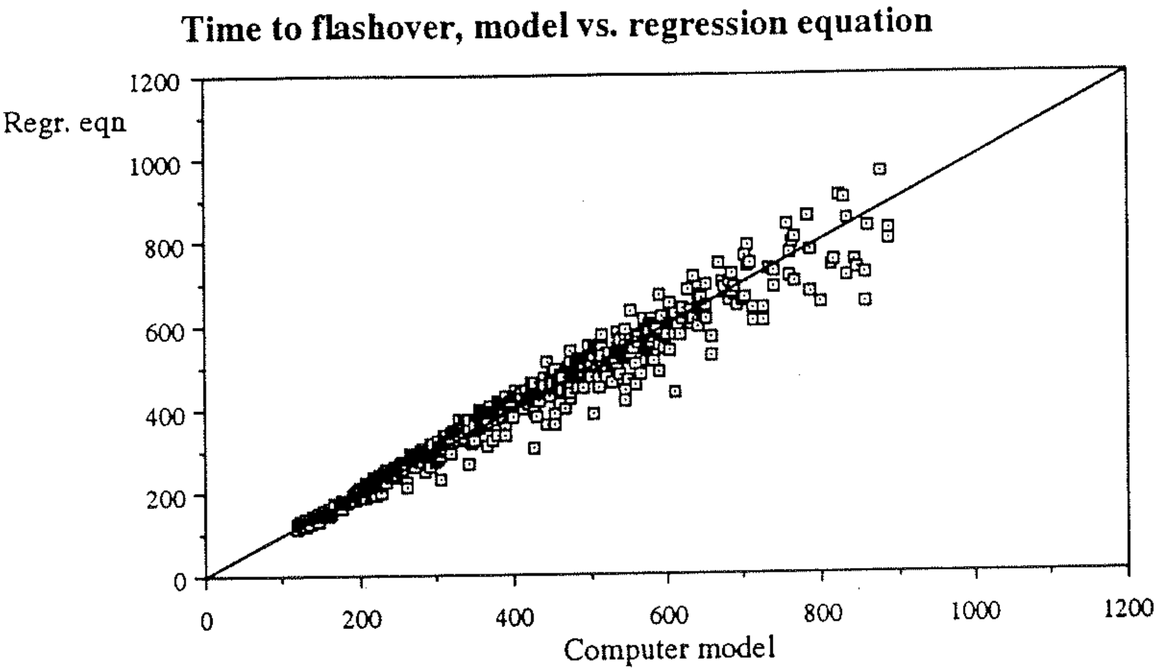

Figure 2.

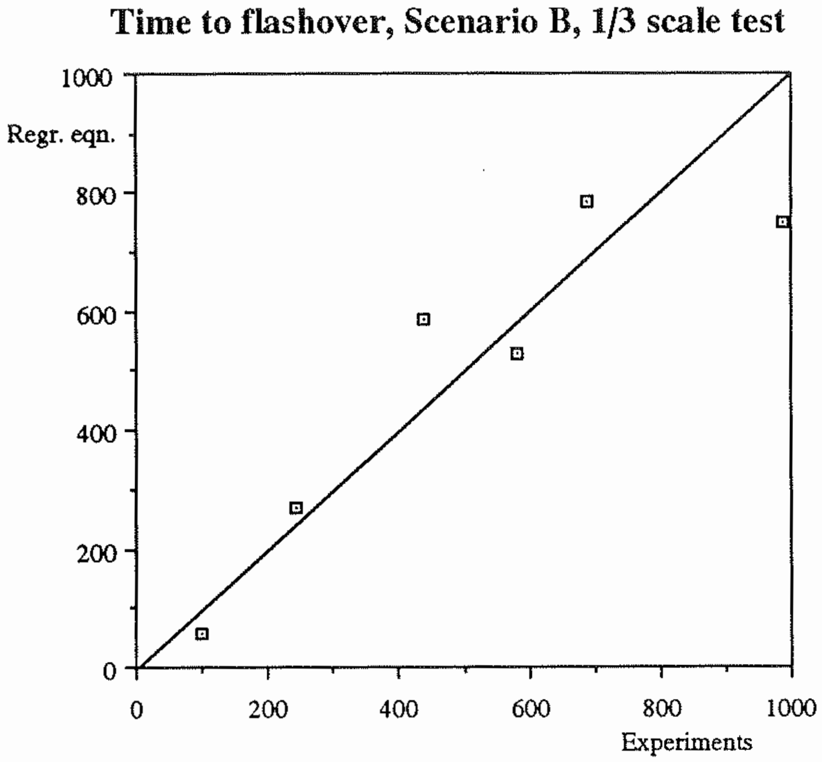

Figure 3 a. Regression equation with independent variables ($k\rho c$), ϕ, $\dot{Q}''_{max}$ and λ

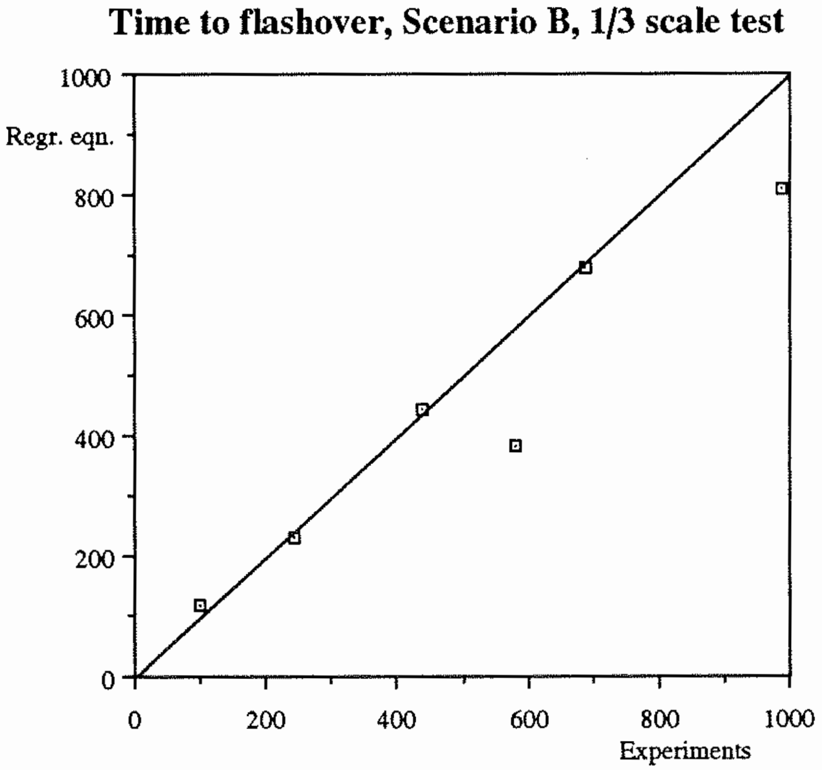

Figure 3 b. Regression equation with independent variables, t_{ig}, I_Q and ϕ

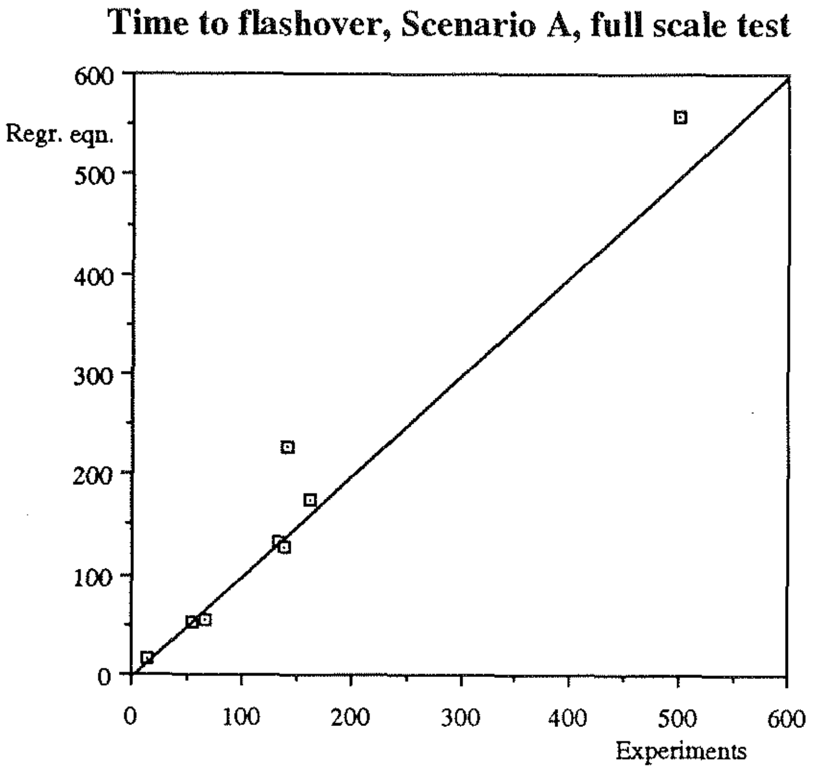

Figure 4. Regression equation with independent variables t_{ig}, I_Q and ϕ

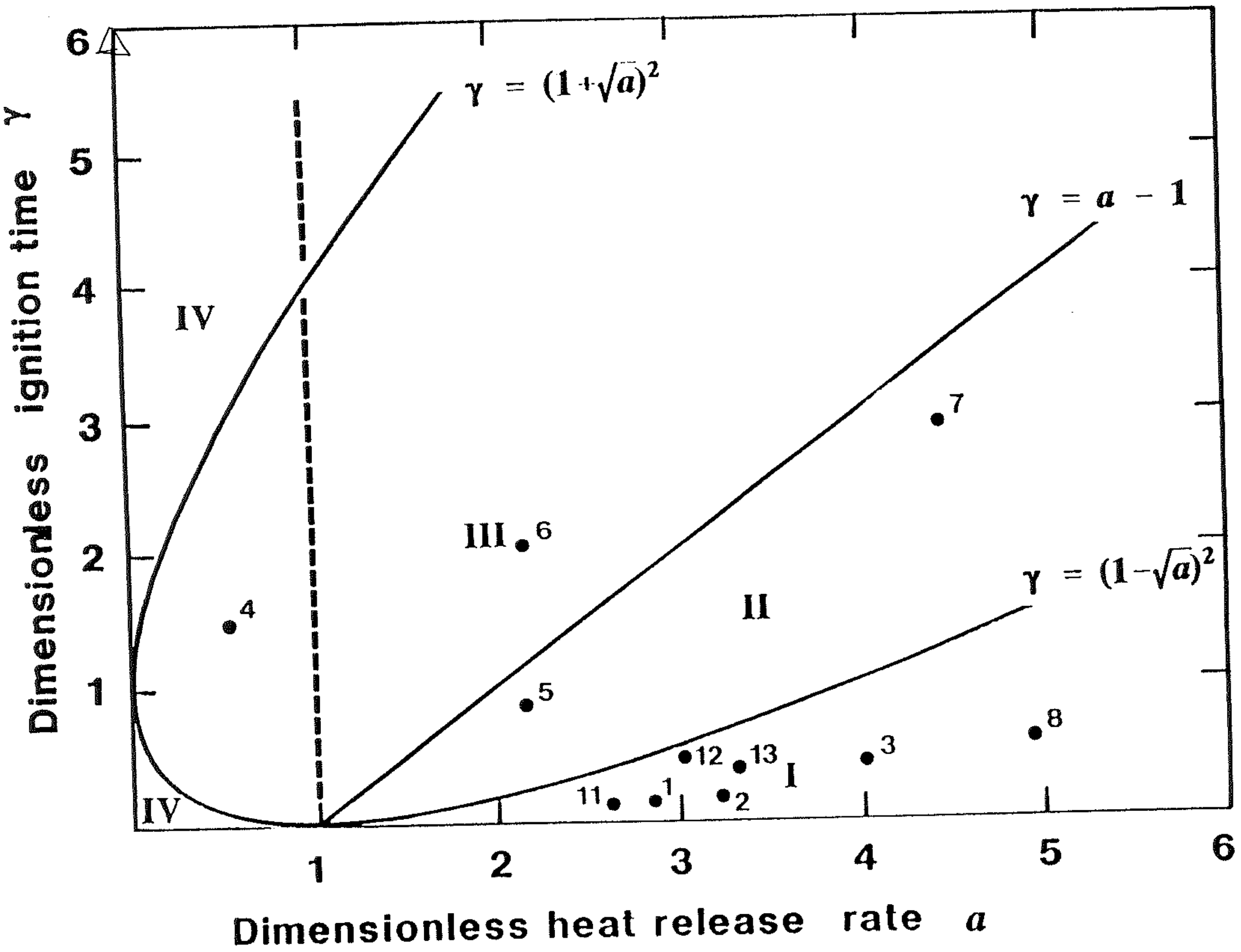

Figure 5, taken from [7]

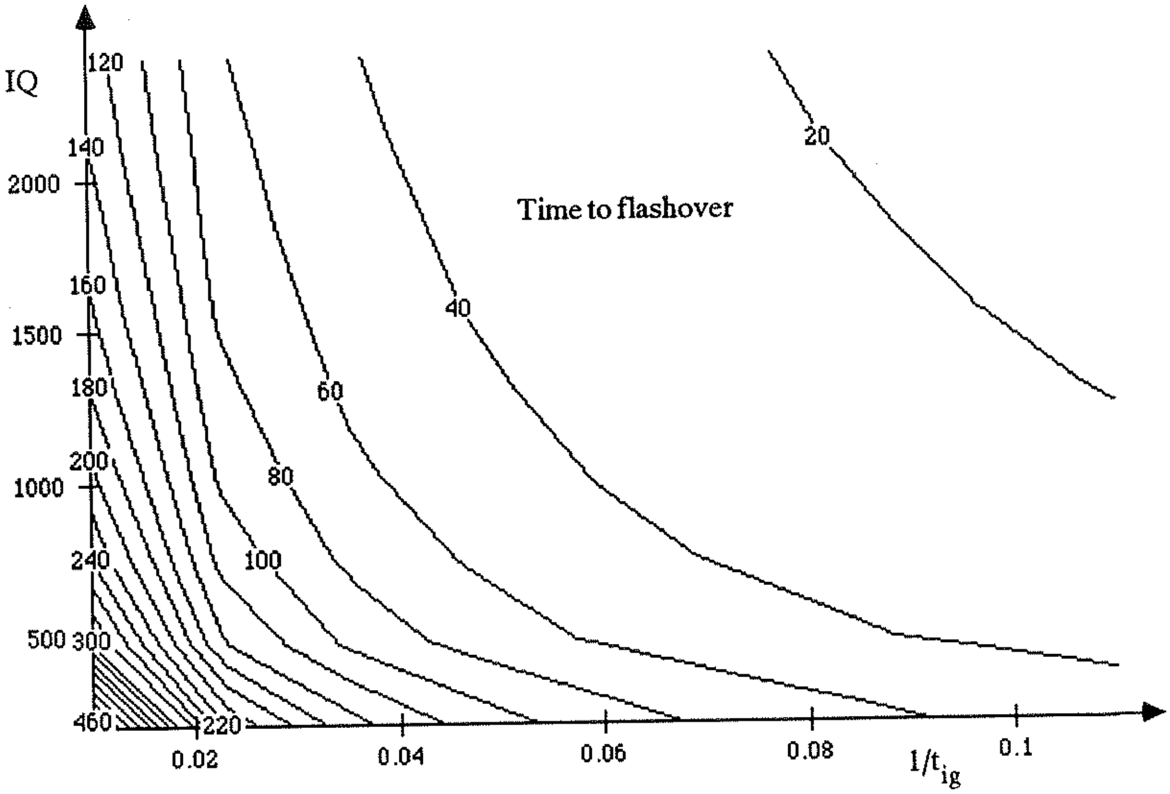

Figure 6. Contour curves for times to flashover (in seconds)

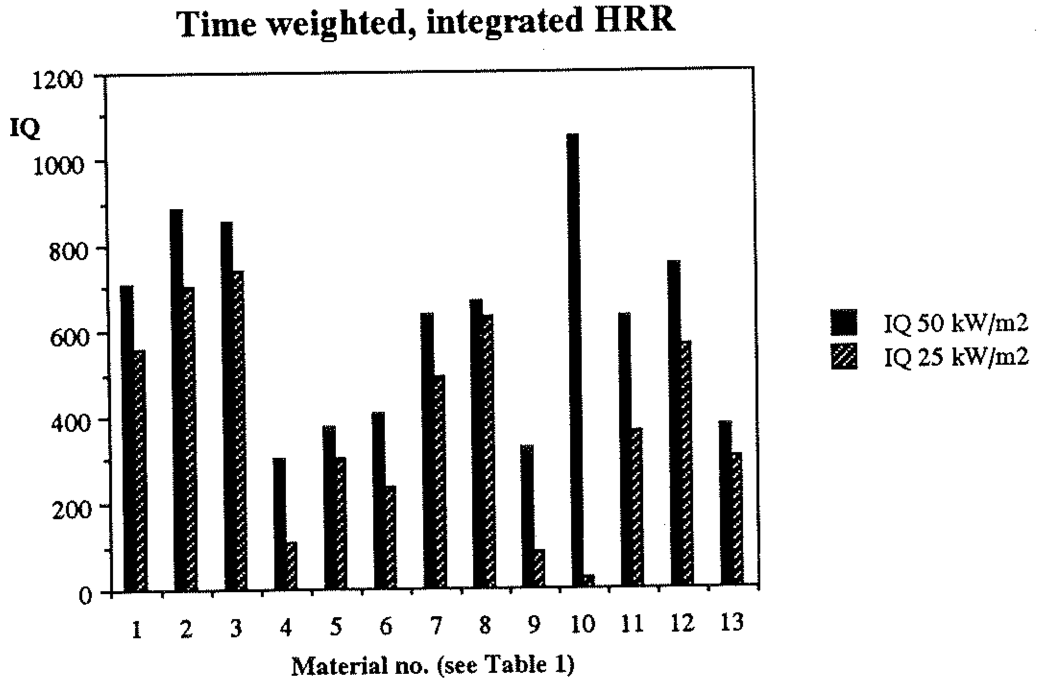

Figure 7.