A Mathematical Model for Calculating Heat Release in the Room Corner Test

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Abstract

A mathematical model is presented for calculating heat release rate in the Room Corner Test, where lining materials are mounted on both walls and ceiling. The model is based on a thermal theory for concurrent flow flame spread. By using a simple mathematical representation of the heat release rate from the Cone Calorimeter, analytical solutions are arrived at for the velocity and position of the pyrolysis front in the Room Corner test as well as the heat release rate from the burning material. Results from calculations are compared with experiments, showing good agreement for 11 materials out of 12.

1 Introduction

Flame spread on wall surfaces has been a matter of concern for legislators and authorities since the advent of building fire safety regulations. Work in this area has included development of bench scale test to derive basic flammability characteristics for materials, which could rationally be used as classification criteria.

Extensive work has been carried out by several workers on lateral, opposed flow flame spread, resulting in the development of bench scale tests and derivation of material parameters that can be used in practice to predict this category flame spread.

Work on concurrent flow flame spread has, however, to a large extent been limited to theoretical considerations. Models, predicting this type of flame spread on materials, using basic flammability parameters derived from simple bench scale tests, have been scarce and experimental validation very limited.

In this paper we shall present one such model and show how material properties obtained from the Cone Calorimeter can be used to predict concurrent flow flame spread for simple scenarios.

In particular, we shall present a model to predict the flame spread velocity on ceiling materials in the Room Corner test (ISO DIS 9705 and NORDTEST 025) and show how the resulting heat release can be calculated.

The reader should note that here, when discussing flame spread velocity on the underside of a ceiling, the velocity is expressed as an area per time (m^2/s) and is therefore not, as is conventional, a linear velocity.

Also, it should be noted that the heat release rate from the Cone Calorimeter can be represented mathematically in many different ways. We have in this work used a very simple such representation, mainly so that the concurrent flow flame spread model can be presented in a simple, comprehensive way.

2 The theories of Parker and Saito, Quintiere and Williams

Parker /1/ considered the one-dimensional flame spread problem for the underside of a surface, in the ASTM E-84 test configuration. He wrote the velocity of the pyrolysis front (in m^2/s) as

$$V(t) = \frac{A_f - A_p}{\tau} \tag{1}$$

where A_f represents the flame area, A_p the pyrolysing area and τ time to ignition.

Saito, Quintiere and Williams /2/ (SQW) also discussed a thermal theory of concurrent flow flame spread on thick solids which lead to an integral equation of the Volterra type for the velocity of spread. They discussed the solution of the equation at short times and at long times. Thomas and Karlsson /3/ obtained a general analytic solution and evaluated it for various conditions.

Certain approximations were required for the integral equation to be obtained. The main assumptions are:

1) The material is thermally thick, homogeneous and its thermal properties are constant with temperature.
2) Chemical kinetics are excluded, so very fast (as well as very slow) rates of spread are not fully dealt with and extinction conditions are therefore only discussed approximately.
3) The flame length, x_f, depends on a power of Q', the rate of convected heat release per unit width of flame front, but the solution below demands a linearisation.
4) Heat flux from the flame only occurs at constant flux within the region $x_f < x < x_p$ (see Fig. 1).

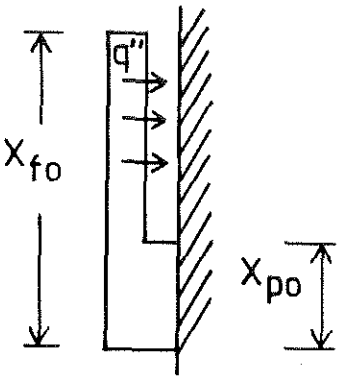

Fig. 1 Heat flux from the flame is assumed to be constant in the region $x_f < x < x_p$.

SQW wrote the linear velocity of the pyrolysis front V_l (in m/s) as

$$V_l(t) = \frac{x_f - x_p}{\tau} = \frac{dx_p}{dt} \tag{2}$$

$$\text{where } \tau = \left[\frac{4\,\dot{q}''^{2}_{f}}{\pi\, k\rho c\,(T_{ig} - T_0)^2}\right]^{-1} \tag{3}$$

This resulted in an integral equation of the Volterra type:

$$V_l(t) = \frac{1}{\tau}\left[K_l\left(\dot{Q}_b(t) + x_{po}\dot{Q}'_w(t) + \int_0^t \dot{Q}'_w(t-t_p)\,V(t_p)\,dt_p\right)^n - \left(x_{po} + \int_0^t V(t_p)\,dt_p\right)\right] \tag{4}$$

where the two terms on the l.h.s. represent x_f and x_p respectively. Here, t_p is the dummy variable of integration, K_l and n are coefficients for flame length, $Q_b(t)$ is the gas burner output and Q'_w is the rate of heat release from the material per unit width of flame front.

To solve equation (4) analytically one has to mathematically represent both the time dependence of the material heat release rate and the flame length as a function of heat release rate. Thomas and Karlsson /3/ did this for several cases.

3 Analytical solutions for flame spread under ceilings

Since the aim of this paper is to model the concurrent flow flame spread under a ceiling we shall follow Parker's example and express the velocity of the pyrolysis

front in terms of areas. The following assumptions will be made to facilitate an analytic solution of equation (1):

1) The heat release rate from the burning material can be expressed mathematically as $Q''_{max}\ e^{-\lambda t}$ where Q''_{max} is the maximum rate of heat release from the Cone Calorimeter test and λ is the decay coefficient (see Fig. 2).

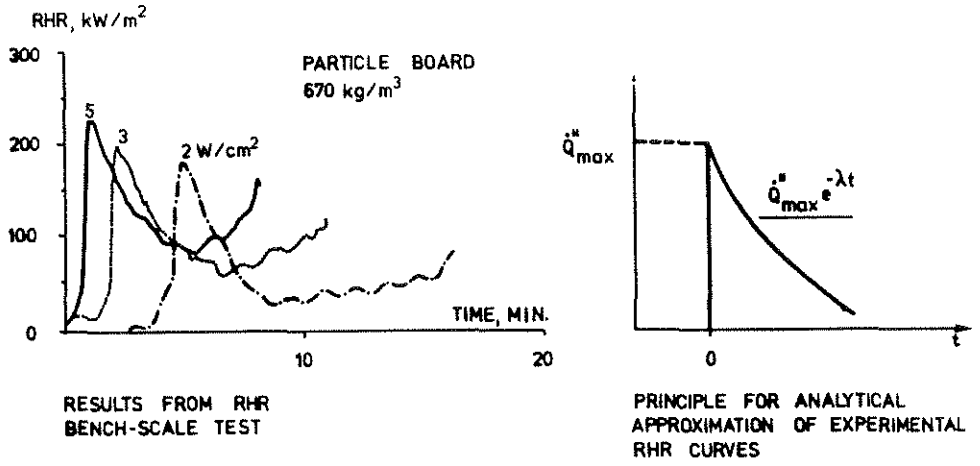

Fig. 2 Mathematical representation of the material heat release rate.

2) We assume that the flame area is linearly dependent upon the total heat release rate and can be written as $A_f = K\ Q$, where K is a constant (in m^2/kW) and Q is the total heat release rate. The coefficient n in equation (4) is thus = 1.
3) The initial pyrolysing area under the ceiling, A_0, depends on the burner output and the energy released from the material in the corner behind the burner. An expression for A_0 is given in section 5.

With regards to the second assumption it should be noted that correlations of heat release rate and flame area in the ceiling are scarce. Andersson and Giacomelli /4/ carried out experiments in a 1/3 scale of the room corner test with only a gas burner, placed in a corner, as an energy source. The burner was 0.07 m square and the energy release rate varied from 5.5 kW to 33 kW. They noted the area of the flame under the ceiling which exhibited a reasonable linear dependence on the heat release rate. It can also be inferred from more recent theoretical work by Thomas and Karlsson /5/ that the assumption is not unreasonable for the range of energy release rates which is important in this study. It should be noted, however, that the validity of the assumption in the full scale test room has not been properly established.

Andersson and Giacomelli /4/ found that the shape of the flame in the ceiling sometimes resembled a quarter circle and sometimes a triangle. Regarding the shape of the flame and the pyrolysing area considered in this study, we simply assume that the flame area correlation is valid for an area of undefined shape.

The resulting integral equation then becomes, with $V(t) = \frac{dA_p}{dt}$ (in m^2/s):

$$V(t) = \frac{1}{\tau}\left[A_0 + K\left(A_0\dot{Q}''_{max}e^{-\lambda t} + \int_0^t \dot{Q}''_{max}e^{-\lambda(t-t_p)}V(t_p)\,dt_p\right) - \left(A_0 + \int_0^t V(t_p)\,dt_p\right)\right] \quad (5)$$

where the first two terms on the l.h.s. represent A_f and the last bracket represents A_p and t_p is the dummy variable of integration. Rearranging equation (5) and taking the Laplace transform gives:

$$\overline{V}(s) = \frac{1}{\tau}\,\frac{K\dot{Q}''_{max}A_0}{s^2 + s\frac{1}{\tau}\left(1 - K\dot{Q}''_{max} + \lambda\tau\right) + \frac{\lambda}{\tau}} \quad (6)$$

For simplification we let $a = K\dot{Q}''_{max}$ and $C_1 = \frac{K\dot{Q}''_{max}A_0}{\tau}$

The inverse Laplace transform is then given as

$$V(t) = \frac{C_1}{s_2 - s_1}\left[s_2 e^{s_2 t} - s_1 e^{s_1 t}\right] \quad (7)$$

where s_1 and s_2 are the real simple roots of the quadratic equation (the denominator of equation (6))

$$s^2 + s\frac{1}{\tau}\left(1 - a + \lambda\tau\right) + \frac{\lambda}{\tau} = 0$$

Therefore

$$s_{1,2} = -\frac{1}{2\tau}\left(1 - a + \lambda\tau\right) \pm \frac{1}{2}\sqrt{\Delta}$$

where the determinant $\Delta = \frac{1}{\tau^2}\left(1 - a + \lambda\tau\right)^2 - \frac{4\lambda}{\tau}$

The conditions for the velocity to accelerate are that s_1 or s_2 or both are positive, otherwise the velocity decelerates.

If the determinant is negative, i.e. $\left(1 - \sqrt{a}\right)^2 < \lambda\tau < \left(1 + \sqrt{a}\right)^2$ a real solution can be achieved by using complex numbers, the factors $e^{s_1 t}$ and $e^{s_2 t}$ then become trigonometric functions. Writing s_1 and s_2 as $\alpha \pm i\beta$ the solution is given as

$$V(t) = \frac{C_1 e^{\alpha t}}{\beta}\left(\alpha \sin(\beta t) + \beta \cos(\beta t)\right) \tag{8}$$

Thomas and Karlsson /3/ identified the above limits of propagation and non-propagation for concurrent flow flame spread. They expressed the velocity in terms of length, following the work of SQW. Kokkala and Baroudi /6/ represented these limits graphically in terms of τ, λ and a.

In this work the velocity is expressed in terms of areas, but the roots of the quadratic in the denominator of equation (4) are the same as in reference /3/ and /6/ so the same limits apply. The limits can therefore be represented graphically, following Kokkala and Baroudi /6/, and are shown in Fig. 3.

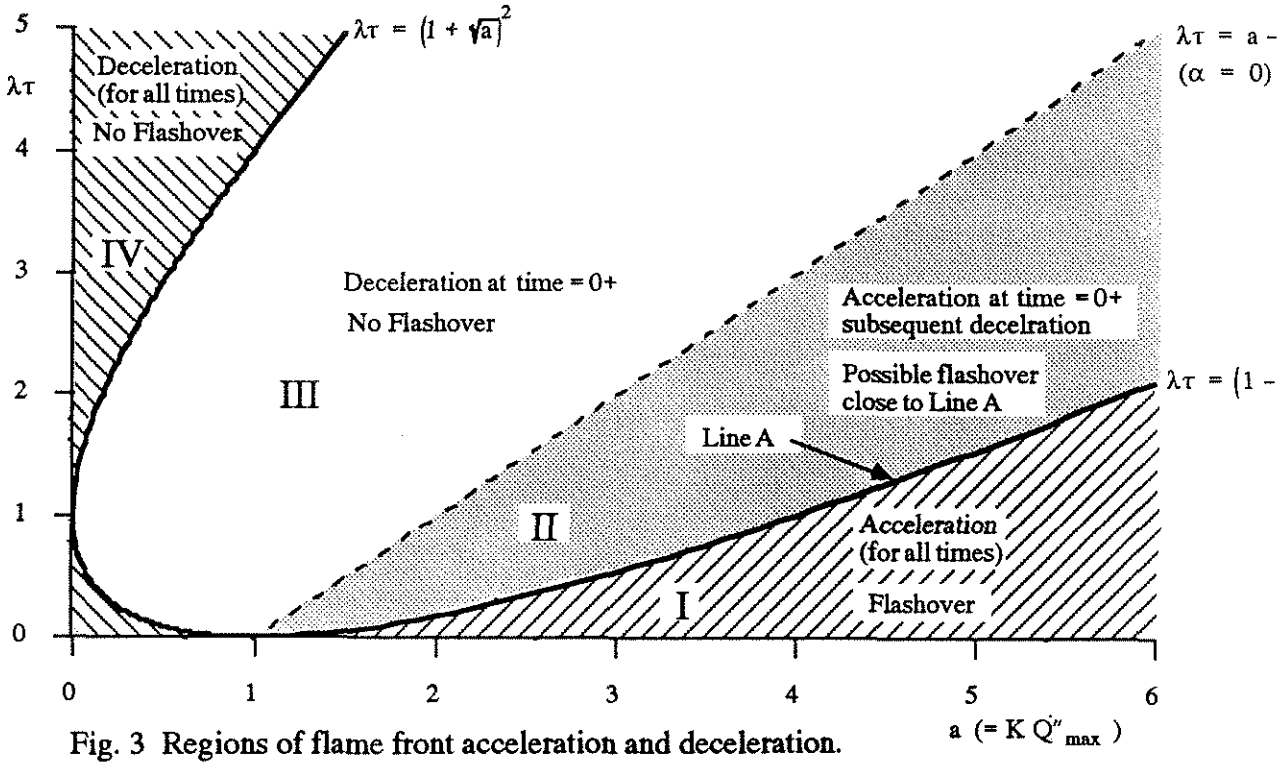

Fig. 3 Regions of flame front acceleration and deceleration.

The characteristic behavior of the solution for different parameters K Q''_{max} (= a) and $\lambda\tau$ is shown in Figure 3. Note that the solutions given above are only valid for a positive velocity since the flame height is always considered to be positive. In regions II and III the solutions are trigonometric and for long times the velocity oscillates between positive and negative values. In region II, V(t) -> ± ∞ as t -> ∞ and in region III, V(t) -> ±zero as t -> ∞. These solutions are, however, cease to be valid for flame spread once the velocity has become negative for the first time.

Exponentially accelerating flame spread appears in region I below line A. Materials no. 1, 2, 3, 8, 9, 11, 12 and 13 (see Table I) fall into this category and all of them go to flashover in the Room Corner test.

In region II the flame starts accelerating but then decelerates and stops at a finite time. A position just above Line A can therefore result in flashover since the flame can spread over a considerable area before it decelerates and finally stops. Material no. 7 (see Table I) shows such behavior, it is quite close to causing flashover in the Room Corner test. Materials no. 5 and 6 are much further away from Line A and the flame starts decelerating much earlier, showing a low risk for flashover.

In region III the solution of the above equations shows an initial deceleration. There is no acceleration until the velocity has been negative for some time. The equation for the velocity is only valid until the velocity has decelerated to zero and for all practical purposes materials in this region do not go to flashover in the Room Corner Test (material no. 4, see Table I). The same is true for region IV, except that the velocity decelerates for all times.

The roots of the quadratic in the denominator of equation (6) are the same whether the equations are set up for velocity in terms of areas under ceilings or linear velocities up a wall. Figure 3 is thus valid for other configurations than the Room Corner test and flame spread under a ceiling. The value and the units of K, the flame length or flame area coefficient, change in each configuration (flame spread up a corner, on a wall or under a ceiling) and so does the initial pyrolysing area, A_0, or pyrolysing length, x_p. Also, τ, the time to ignition, depends on the configuration.

4 Expressions for heat release rate and pyrolysing area

In order to calculate how far the flame front has travelled and the resulting heat release rate we must set up expressions, in terms of velocity, for the pyrolysing area, A_p, and the heat release from the ceiling, Q_c. The solutions are given in two parts, one for the region $\left(1-\sqrt{a}\right)^2 > \lambda\tau > \left(1+\sqrt{a}\right)^2$, when the flame accelerates or decelerates monotonously and another for the region $\left(1-\sqrt{a}\right)^2 < \lambda\tau < \left(1+\sqrt{a}\right)^2$, where flame spread will eventually cease.

The pyrolysing area as a function of time can be written as

$$A_p(t) = A_0 + \int_0^t V(t)\,dt \tag{9}$$

For $\left(1-\sqrt{a}\right)^2 > \lambda\tau > \left(1+\sqrt{a}\right)^2$ the solution is given as

$$A_p(t) = A_0 + \frac{C_1}{s_2 - s_1}\left(e^{s_2 t} - e^{s_1 t}\right) \tag{10}$$

and for $\left(1-\sqrt{a}\right)^2 < \lambda\tau < \left(1+\sqrt{a}\right)^2$ the solution is

$$A_p(t) = \frac{C_1 e^{\alpha t}}{\beta}\sin(\beta t) \tag{11}$$

Similarly, the heat release rate can be written

$$Q_c(t) = A_0 \dot{Q}''_{max} e^{-\lambda t} + \int_0^t \dot{Q}''_{max} e^{-\lambda(t-t_p)} V(t_p)\, dt_p \tag{12}$$

For $\left(1-\sqrt{a}\right)^2 > \lambda\tau > \left(1+\sqrt{a}\right)^2$ the solution is given as

$$Q_c(t) = A_0 \dot{Q}''_{max} e^{-\lambda t} + \frac{C_1}{s_2 - s_1}\left(\frac{s_2 \dot{Q}''_{max}\left(e^{s_2 t} - e^{-\lambda t}\right)}{s_2 + \lambda} - \frac{s_1 \dot{Q}''_{max}\left(e^{s_1 t} - e^{-\lambda t}\right)}{s_1 + \lambda}\right) \tag{13}$$

and for $\left(1-\sqrt{a}\right)^2 < \lambda\tau < \left(1+\sqrt{a}\right)^2$ the solution is given as

$$Q_c(t) = A_0 \dot{Q}''_{max} e^{-\lambda t} + C_1 C_2 \dot{Q}''_{max}\left[e^{at}\left(\cos(\beta t) + \frac{C_3}{\beta}\sin(\beta t)\right) - e^{-\lambda t}\right] \tag{14}$$

where $C_2 = \left(\frac{1}{\lambda}\left(\alpha^2 + \beta^2\right) + 2\alpha + \lambda\right)^{-1}$ and $C_3 = \frac{1}{\lambda}\left(\alpha^2 + \beta^2\right) + \alpha$

5 A simple model for calculating heat release rate in the Room Corner test (ISO 9705)

In the ISO 9705 procedure combustible lining materials are placed on both walls and ceiling. Time to flashover is, however, mainly due to ignition of the wall material behind the burner and a subsequent ignition and flame spread over the material in the ceiling. We shall therefore not consider the combustible material on the walls, other than that behind the burner.

The heat released in the Room Corner test is thus assumed to come from three sources. First, the gas burner releases around 100 kW, with flame heights that nearly reach the ceiling. After an ignition time τ, the material behind the burner ignites.

This causes the flames to hit the ceiling, the flame area in the ceiling being = A_0. After yet another ignition period τ, this ceiling area ignites and the flames spread along the ceiling.

The procedure for calculating the heat release rate is the following:

1) For $t < \tau$ $\quad Q(t) = Q_b$ (15)

2) For $\tau < t < 2\tau$ $\quad Q(t) = Q_b + Q''_{max} * A_w * e^{-\lambda(t-\tau)}$ (16)

3) For $t > 2\tau$ $\quad Q(t) = Q_b + Q''_{max} * A_w * e^{-\lambda(t-\tau)} + Q_c(t - 2\tau)$ (17)
where Q_c is calculated from equations (13) and (14).

Here, A_w stands for the wall area behind the burner, an area assumed to be equal to twice the burner width times the hight from the burner to the ceiling ($\approx$ 0.65 m^2 in the Room Corner test). Q_b is the burner output ($\approx$ 100 kW in the Room Corner test).

In equations (13) and (14) there are three parameters which have not yet been defined numerically, i.e. A_0, K and τ.

The time to ignition in the room corner test, τ, correlates strongly with time to ignition in the Cone Calorimeter (t_{ig}) at an irradiance level of 50 kW/m^2. It was found that a value of $\tau \approx 1.7 * t_{ig}$ gave a resonable representation of both time to ignition of the material behind the burner as well as the ignition time in the ceiling.

It is difficult to determine the numerical value of the flame length coefficient, K, from experiments. Parker /1/ reported a value of 0.022 [m^2/kW] from experiments in the ASTM E 84 Tunnel test. Saito, Quintiere and Williams /2/ report a value of 0.010 [m^2/kW] for upward flame spread on a wall. We assumed the value of this coefficient, for flame spread under a ceiling in the room corner test, to be between these two, a good fit was obtained by choosing K = 0.015 [m^2/kW].

It can be noted that the flame length coefficient has been expressed by Baroudi and Kokkala /6/ as $E'' = 1/K$, where E'' has a real physical meaning; the heat release rate per unit area of flame. The dimensionless parameter $a = Q''_{max}/E''$ is then easier to comprehend.

The initial pyrolysis area, A_0, depends on the amount of energy carried by the plume to the ceiling. We have assumed this amount of energy to be the burner output and the energy released by the material behind the burner, minus the energy lost in the wall corner plume.

Magnusson and Sundström /7/ have estimated the amount of energy lost in the plume to be in the area of 60 - 150 kW. When Q = 100 kW the flames do not reach the ceiling, so we have here used the value 150 kW for the energy lost in the plume and thus write

$$A_0 = K*[Q_b + Q''_{max}*A_w*e^{-\lambda\tau} - 150] \qquad (18)$$

Since there are difficulties in determining both A_0 and K experimentally, a proper parameter study should be carried out. The above values and expressions for these parameters must therefore be considered to be preliminary.

6 Comparison with experiments

Table I lists 13 materials which were both tested in the Cone Calorimeter /8/ and in the Room Corner test /9/. It lists the parameters Q''_{max} and t_{ig}, measured at an irradiance level of 50 kW/m^2 by Tsantaridis and Östman /8/. The heat release rate measured in the Cone Calorimeter is modelled mathematically as $Q(t) = Q''_{max}\, e^{-\lambda t}$.

The decay coefficient, $\lambda(t)$, can therefore be calculated, for each measured value of heat release in the Cone Calorimeter, from the expression

$$\lambda(t) = -\frac{\ln\left(\dot{Q}''_{Cone}(t) / \dot{Q}''_{max}\right)}{t} \qquad (19)$$

where $Q''_{Cone}(t)$ is the time dependent heat release rate from the Cone Calorimeter. This allows the average value of λ to be calculated, this value is listed in Table I. This way of determining λ is, however, not straight forward since only the first, decaying part of the heat release curve from the Cone is used in order to get a "best fit" (see Figure 2).

This problem can be avoided by solving equation (1) numerically, thus allowing the results from the Cone to be used directly. The drawback is that no analytical solutions can be obtained, thus clouding the physical meaning behind the equations and figures such as Figure 3 can not be obtained.

The equations above assume that the materials are thermally thick, the properties of composit materials are thus assumed to reflect their bulk properties.

Table I: Values of Q''_{max} and t_{ig} measured at an irradiance level of 50 kW/m^2 /8/, λ is an average of the values obtained by equation (19). The parameters KQ''_{max} and $\lambda\tau$ are used in Figure 3.

Mat. no.	Material name	Q''_{max} [kW/m^2]	λ [s^{-1}]	t_{ig} [s]	KQ''_{max} [-]	$\lambda\tau$ [-]
1	Insulating fiberboard	184	0.0090	12	2.76	0.18
2	Medium density fiberboard	208	0.0027	28	3.12	0.13
3	Particle board	204	0.0030	34	3.06	0.17
4	Gypsum plasterboard	151	0.0390	34	2.26	2.25
5	PVC cover on gypsum pl. board	210	0.0600	10	3.15	1.02
6	Paper cover on gypsum pl. board	254	0.0600	21	3.81	2.14
7	Textile cover on gypsum pl. board	408	0.0700	20	6.12	2.38
8	Textile cover on mineral wool	466	0.0800	11	6.99	1.50
9	Melamine-faced particle board	150	0.0016	40	2.25	0.11
10	Expanded polystyren	-	-	-	-	-
11	Rigid polyurethane foam	247	0.0200	2	3.71	0.68
12	Wood panel, spruce	168	0.0075	21	2.52	0.27
13	Paper cover on particle board	197	0.0041	27	2.96	0.18

The above procedure was applied to all these materials except material no. 10, Expanded Polystyrene, since this material melts in both the bench scale and full scale test and the theory is not considered to be valid for such materials. Using the model on this material results in a longer time to flashover than in the experiments.

The results are shown in Figures 4 through 15. The agreement with experimental data is good, except for material no. 9, Melamine Faced Particle Board. This is due to the way this material behaves in the Cone Calorimeter; there is a sharp pulse of heat release at time = 40 seconds (=t_{ig}), but then the material releases no more heat until time ≈ 200 seconds, thereafter showing a typical curve for the heat release rate.

7 Discussion

An extensive research program on combustible wall lining materials has been ongoing in Sweden for a number of years, where mathematical modelling of the Room Corner test has been one of the objectives /10/, /11/, /7/.

Among the modelling efforts is the work by Magnusson and Sundström /7/, who presented a model for calculating the heat release in the same scenario as has been

discussed above. The regression equation was capable of predicting heat release rates in both a full scale and a 1/3 scale of the Room Corner test, showing good agreement with experiments. The drawback with their approach was that materials which did not go to flashover could not be modelled, since no mechanism for a retreating flame was included.

Here, this drawback has been amended by applying a thermal theory for concurrent flow flame spread to the underside of a ceiling, thus including a possible retreat of the flame.

To summarize, a simple mathematical model for calculating heat release rate in the Room Corner test has been presented. The model is based on a thermal theory for concurrent flow flame spread. Pre-heating of the material is assumed to be due to radiation from the advancing flame, no account is taken of heating from other sources. Further, the radiation from the flame is assumed to be of a constant intensity over the flame length and zero beyond that.

Several other assumptions are made with respect to flame lengths, heat release rate and time to ignition. In spite of the simplicity of the model and the numerous assumptions, the results show good agreement with experiments. However, a parameter study should be carried out to determine the value of the flame length coefficient, K, and the initial pyrolysing area, A_0.

No sensitivity testing has so far been carried out with respect to the different assumptions and procedures enumerated above, such a study is being carried out but is not considered to lie within the scope of this article.

Finally, a recently (August 1991) published paper by Cleary and Quintiere /12/ is recommended to the interested reader. They discuss a an independently developed but somewhat similar mathematical model for calculating flame spread and heat release rates in the Room Corner test.

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List of Symbols

A_f	Flame area under ceiling (m^2)
A_p	Area of pyrolysing region under ceiling (m^2)
A_0	Initial area of pyrolysing region under ceiling (m^2)
A_w	Combustible wall area behind the burner (m^2)
a	Constant ($=K\ Q''_{max}$)
C_1	Constant (m^2/s)
C_2	Constant (s)
C_3	Constant (s^{-1})
K	Constant in flame area correlation (m^2/kW)
K_1	Constant in flame length correlation (m/kW^n)
k	Thermal conductivity of the solid fuel (kW/mK)
n	Constant in flame length correlation (-)
Q_b	Energy release rate from burner (kW)
Q'_w	Energy release rate from fuel per unit width (kW/m)
Q''_{max}	Maximum heat release rate of the fuel per unit area measured in the Cone Calorimeter at an irradiance level of 50 kWw/m^2 (kW/m^2)
Q''_{Cone}	Heat release rate from the Cone Calorimeter per unit area (kW/m^2)
Q_c	Total heat release rate from fuel in ceiling (kW)
Q	Total heat release rate (kW)
q''_f	Heat flux from the flame to the solid fuel (kW/m^2)
s	Laplace transform operator
s_1	Constant (s^{-1})
s_2	Constant (s^{-1})
T_{ig}	Surface temperature at ignition (K or °C)
T_0	Ambient temperature (K or °C)
t	Time (s)
t_{ig}	Time to piloted ignition in the Cone Calorimeter at an irradiance level of of 50kW/m^2 (s)
t_p	Dummy variable of integration (s)
V(t)	Velocity of the pyrolysis front (m^2/s)
$V_1(t)$	Linear velocity of the pyrolysis front (m/s)
x_f	Wall flame height (m)
x_p	Height of the pyrolysis front (m)
x_{p0}	Initial height of the pyrolysis front (m)
α	Constant (s^{-1})
β	Constant (s^{-1})
λ	Decay coefficient when simulating results from the Cone Calorimeter (s^{-1})
ρ	Density of the solid fuel (kg/m^3)
τ	Ignition time (s)
Δ	Constant (s^{-2})

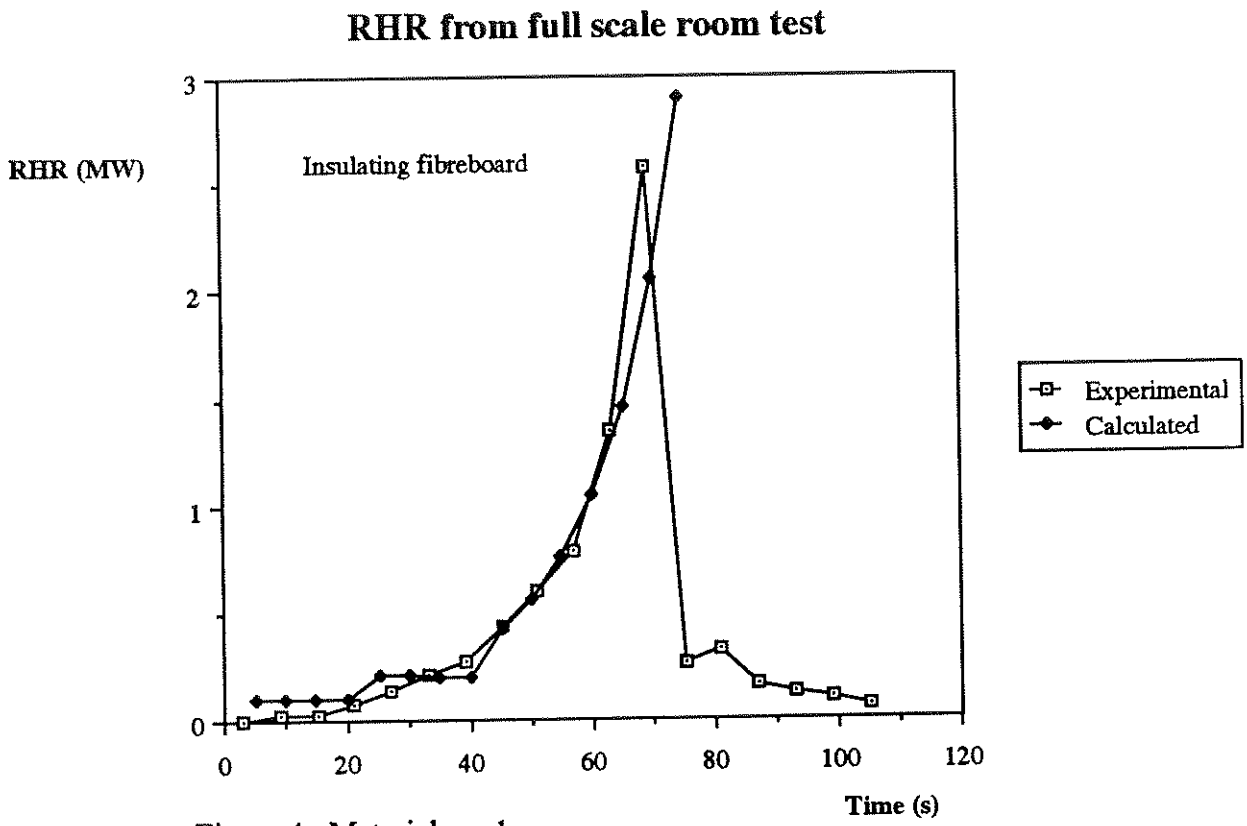

Figure 4. Material no. 1

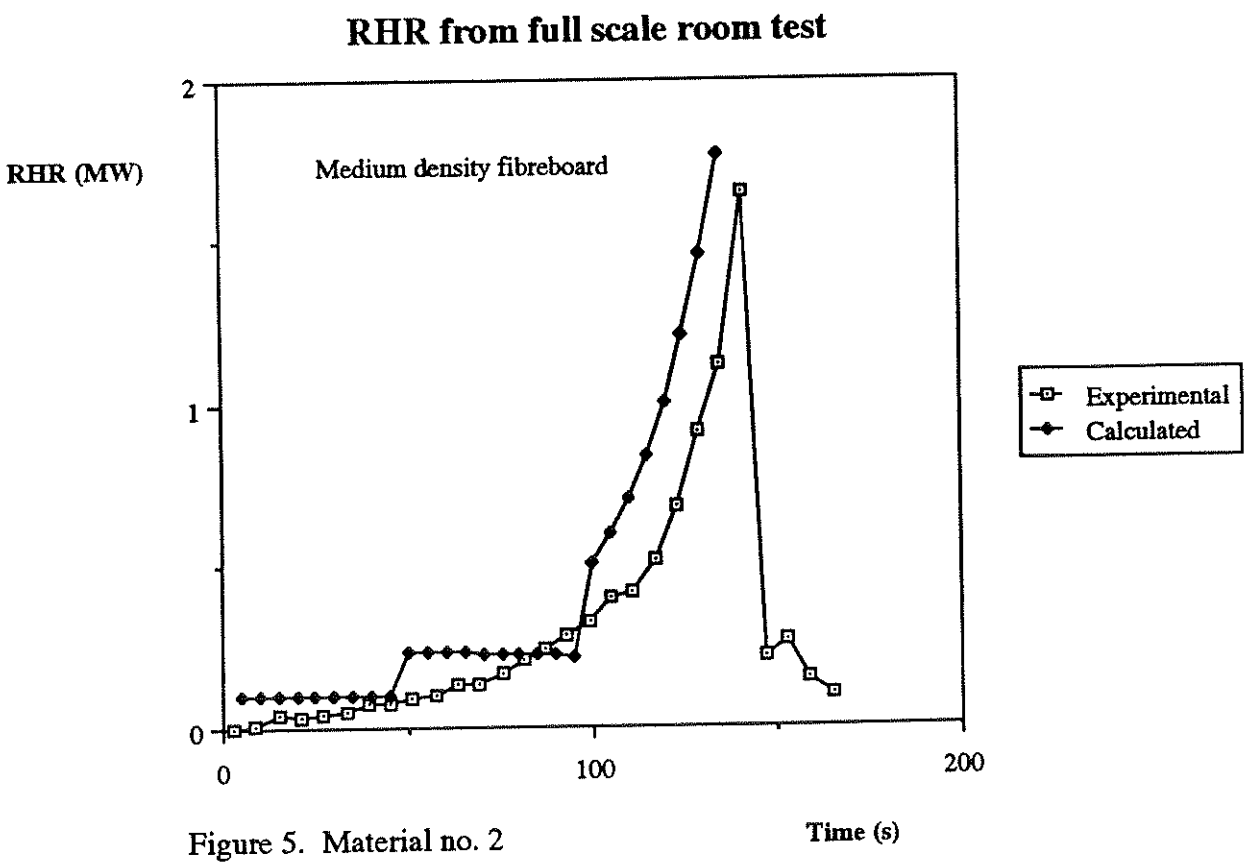

Figure 5. Material no. 2

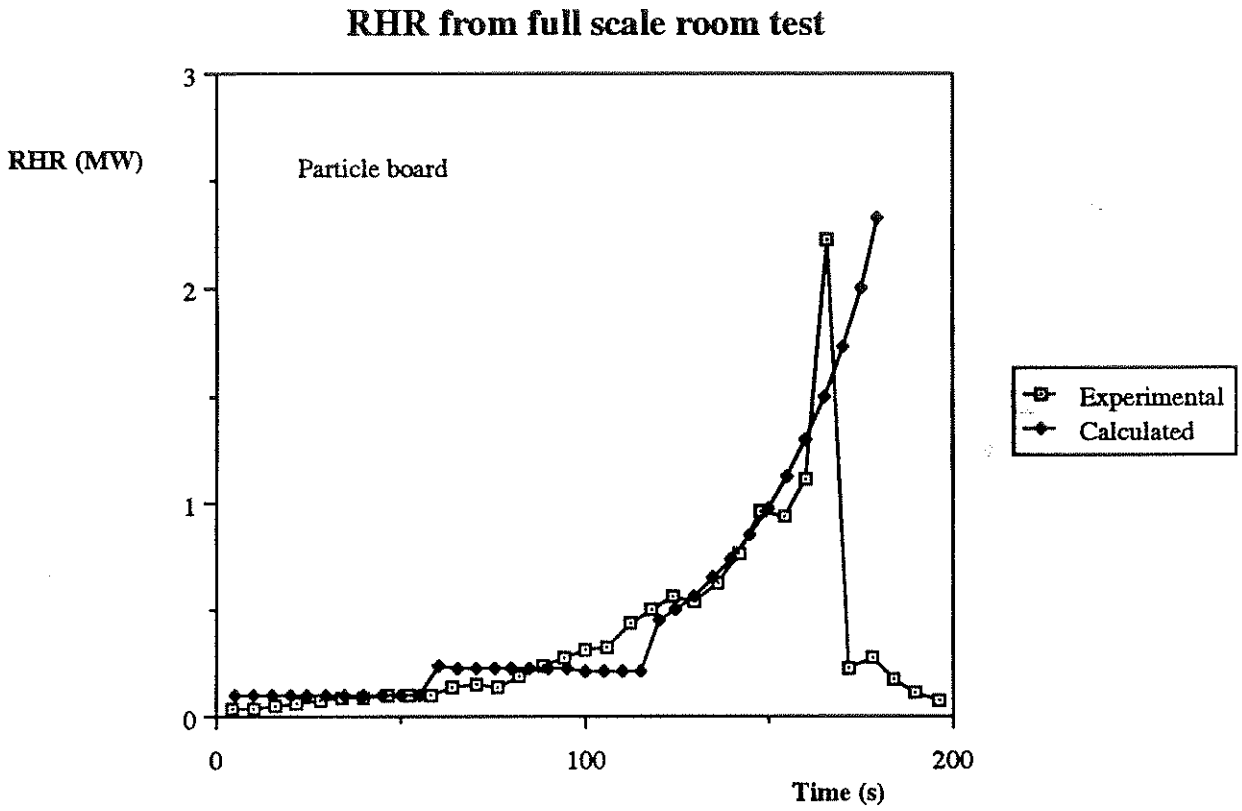

Figure 6. Material no. 3

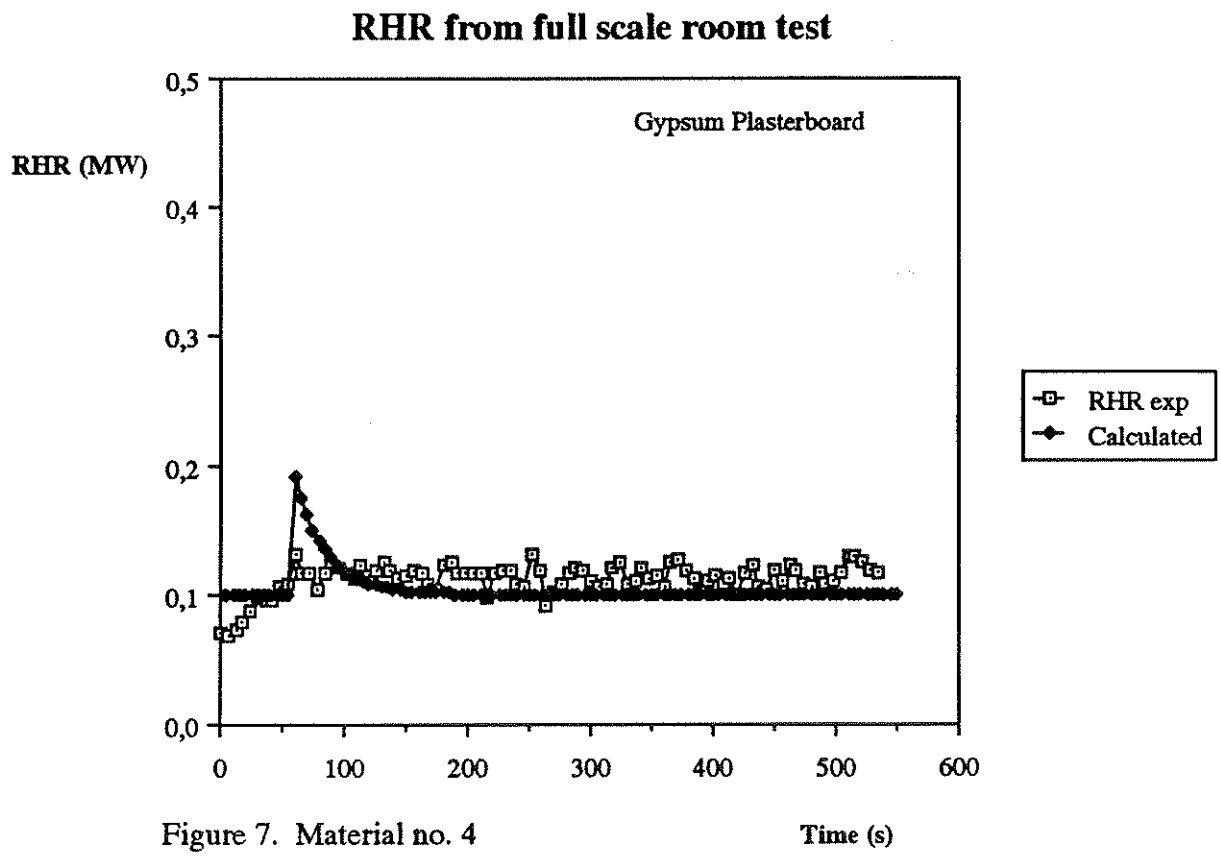

Figure 7. Material no. 4

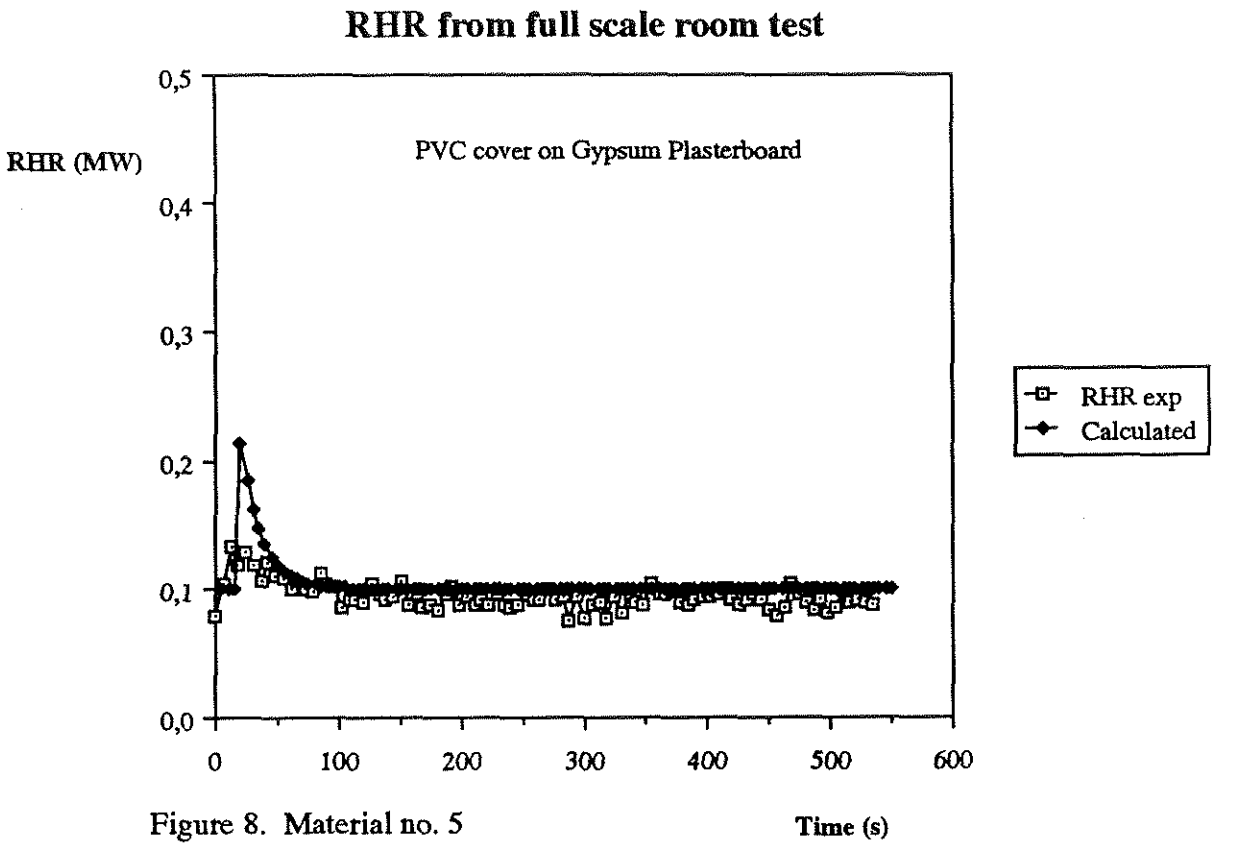

Figure 8. Material no. 5

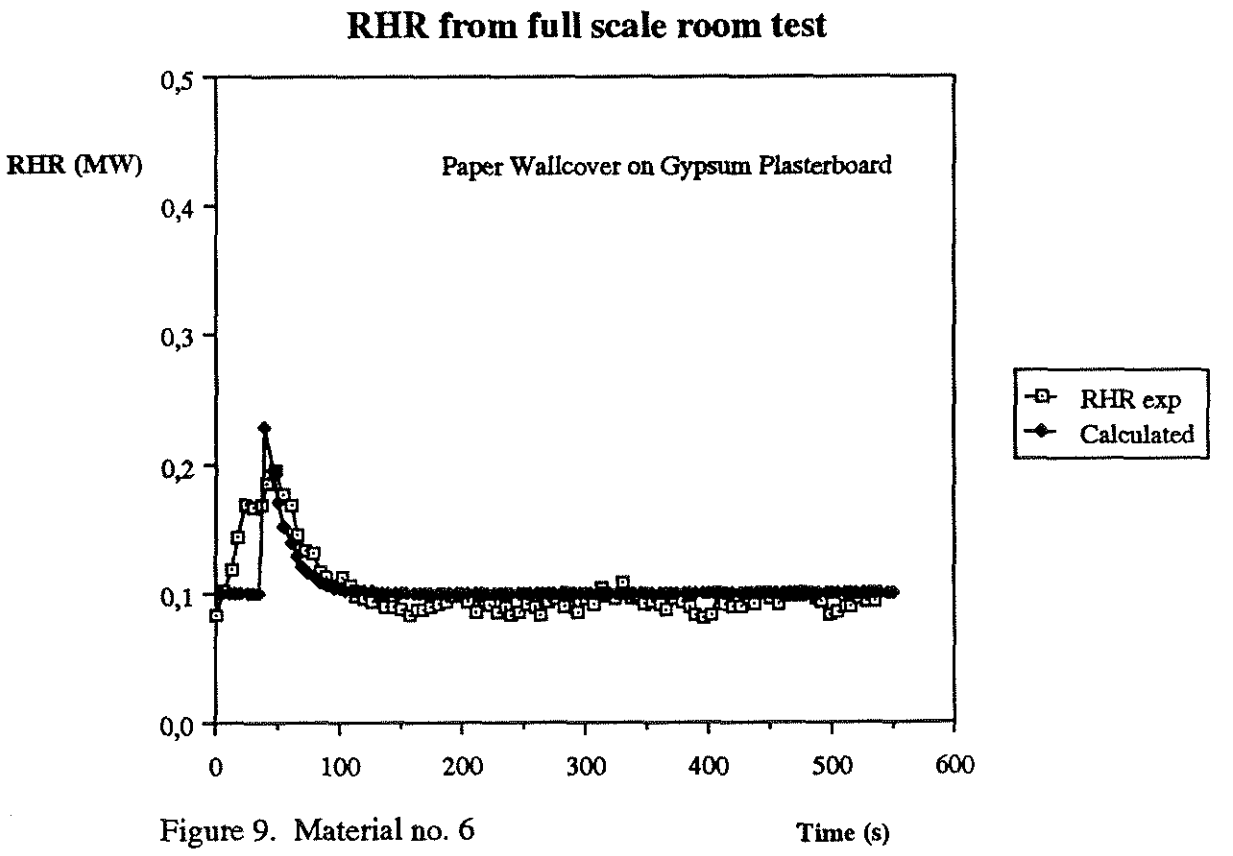

Figure 9. Material no. 6

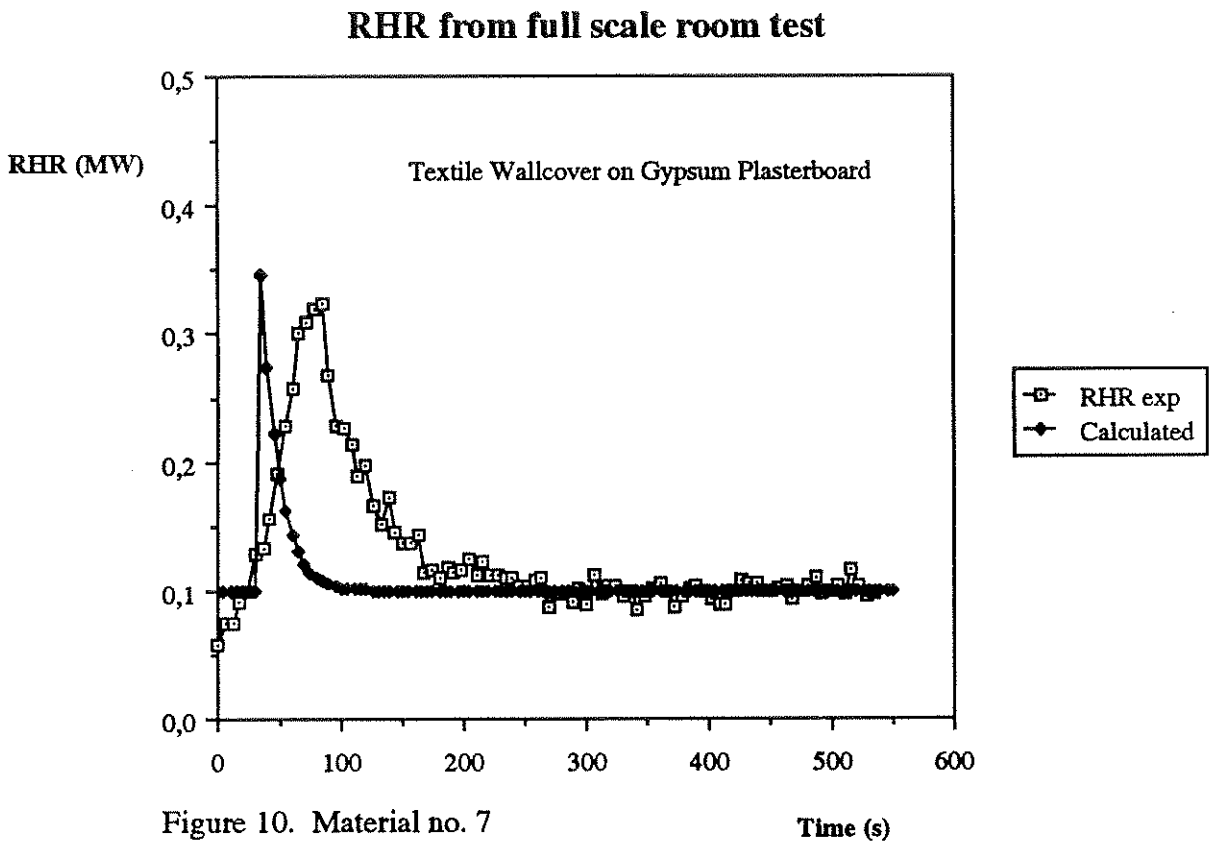

Figure 10. Material no. 7

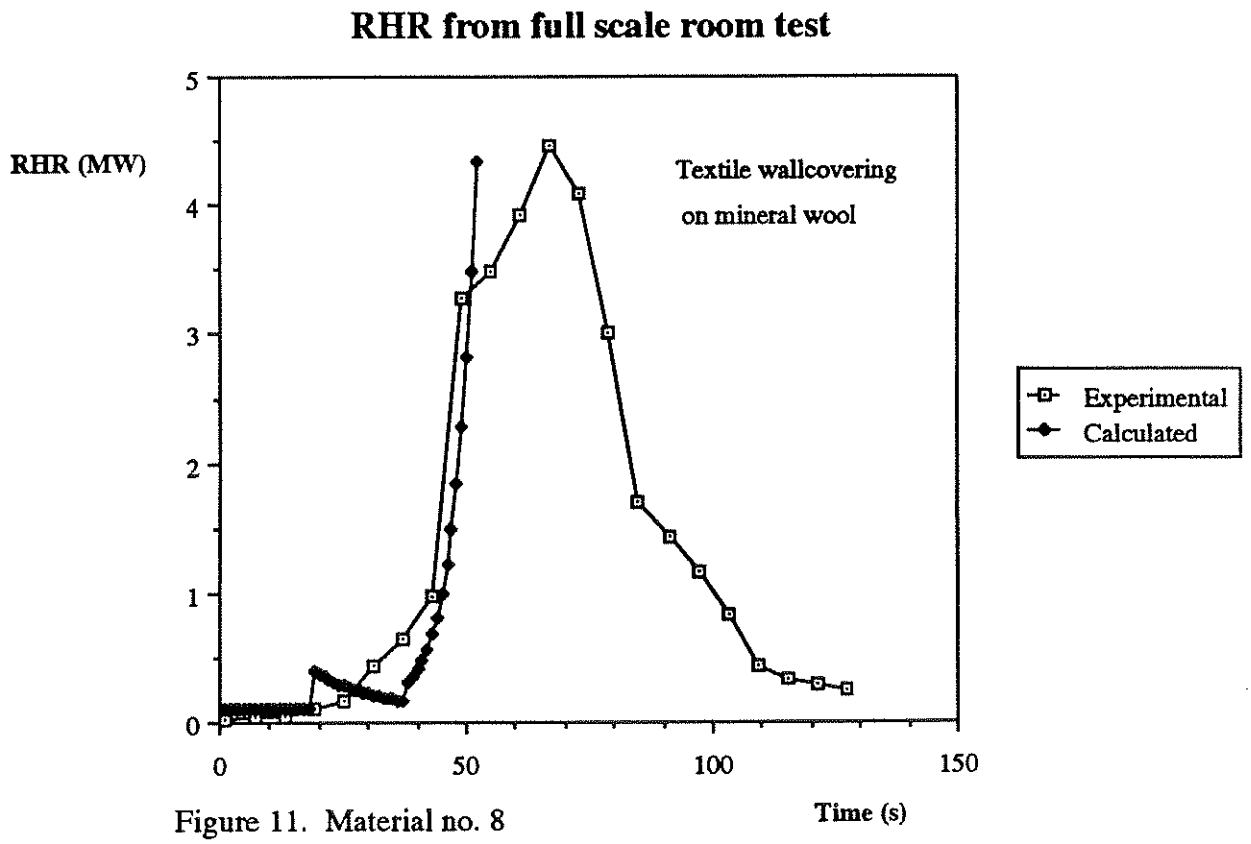

Figure 11. Material no. 8

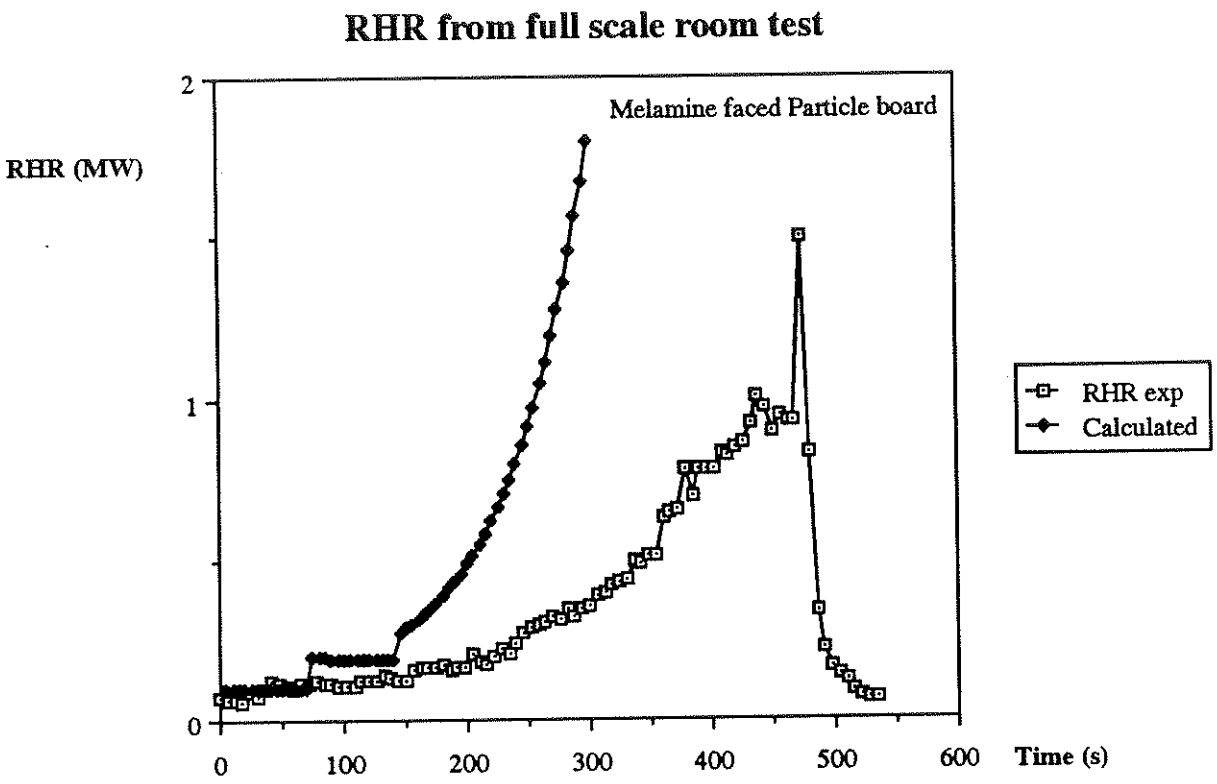

Figure 12. Material no. 9 (note comments on the results in the text)

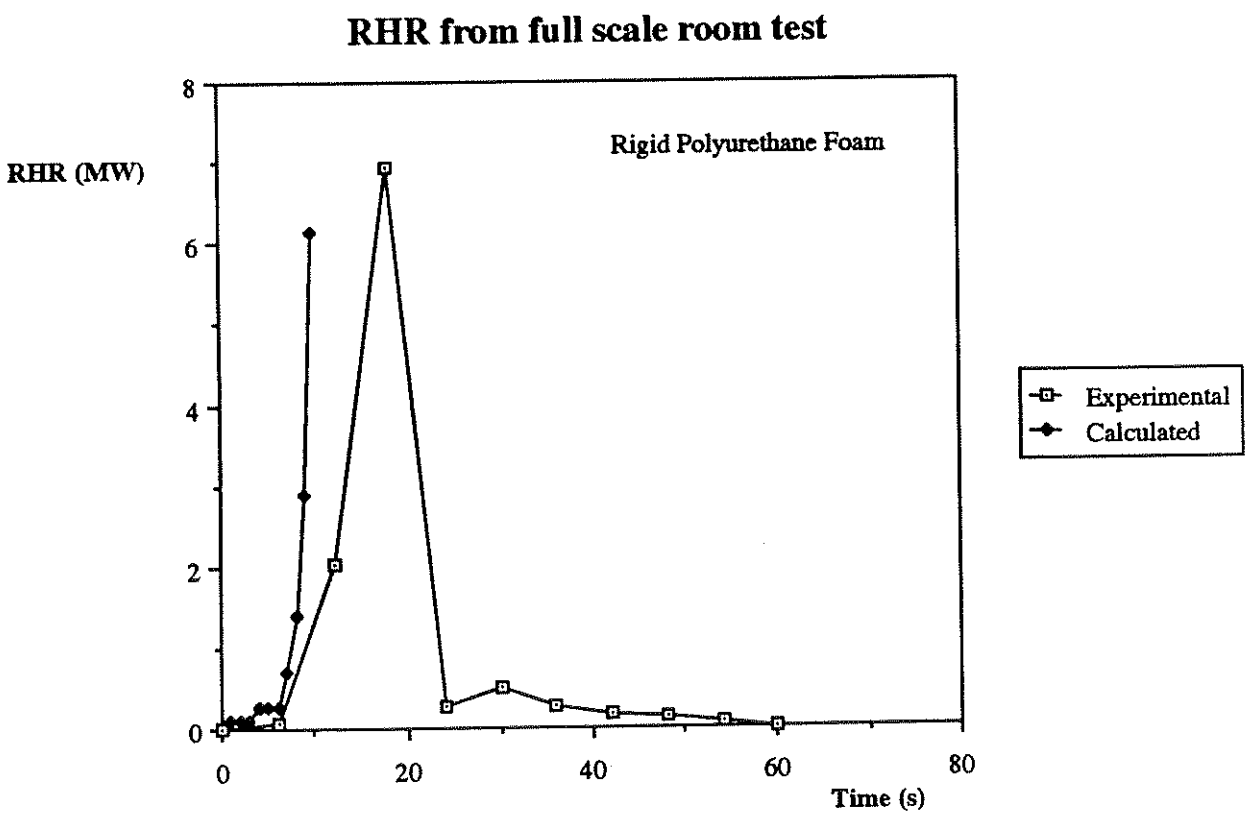

Figure 13. Material no. 11

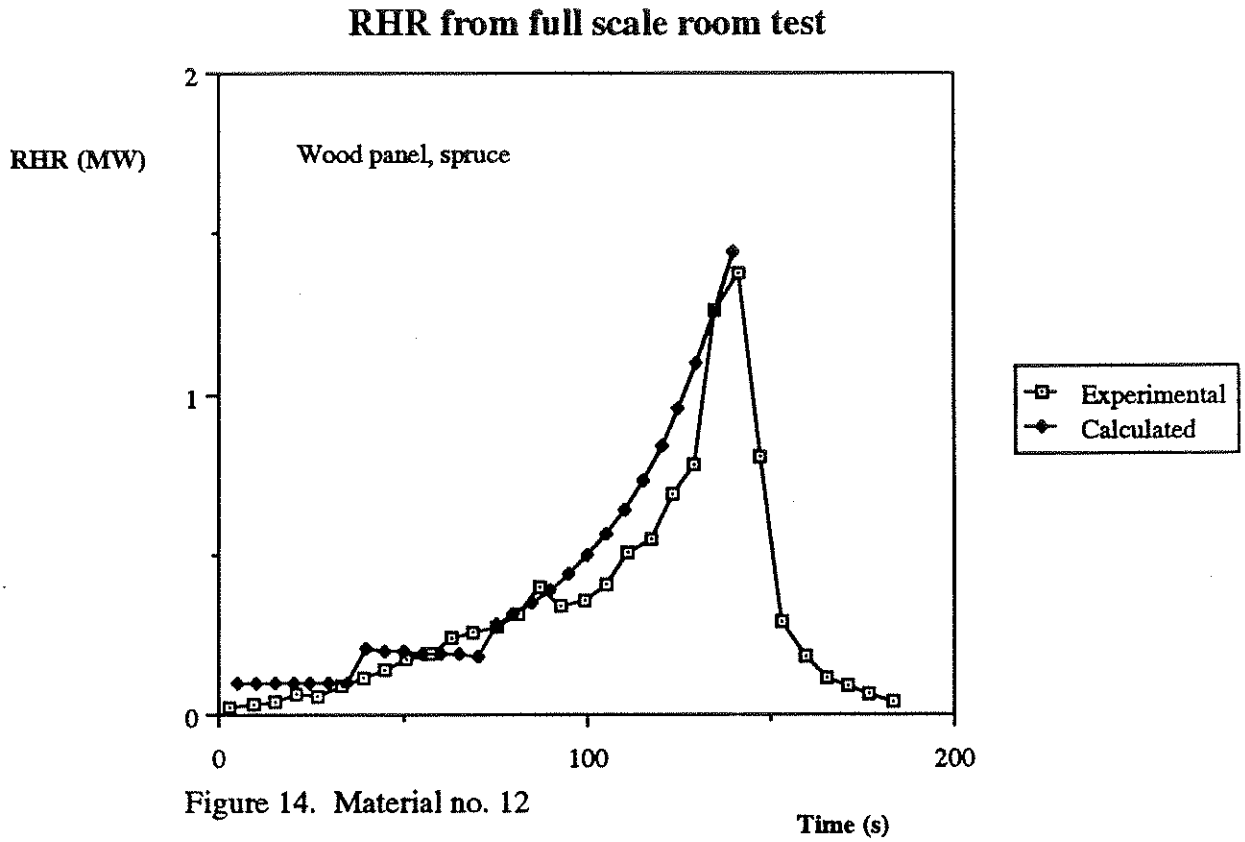

Figure 14. Material no. 12

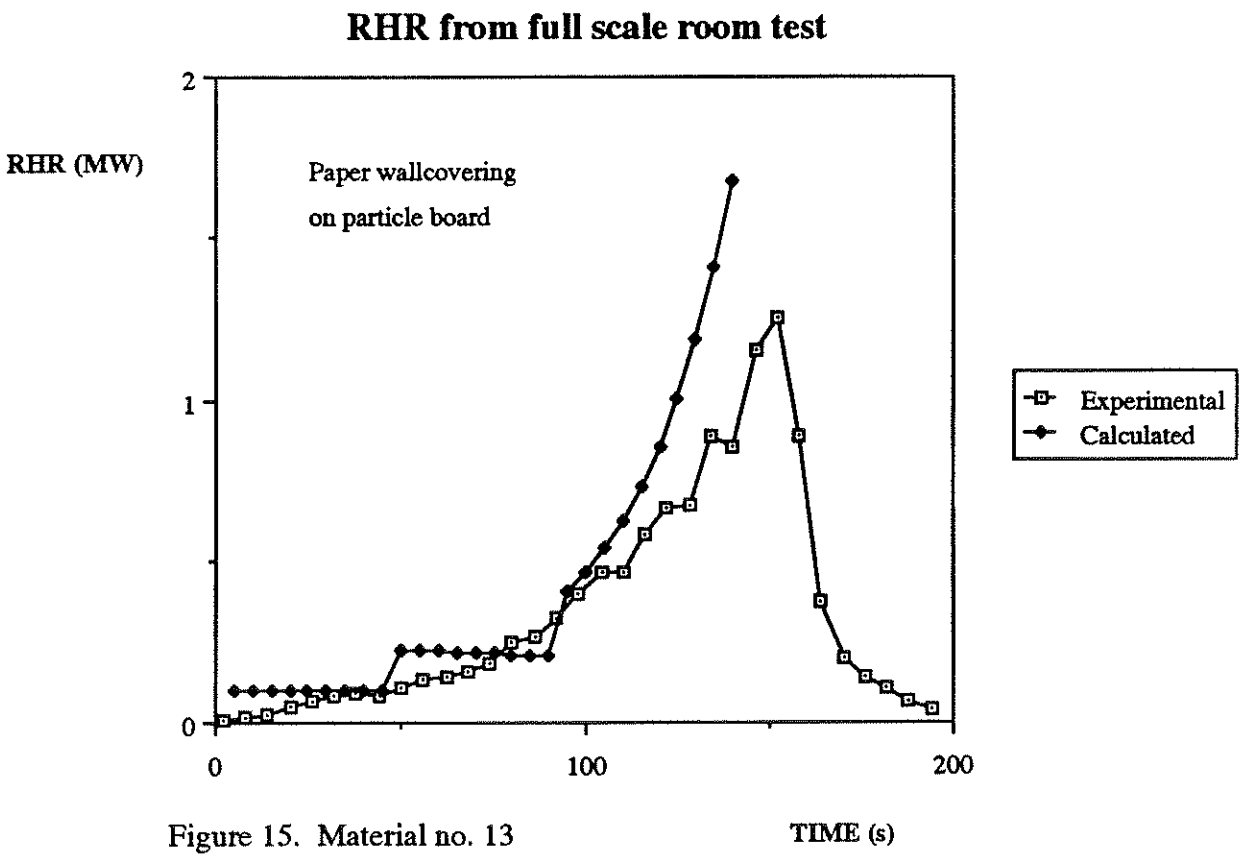

Figure 15. Material no. 13