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A ROOM-CORNER FIRE GROWTH & ZONAL MODEL FOR LINING MATERIALS

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A Room-Corner Fire Growth & Zone Model for Lining Materials

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ABSTRACT

This paper describes a computer fire model *BRANZFIRE*, intended for evaluating the performance and hazards associated with combustible room lining materials in a room-corner fire scenario. It comprises a single-room[1] zone model fully integrated or coupled with a flame spread and fire growth model applicable to a room-corner fire scenario. The fire growth model is a modified form of Quintiere's room-corner model which uses fire property data obtained from a Cone Calorimeter as input.

The computer model is compared with experimental data from the EUREFIC research project, with reasonable agreement. It is concluded that the model has the potential to differentiate the fire hazards associated with different combustible walls and ceilings in enclosures using a sound scientific approach.

Keywords: computer models, fire growth, fire hazard, flame spread, smoke filling.

INTRODUCTION

The purpose of this paper is to describe a model for predicting the fire environment in an enclosure resulting from a room-corner fire involving combustible wall and ceiling linings. The model combines a fire growth model for a room-corner fire scenario with a conventional zone model based on mass and energy conservation for a room. A description of the model physics is described by Wade [1].

Many existing fire zone models do not account for the ignition and burning of wall and/or ceiling lining materials, and as a result may underestimate the actual rate of fire development and hazard in cases where combustible room linings are present. Furthermore, unlike many computer models that have been developed, emphasis has been placed here on developing a user-friendly interface for this model, based on the Microsoft Windows environment, thus making it more accessible to fire protection engineers as well as other researchers.

The model described couples flame spread and fire growth calculations with a zone model. The advantage of this is that the effect of the developing hot layer on the lining flame spread rate due to pre-heating effects can be considered. The interaction between the fire growth and zone models is illustrated in Figure 1.

[1]recently extended to multi-room by LeBlanc and Ierardi, but not the subject of this paper.

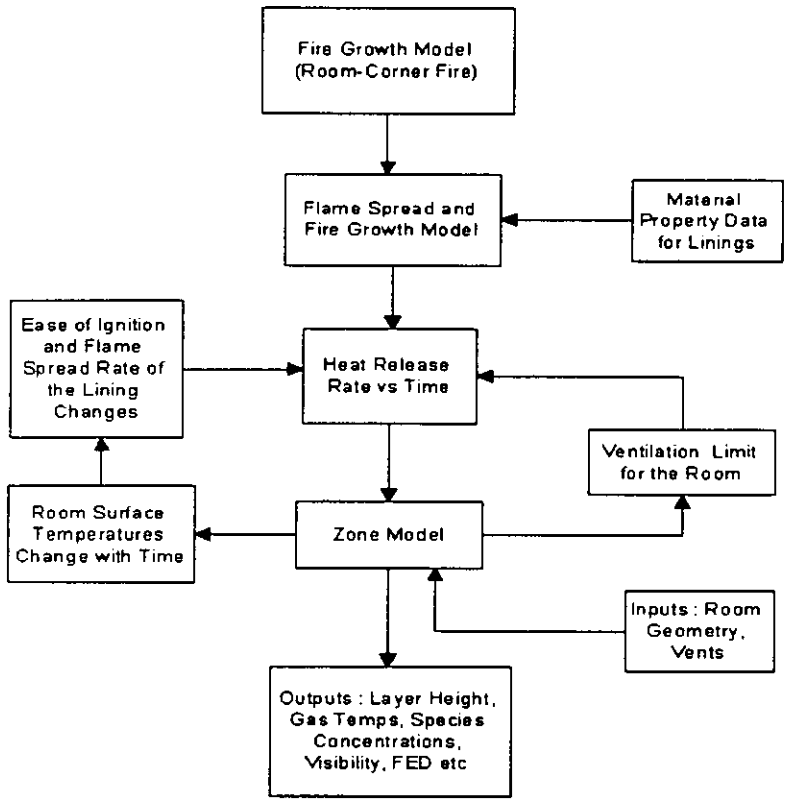


Figure 1: Structure of *BRANZFIRE* Model

THE FIRE GROWTH MODEL

The flame spread and fire growth model used is based on Quintiere's work [2]. The model predicts ignition, flame spread and the resultant heat released by the wall and ceiling lining material. Two modes of flame spread are considered. Upward flame spread includes the spread beneath the ceiling and along the wall/ceiling intersection in the region of the ceiling jet. The opposed flow flame spread includes lateral flame spread on the wall and downward spread from the ceiling jet.

While Quintiere's model has been used as the basis of the model described here, a number of significant modifications have been incorporated. These include:

- Assuming a non-uniform burning rate based on the time-dependent heat release rate data measured in a cone calorimeter. This assumption also negates the need to solve separately for the upward and lateral burnout fronts, as burnout is implicitly included in the heat release rate curve.
- Re-radiation from the lining material in the pyrolysis region is assumed to be based on a vaporisation temperature 100°C higher than the ignition temperature of the material as used by Janssens et al [3].
- The assumed flame flux from the burner is reduced as described in the next section following the recommendations of Janssens et al [3]. Quintiere originally assumed 60 kW/m^2.
- The surface temperatures for the wall and ceiling are determined using a finite difference method with the upper layer temperature as a boundary condition. The upper layer temperature is determined from a mass and energy balance for the room. As a result, an upper layer temperature correlation is not used.

Characterising the ignition source

In the ISO 9705 room-corner test, the wall is ignited with a propane gas burner of output 100 kW for the first 600 seconds, which is then increased to 300 kW until completion of the test at 1200 seconds.

The heights of the burner flame in the room-corner test [4] are assumed to be 1.3 m and 3.6 m for the 100 kW and 300 kW heat outputs respectively [2]. The burner flame is assumed to impinge a uniform heat flux onto the wall region defined by the flame height and the burner width. The burner flame heat flux follows the recommendations of Janssens et al [3] for the Nordic burner and is assumed equal to 44 kW/m^2 and 47 kW/m^2 for the 100 kW and 300 kW burner outputs respectively.

Ignition of the wall lining

The surface temperature of the wall adjacent to the burner flame is modelled using an implicit finite difference method for calculating heat conduction through the wall. The time to ignition is taken as the time at which the surface temperature first reaches or exceeds the ignition temperature of the lining material.

The net heat flux into the wall in the region of the burner flame, $\dot{q}''_{\text{net}}$, is given by summing the incident heat flux from the flame, $\dot{q}''_w$, the incident heat flux due to the heated gas layers and other room surfaces $\dot{q}''_{int}$ as determined by the zone model, less the re-radiation from the wall surface as follows:

$$\dot{q}''_{\text{net}} = \dot{q}''_w + \dot{q}''_{int} - \epsilon\sigma T_s^4 \qquad (1)$$

Energy release rate

The peak heat release rate per unit area for the lining material is estimated as generally described by Quintiere, as follows:

$$\dot{Q}''_p = \frac{\Delta H_c}{L_g}(\dot{q}''_w + \dot{q}''_{\text{int}} - \epsilon\sigma T_v^4) \qquad (2)$$

where $\dot{q}''_w$ is the burner flame heat flux over the pyrolysis region as described previously, $\dot{q}''_{\text{int}}$ is the heat flux from the hot gas layer and other room surfaces (excluding the reradiation term), and T_v is the assumed temperature of the pyrolysing surface and is assumed to be 100°C higher than the ignition temperature of the surface [3] or the surface temperature determined from the zone model, whichever is the higher. ΔH_c is the effective heat of combustion from the Cone Calorimeter, and L_g is the heat of gasification determined by the model from a correlation of the peak heat release rate data.

The model normalises the input heat release rate curve (from the Cone Calorimeter) by dividing by the peak heat release rate ($\dot{Q}''_{\text{p,cone}}$, from the Cone test) at each time. The value of the peak rate of heat release rate determined by equation 2 is then multiplied by the normalised ratio given that the elapsed time from ignition is known.

$$\dot{Q}''(t) = \frac{\dot{Q}_c''(t)}{\dot{Q}_{\mathrm{p,cone}}''}\dot{Q}_p'' \tag{3}$$

The total energy released is the sum of that from the burner, the walls and the ceiling and this is given by:

$$\dot{Q}(t) = \dot{Q}_b + \Sigma(\dot{Q}''(t)\Delta A_p(t)) \tag{4}$$

where $\dot{Q}_b$ is the heat release rate of the burner, $\dot{Q}''(t)$ is the heat release rate per unit area from the lining material at time t, and ΔA_p is the incremental pyrolysis area. At each timestep the pyrolysis area is calculated as described below, and the timestep at which each incremental area first ignited is therefore known. The total heat release rate is the sum of the incremental pyrolysis areas multiplied by the time-dependent heat release rate for each incremental area.

Determining the pyrolysis area

There are two cases to consider. The first is when the pyrolysis front has not yet reached the ceiling, and the second is when it has. The area calculations are the same as those described by Quintiere [2]. In the first case, the wall adjacent to the burner has ignited and is pyrolysing, while the pyrolysis front has not yet reached the ceiling, as shown in Figure 2. The region initially adjacent to the burner is defined by $(x_{p,o}, y_{p,o})$. On ignition of the wall, $x_{p,o} = 0.17$ m and $y_{p,o} = 1.3$ m for the ISO 9705 burner, where $y_{p,o}$ represents the height of the burner flame above the floor, and $x_{p,o}$ represents the width of the burner. The assumed flame height for the 300 kW burner regime is 3.6 m.

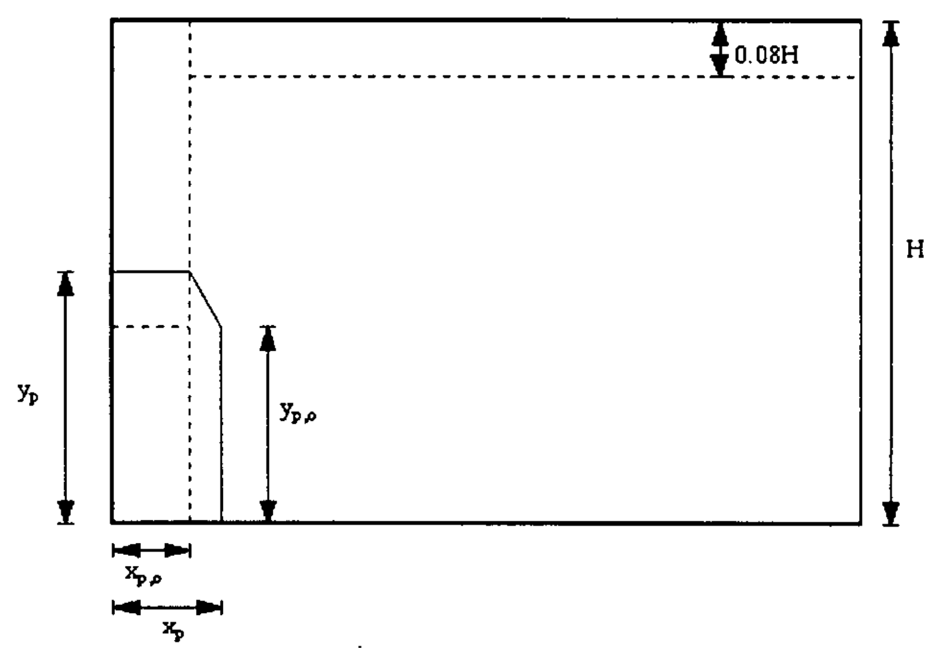


Figure 2: Wall ignited; pyrolysis front has not reached the ceiling

The pyrolysis area is given by:

$$A_p = 2\left[y_p x_{p,o} + (x_p - x_{p,o})y_{p,o} + 0.5(y_p - y_{p,o})(x_p - x_{p,o})\right] \tag{5}$$

In the second case, the wall adjacent to the burner has ignited and is pyrolysing, and the pyrolysis front has reached the ceiling, as shown in Figure 3.

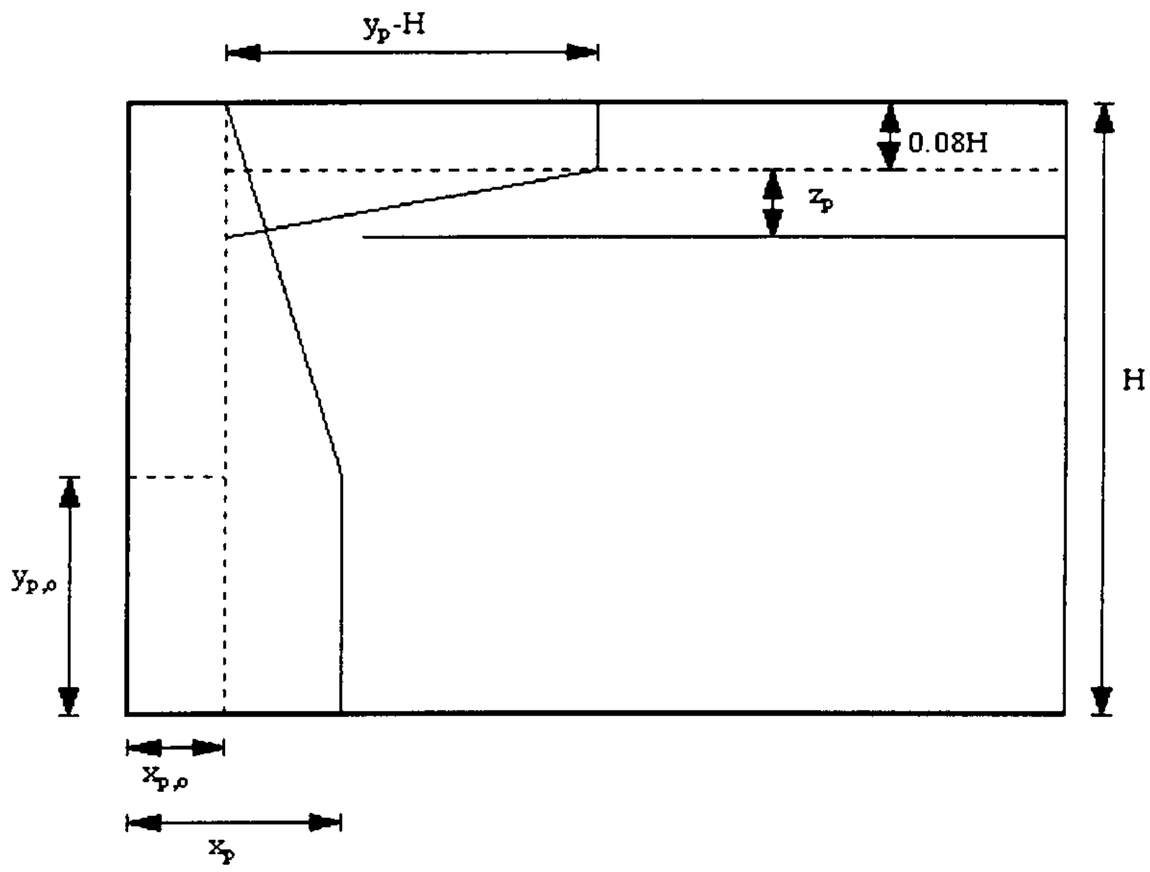


Figure 3: Wall ignited; pyrolysis front has reached the ceiling

The total pyrolysis area will be the sum of three areas - the wall area A_{p1}, the ceiling jet area A_{pj1}, and the ceiling area A_{pc1}. These required equations are given by:

$$A_{p1} = 2\left[Hx_{p,o} + (x_p - x_{p,o})y_{p,o} + 0.5(x_p - x_{p,o})(H - y_{p,o})\right] \quad (6)$$

$$z_p = x_p - x_p(t_H) \quad (7)$$

t_H is the time when the y-pyrolysis front reaches the ceiling.

For $z_p = 0$,

$$A_{pj1} = 2(y_p - H)(0.08H) \quad (8)$$

And for $z_p > 0$,

$$A_{pj1} = 2\left[(y_p - H)(0.08H) + 0.5z_p(y_p - H) - 0.5(0.08H + z_p)^2\left(\frac{x_p - x_{p,o}}{H - y_{p,o}}\right)\right] \quad (9)$$

$$A_{pc1} = \text{ the lesser of } \frac{\pi}{4(y_p - H)^2} \text{ or the ceiling area} \quad (10)$$

$$A_p = A_{p1} + A_{pj1} + A_{pc1} \quad (11)$$

Upward flame spread

The governing equation for upward flame spread is given by Quintiere as:

$$\frac{dy_p}{dt} = \frac{y_f - y_p}{t_{ig}} \tag{12}$$

where t_{ig} is given by:

$$t_{ig} = \frac{\pi}{4} k\rho c \left[\frac{T_{ig} - T_s}{\dot{q}''_{ff}}\right]^2 \tag{13}$$

The heat flux ahead of the flame, $\dot{q}''_{ff}$, is assumed to be 30 kW/m^2, while T_s is the lining surface temperature. y_p is the position of the upward pyrolysis front and y_f is the flame length in the upward direction and is given by:

$$y_f = K(\dot{Q}'_b + \dot{Q}''_p y_p)^n \tag{14}$$

where K is the flame area constant (=0.067), n is the flame length power (=2/3) and $\dot{Q}''_p$ is the heat release rate per unit area for the lining material. $\dot{Q}'_b$ is the energy release rate for the burner equivalent to a line source such that the burner flame length is equal to $K\dot{Q}'^n_b$ as follows:

$$\dot{Q}'_b = \left(\frac{L}{K}\right)^{1/n} \tag{15}$$

In addition, the model allows for the height of the burner above the floor, and takes this into account in the calculations although this is not shown in the above equations. This height is taken as 0.3 m for the ISO 9705 burner.

Lateral and downward flame spread

The lateral pyrolysis front is given by:

$$\frac{x_p}{dt} = \frac{\Phi}{k\rho c(T_{ig} - T_s)^2} \tag{16}$$

where Φ is a flame spread parameter. Equation 16 is only applicable for $T_s \geq T_{s,min}$. $T_{s,min}$ is the minimum surface temperature for spread. Φ and $T_{s,min}$ are determined from the LIFT test [5].

Numerical solution

Equations 12 and 16 are solved using a fourth order Runge-Kutta technique. The routine comprises an adaptive driver which estimates the step size to achieve the desired accuracy.

THE FIRE ZONE MODEL

Conservation terms

The zone model solves for the upper and lower layer temperatures, upper layer volume and species concentrations. The pressure equation is not solved. The ordinary differential equations for the upper layer volume, V_u, and for the upper layer temperature, T_u, based on conservation of mass and energy for the upper layer are given by:

$$\frac{dV_u}{dt} = \frac{(1-\lambda_r)\sum \dot{Q}_f + \sum \dot{m}_p c_p T_l - \sum \dot{m}_o c_p T_u + \dot{q}_u}{\rho_\infty T_\infty c_p} \tag{17}$$

$$\frac{dT_u}{dt} = -\frac{T_u \left(c_p(T_u - T_l)\sum \dot{m}_p - (1-\lambda_r)\sum \dot{Q}_f - \dot{q}_u\right)}{\rho_\infty T_\infty c_p V_u} \tag{18}$$

where λ_r is the radiant loss fraction, $\dot{Q}_f$ is the total heat release rate of the fire, $\dot{m}_p$ is the mass flow in the plume, T_l is the lower layer temperature, $\dot{m}_o$ is the mass flow out the vent, $\dot{q}_u$ is the net heat transfer to the upper gas layer, c_p is the specific heat of air, while ρ_∞ and T_∞ are the reference ambient density and temperature respectively. Similar equations are also formulated for the lower layer temperature and species concentrations. These equations are then solved using a fourth order Runge-Kutta technique. The routine comprises an adaptive driver which estimates the error and adapts the step size to achieve the specified accuracy. A more complete description of the zone model is given by Wade [1].

Plume entrainment and vent flows

The mass flux entrained into the plume for the continuous flaming, intermittent and buoyant plume regions respectively is given by McCaffrey [6], with modifications for the room-corner environment as suggested by Mowrer and Williamson [7].

For the corner fire the entrainment rate is taken as 0.59 × the entrainment rate for the same fire in the center of the room [7]. The heat release rate used in the plume correlation is the sum of the heat release from the burner and from the wall lining material below the smoke layer interface height. The entrainment model used here is a simplification of the actual situation.

The mass flow of air and hot gases through a wall vent is driven by buoyancy. Bernoulli's equation can be used to calculate the flows. For two-way flow, the expressions given by Rockett [8] are used.

The mass flow of hot gases flowing out of, and cooler gases flowing in through, a rectangular vent is given by the following equations [8]:

$$\dot{m}_o = \frac{2}{3} c_d W_o \frac{\rho_\infty T_\infty}{T_{\text{ext}}} \left[2g\frac{T_{\text{ext}}}{T_u}\left(1 - \frac{T_{\text{ext}}}{T_u}\right)\right]^{1/2} (H_o - Z_N)^{3/2} \tag{19}$$

$$\dot{m}_i = \frac{2}{3} c_d W_o \frac{\rho_\infty T_\infty}{T_{\text{ext}}} \left[2g\left(1 - \frac{T_{\text{ext}}}{T_u}\right)\right]^{1/2} (Z_N - Z)^{1/2}(Z_N + Z/2) \tag{20}$$

where m_o and $\dot{m}_i$ are the mass flows out and in through the vent, W_o and H_o are the width and height of the vent, Z_N is the height of the neutral plane and Z is the layer interface height. The position of the neutral plane can be found by equating equations 19 and 20 assuming the mass loss from the fuel is negligible compared to the vent flows. This is done by a process of iteration at each timestep after assuming an initial value for the location of the neutral pressure plane. A discharge coefficient, c_d, of 0.68 is assumed as recommended by Prahl and Emmons [9].

Heat transfer

The model incorporates a four-wall radiation exchange algorithm following the method described by Forney [10]. This algorithm allows the ceiling, upper wall, lower wall and floor to transfer radiation independently. Radiant heating of these surfaces by the flames is also considered by treating the fire as a point source. The emission of radiation by soot particles in the upper layer and absorption by carbon dioxide and water vapour is also considered for both layers. The radiation exchange submodel is required to determine the net radiant heat flux emitted or absorbed by each room surface (i.e. upper and lower walls, ceiling and floor). These radiant fluxes are combined with the convective heat flux and used as the boundary condition for the heat conduction calculations, while the gas layer absorption due to carbon dioxide and water vapour, and emission due to soot particles, are required for the energy source terms in the ordinary differential equations of the zone model.

An implicit one-dimensional, 20-node[2] finite-difference scheme was used to calculate heat conduction through the ceiling, upper walls, lower walls and floor. This allows the temperature at any node to be calculated by solving a set of simultaneous equations for the unknown nodal temperatures at each time step [11]. The detailed calculations for all the heat transfer processes can be found elsewhere [1].

THE EUREFIC EXPERIMENTS

The EUREFIC [12] (EUropean REaction to FIre Classification) research programme aimed at developing evaluation and classification methods for the fire behaviour of wall and ceiling lining materials in the Nordic countries. Eleven room lining materials were tested at small-scale in the Cone Calorimeter [13] and at full-scale in a room-corner test [4].

The times to ignition in the Cone Calorimeter were correlated following the method of Grenier and Janssens [14] in order to estimate the ignition temperature, T_{ig}, and the effective thermal inertia, $k\rho c$. Time to ignition was generally taken as the time for the heat release rate to reach 30 kW/m^2 [15]. The heat of combustion, ΔH_c, and the latent heat of gasification, L_g, were also estimated from the Cone Calorimeter data, with the latter determined from the slope of a linear regression line through a plot of the peak heat release rate versus the external heat flux [2]. These correlations are carried out automatically by the *BRANZFIRE* model given a series of test heat fluxes, ignition times and peak heat release rate values as input data. Approximate estimates for the flame spread parameter, Φ, and the minimum temperature for surface spread, $T_{s,min}$, were made from the literature. The thermal conductivity for each material was also estimated from the literature.

[2]two layers can be specified with 20 nodes each layer.

For two of the eleven materials the small scale data did not correlate well enough for the ignition temperature and thermal inertia to be determined, and these materials were therefore omitted from the comparison shown here. The flame spread and heat release rate properties used as input to the *BRANZFIRE* model are given in Table 1. For each material, a time-dependent heat release rate curve is also required to be input to the model. The model uses the shape of the curve in conjunction with a calculated peak value to determine the applicable heat release rate for each incremental area at each time step.

Surface emissivities were assumed to be 0.88 for all materials except the polyurethane foam covered with steel sheet, where 0.22 was assumed. The lining material was assumed to be fixed to the walls and ceiling and in contact with a substrate comprising 150 mm thick lightweight concrete with an assumed thermal inertia of 0.15 $(kW/m^2K)^2s$. This was taken into account by the model when determining the ignition time of the surface material, and when determining the conduction losses into the room boundaries.

Material	T_{ig} (°C)	$k\rho c$ $(kW/m^2K)^2s$	Φ (kW^2/m^3)	$T_{s,min}$ (°C)
painted gypsum paper-faced plasterboard	467	0.366	14	380
ordinary plywood	428	0.182	13	120
textile wallcovering on gypsum paper-faced plasterboard	327	0.369	9	270
melamine-faced high density noncombustible board	542	0.207	1	435
plastic-faced steel sheet on mineral wool	294	0.772	25	300
FR particleboard	423	0.088	8	180
polyurethane foam covered with steel sheet	199	0.027	3	105
PVC wall carpet on gypsum paper-faced plasterboard	307	0.251	25	300
FR polystyrene	299	0.398	31	130

Table 1: Flame Spread and Heat Release Properties for the EUREFIC Materials

Results and computer simulations

Figures 4 to 12 compare the predicted and measured heat release rates in the room-corner test for the nine EUREFIC materials. In seven of the nine cases, the model correctly predicted whether a 1MW heat output was reached, and if so, whether this occurred before or after 600 seconds. In the case of the textile wall covering on gypsum board (Figure 6), the model predicted the initial rate of fire growth reasonably well, although the experiment peaked early, at about 600 kW, while the model predicted accelerating fire growth at this time. In the case of the polyurethane foam covered with steel sheet (Figure 10), again the initial rate of fire growth was well predicted but the model peaked at about 900 kW, while the fire growth in the experiment continued to flashover. For each material, the model input consisted of a heat release rate curve from the Cone Calorimeter for the material, and the time to ignition and peak heat release rate for a series (at most four) of external heat fluxes. A lateral flame spread parameter and minimum temperature for spread were also specified. In general the *BRANZFIRE* model is able to predict the material behaviour in the ISO 9705 room-corner test reasonably well.

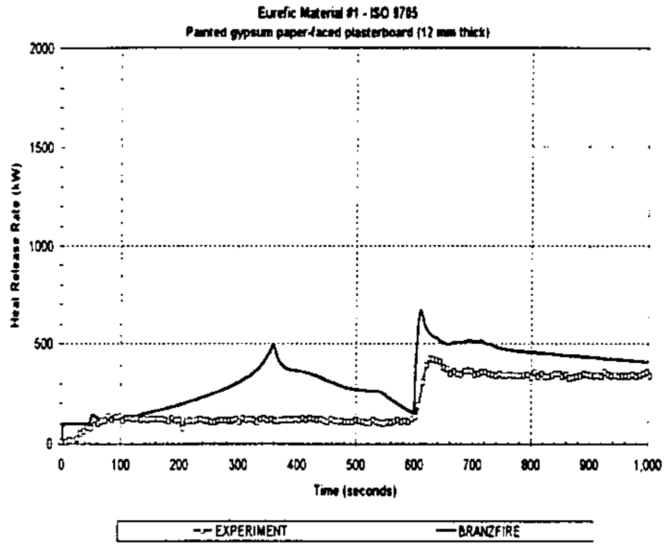
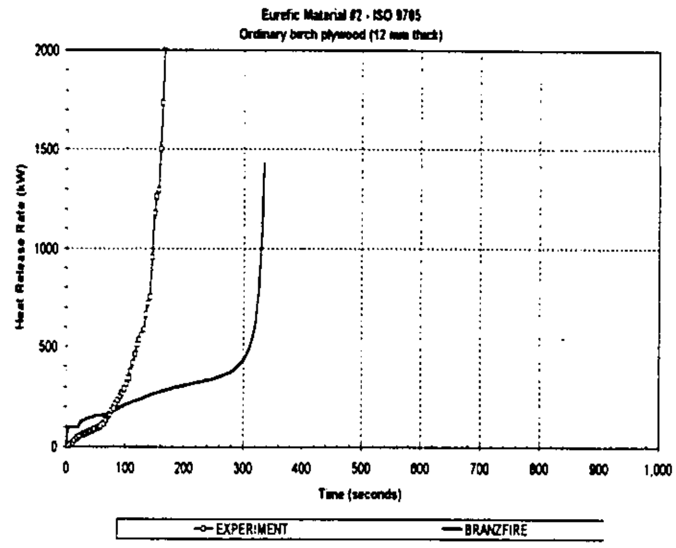


Figure 4



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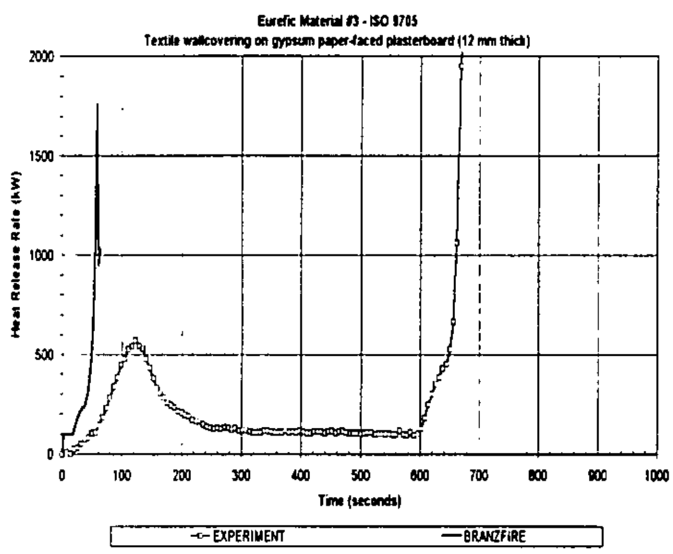

Figure 6

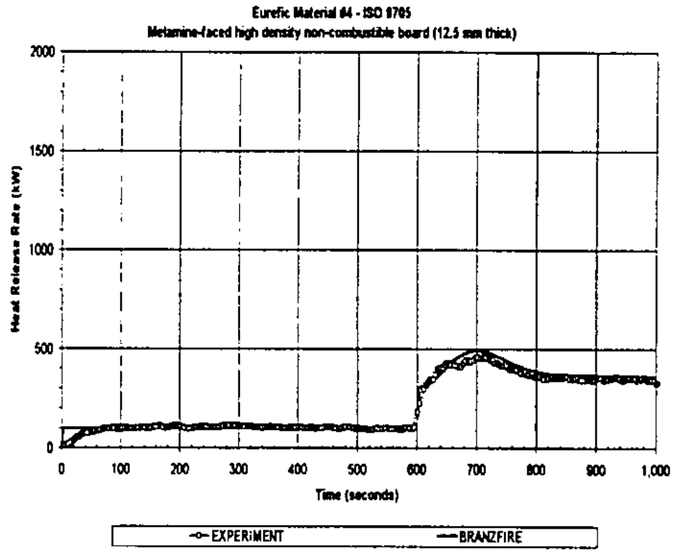

Figure 7

CONCLUSIONS

The combined fire zone and fire growth model described here can be used to differentiate the fire performance and likely fire hazards associated with different room lining materials in a manner consistent with sound scientific and engineering principles.

The *BRANZFIRE* model [3] is being further developed at the Building Research Association of New Zealand, in collaboration with Worcester Polytechnic Institute (USA).

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[3] beta software available for download on the internet from http://www.branz.org.nz/~fireres/software.htm

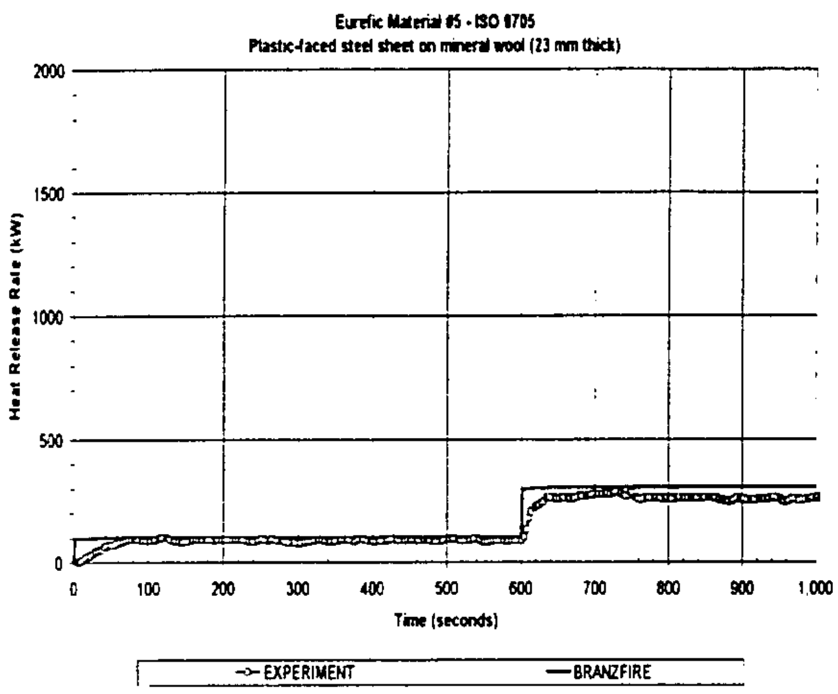

Figure 8

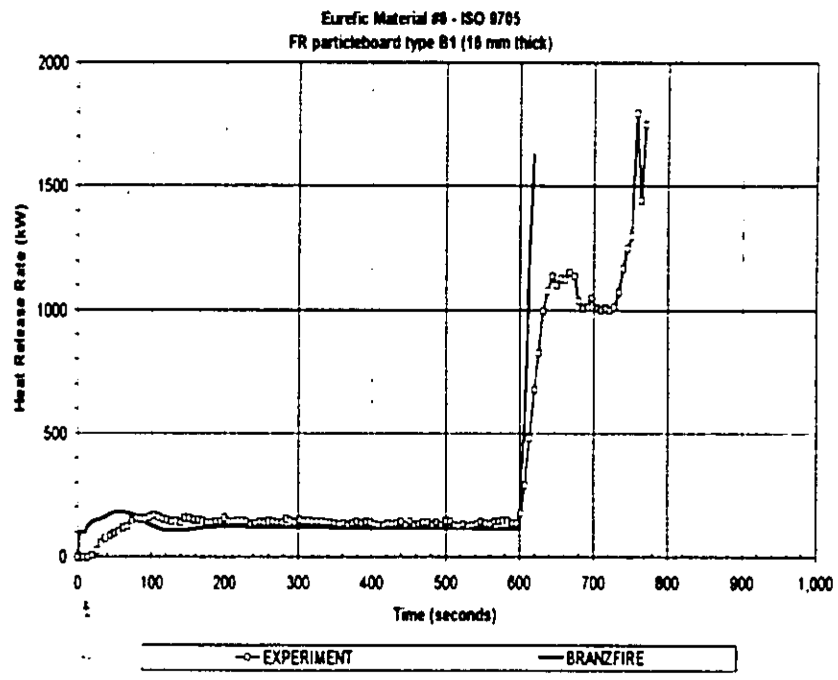

Figure 9

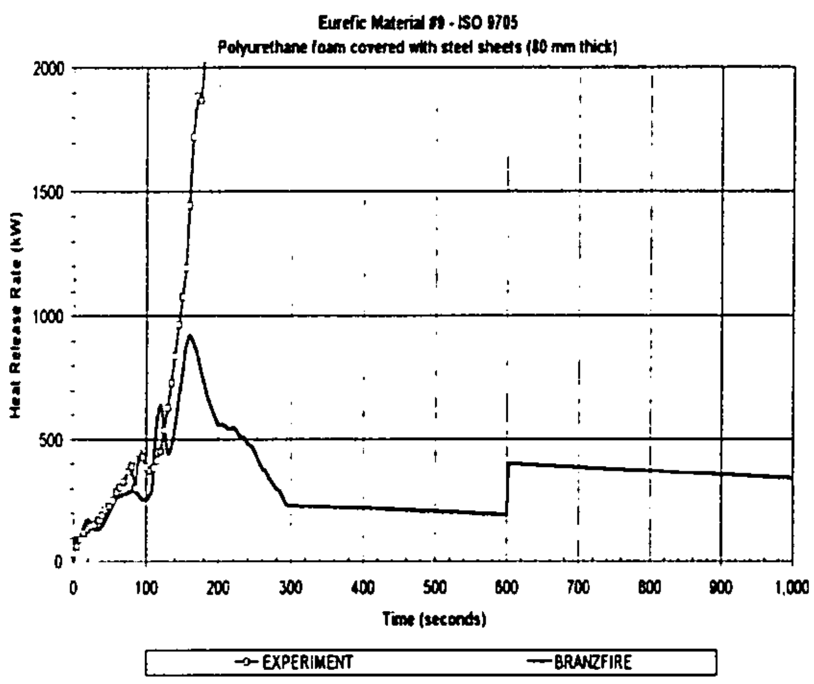

Figure 10

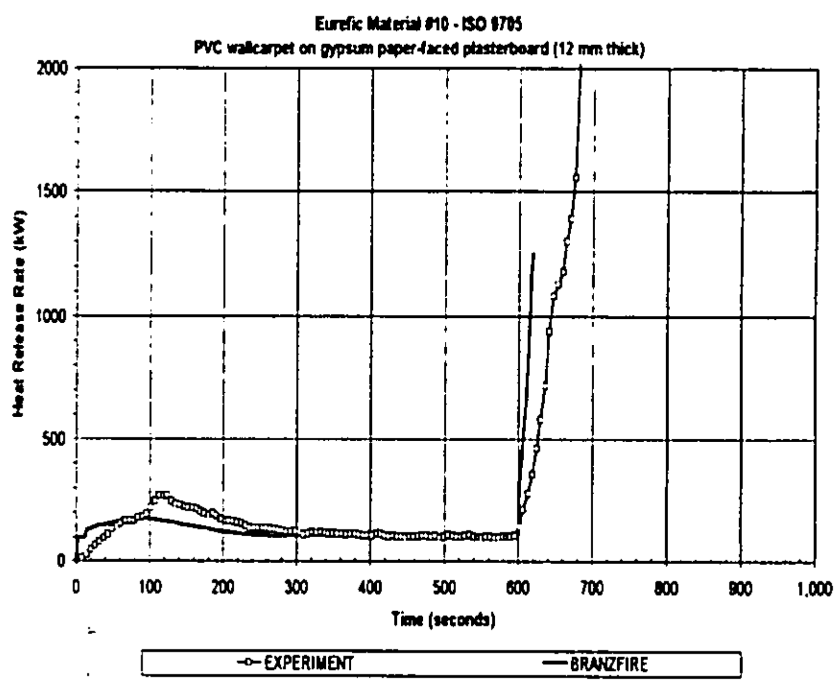

Figure 11

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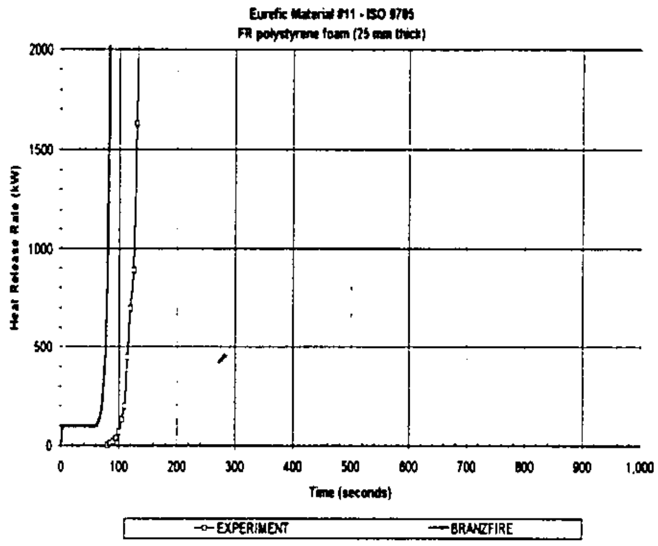

Figure 12

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