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A Theoretical Model for Fire Spread in a Room Corridor Configuration

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A THEORETICAL MODEL FOR FIRE SPREAD IN A ROOM CORRIDOR CONFIGURATION

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INTRODUCTION

This paper describes a theoretical model for predicting the ignition of combustible linings in a corridor adjacent to a room of fire origin. The fire scenario modelled is a developing or fully developed fire which produces a flow of hot gases through a vent, and/or a vent fire due to ventilation-limited burning in an opening (e.g doorway), between the room of fire origin and the connecting corridor (or adjacent room). The flow of hot gases into the adjacent room or corridor is a contributing factor as it preheats the surface linings in the adjacent space. Existing models for evaluating the hazard of room lining materials focus only on fire spread within the room of origin. This new model uses a similar methodology to predict ignition and flame spread on room surfaces in an adjacent room.

The model described is implemented as a sub-model within BRANZFIRE, a multi-compartment zone model that also includes flame spread and fire growth calculations [1, 2]. This will increase the utility and usefulness of the approach and make it more accessible to fire protection engineers.

BASIS OF THE MODEL

The model is intended to account for the ignition and burning of combustible wall and ceiling linings in a room directly adjacent to the room of fire origin. Ignition results from the flow of gases through the vent and the combustion of unburned fuel contained within the flow which exposes the wall (by convection and radiation) directly above the vent opening in the adjacent room. When the surface temperature just above the vent soffit reaches the ignition temperature for the material, progressive flame spread over the wall and along the corridor ceiling is then possible. This flame spread is modelled using existing methodology as described by Wade [1, 2] and Quintiere [3].

Characteristics of the Vent Flame

The BRANZFIRE zone model determines the concentration of unburned fuel in the upper layers and the amount of energy released in a vent fire. Under ventilated-limited burning conditions there will be insufficient oxygen for complete combustion of the fuel. When the mass flow passes through the vent it is assumed to mix with oxygen from the adjacent space and burn in the form of a vent fire. Combustible volatiles in the vent flow are assumed to ignite and burn in the vent if their temperature is more than 100 K above ambient.

A continuous flame height correlation by Hasemi [4] for the flame height of line fires against a wall has been used to characterise the vent fire. His correlation used a modified non-dimensional heat release rate.

$$\dot{Q}_l^* = \frac{\dot{Q}_l}{\rho_\infty c_p T_o g^{1/2} D^{3/2}} \quad (1)$$

$\dot{Q}_l$ is the heat release per unit length of the fire source and D is the length of the fire source (ie the vent width w). Hasemi's correlation for the continuous flame height is:

$$L = 2.8\dot{Q}_l^{*2/3} D \quad (2)$$

The depth or thickness of the flame (x) is approximated by the distance of the layer interface height in the room of origin below the vent soffit. The width of the flame is taken as equal to the width of the vent (w). The flame dimensions are shown in Figure 1.

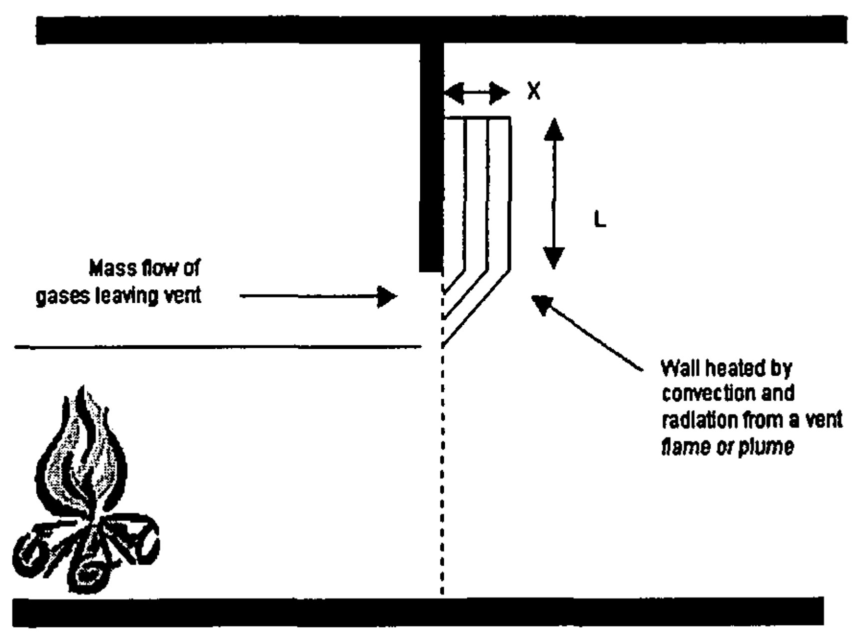

Figure 1: **Flame dimensions for fire spread into an adjacent space.**

The emissivity of the flame assuming the thickness or depth (x), given above and an effective absorption coefficent (k) is:

$$\epsilon_f = 1 - e^{-kx} \quad (3)$$

Determining the Surface Heat Flux Due to a Vent Fire

The wall above the vent opening to the adjacent room is assumed to be exposed to convective and radiative heating from the flame, the hot gas layer and other room surfaces, and reradiation losses from the wall surface. One-half of the heat release in the vent fire is assumed directed towards the wall with the radiant flux per unit area exposing the wall given by:

$$\dot{q}''_r = \frac{\lambda_r \epsilon_f \dot{Q}/2}{Lw} \tag{4}$$

$\dot{Q}$ is the energy released in the vent fire and λ_r is the radiant loss fraction from the fire plume. The net flux to the wall is then given by:

$$\dot{q}'' = \dot{q}''_r + h(T_f - T_s) + \dot{q}''_{\text{int}} - \epsilon_s \sigma T_s^4 \tag{5}$$

The flame temperature T_f is taken as a constant 1250 K and ϵ_s is the emissivity of the wall surface. In the absence of a vent fire, the flame temperature is taken as the upper layer temperature in the room of fire origin for the purposes of determining convective heat transfer. The wall surface temperature T_s directly above the vent opening is calculated using an implicit finite difference conduction scheme, using the net heat flux above as one of the boundary conditions. The boundary condition for the rear side of the wall corresponds to the upper layer temperature in the room of fire origin. When the wall surface temperature reaches the ignition temperature for the material, ignition is assumed to occur and flame spread commences.

The heat flux due to heat transfer from the gas layers and the room surfaces ($\dot{q}''_{\text{int}}$) is obtained as intermediate output from the zone model calculations. The convective heat transfer coefficient (h) is calculated for convective flow past a vertical flat plate, where $h = k\text{Nu}/L$. The gas thermal conductivity (k), kinematic viscosity (ν) and Nusselt and Reynolds numbers are as follows with Prandtl Number (Pr) =0.72. A_{vu} is the vent area located above the level of the layer interface height in the room of fire origin (which is used to approximate the height of the neutral pressure plane) and $\dot{m}_o$ is the mass flow of gases leaving through the vent.

$$k = 2.72 \times 10^{-4} \left(\frac{T_f + T_s}{2}\right)^{0.8} \tag{6}$$

$$\text{Nu} = 0.0332\text{Re}^{1/2}\text{Pr}^{1/3} \text{ for Re} \leq 500000 \text{ laminar flow} \tag{7}$$

$$\text{Nu} = 0.0296\text{Re}^{4/5}\text{Pr}^{1/3} \text{ for Re} > 500000 \text{ turbulent flow} \tag{8}$$

$$\text{Re} = \frac{\dot{m}_o L}{A_{vu} \rho_u \nu} \tag{9}$$

$$\nu = 7.18^{-10} \left(\frac{T_f + T_s}{2}\right)^{7/4} \tag{10}$$

Determining Pyrolysis Area

Following ignition of the wall above the vent, the pyrolysis area and heat release is determined at each time step. The area first ignited is assumed to be a rectangular region defined by the width of the vent and the flame height at the time of ignition as shown in Figure 2. For this case the pyrolysis area on the wall is given by equation 11 where y_p is measured from floor level.

$$A_{pw} = 2\left[(y_p - h)x_{po} + (x_p - x_{po})y_{po} + 0.5((y_p - y_{po})(x_p - x_{po}))\right] \quad (11)$$

where x_{po} is equal to one-half the vent width (w). For the case where the upward pyrolysis front has reached the ceiling, the pyrolysis area on the wall is given by:

$$A_{pw} = 2\left[(H - h)x_{po} + (x_p - x_{po})y_{po} + 0.5(x_p - x_{po})(H - y_{po})\right] \quad (12)$$

There is also an additional pyrolysis area in the ceiling jet region as shown in Figure 3, given by $z_p = x_p - x_{t_H}$ where t_H is the time when the upward pyrolysis front reaches the ceiling. For $z_p = 0$, the pyrolysis area in the ceiling jet region is:

$$A_{pj} = 2\left[y_p - (H - h)(0.12(H - h))\right] \quad (13)$$

For $z_p > 0$, the pyrolysis area in the ceiling jet region is:

$$\begin{aligned} A_{pj} &= 2\left[(y_p - (H - h))(0.12(H - h)) + 0.5z_p(y_p - (H - h))\right] \\ &\quad - \left[(0.12(H - h) + z_p)^2 \left(\frac{x_p - x_{po}}{(H - h) - y_{po}}\right)\right] \end{aligned} \quad (14)$$

The height of the ceiling jet region is conservatively taken as 12% of the fire to ceiling height $(H - h)$ being an upper estimate from Evans [5].

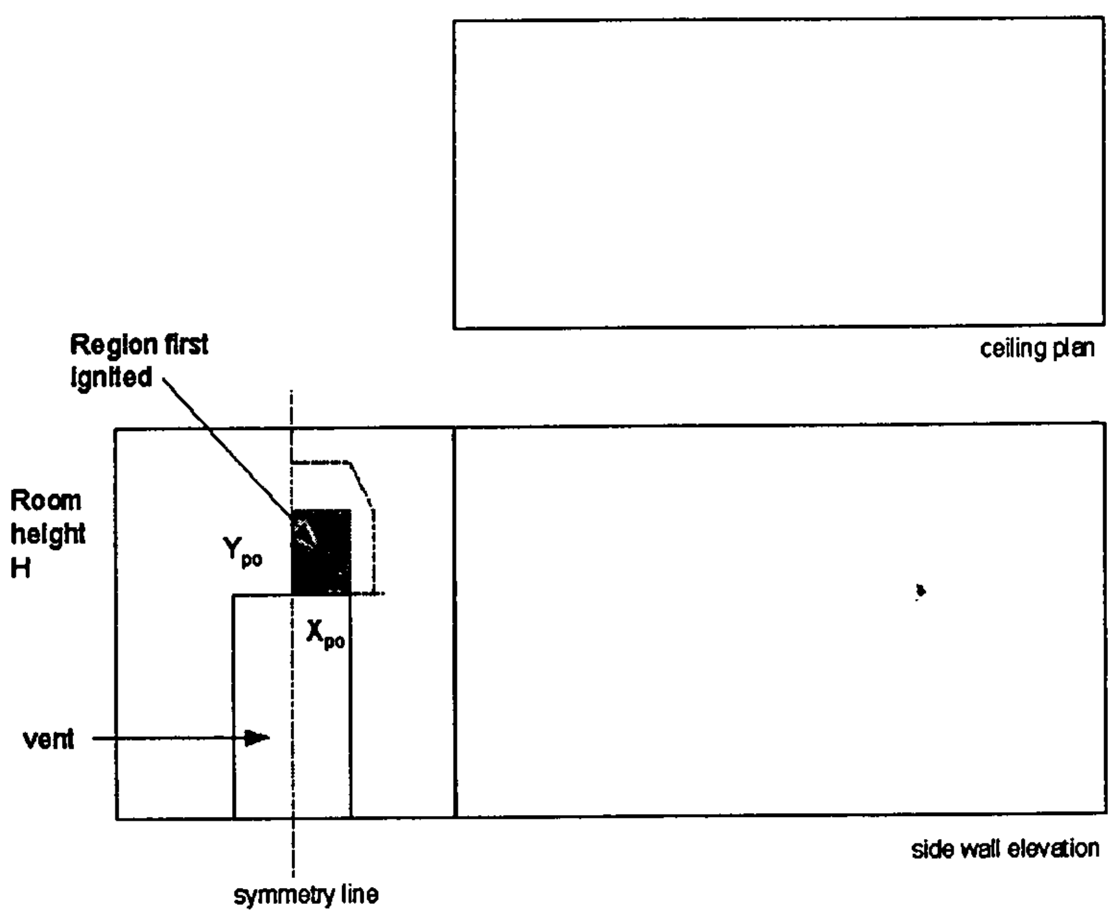

Figure 2: **Wall above the vent has ignited; pyrolysis front not yet reached ceiling.**

When the pyrolysis front reaches the ceiling, the flame is assumed to spread in a semi-circular shape from a point directly above the centre line of the vent as shown in Figure 4. The vent is assumed to be located centrally in the wall. Figure 3 shows the pyrolysis areas (shaded) for the case where the upward pyrolysis front has reached the ceiling.

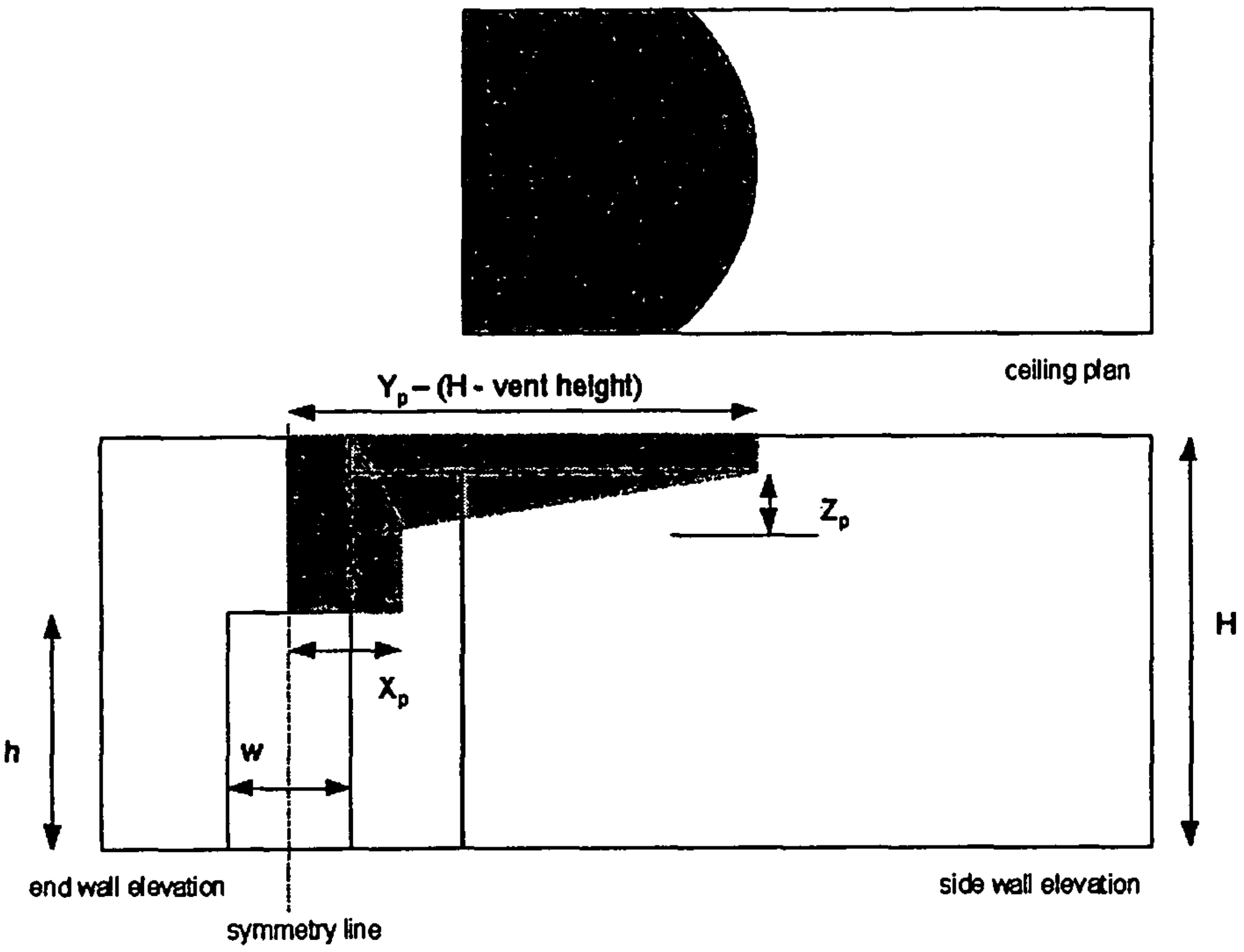

Figure 3: **Wall above the vent has ignited; pyrolysis front has reached ceiling.**

When the pyrolysis front on the ceiling reaches the side walls in the adjacent room, as shown in Figure 4, the ceiling pyrolysis area is calculated by subtracting twice area B from the area of the semi-circle defined with a radius of y_p. For the length of the pyrolysis front, $y_p \leq$ one-half the width of the source room, the pyrolysis area on the ceiling is given by:

$$A_{pc} = \pi y_p^2/2 \tag{15}$$

For the length of the pyrolysis front, $y_p >$ one-half the width of the corridor,

$$\text{pyrolysis area, } A_{pc} = \frac{\pi y_p^2}{2} - 2\left[\frac{\theta \pi y_p^2}{360} - wx/4\right] \tag{16}$$

The maximum ceiling pyrolysis area permitted is equal to the ceiling plan area of the adjacent room.

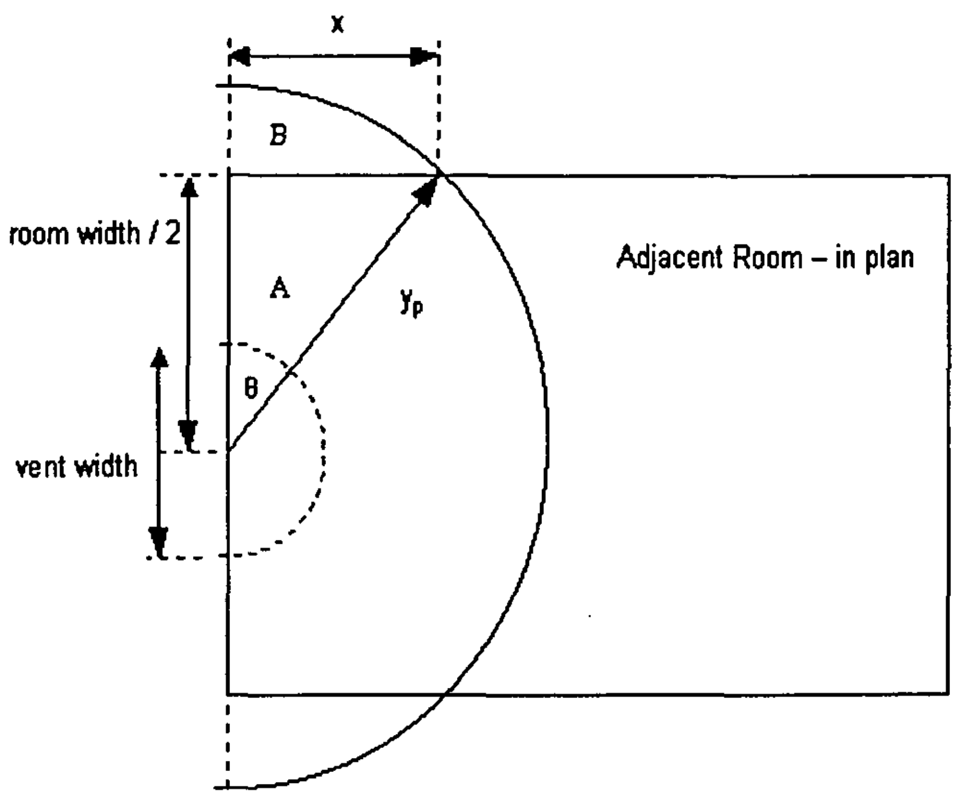

Figure 4: **Pyrolysis front on ceiling in adjacent room or corridor.**

Determining Upward Flame Spread

The governing equation for upward flame spread is given by Quintiere [3] as:

$$\frac{dy_p}{dt} = \frac{y_f - y_p}{t_{ig}} \tag{17}$$

$$\text{with } t_{ig} = \frac{\pi}{4} k\rho c \left[\frac{T_{ig} - T_s}{\dot{q}''_{ff}}\right]^2 \text{ assuming the material is thermally thick} \tag{18}$$

$\dot{q}''_{ff}$ is the heat flux ahead of the flame and is taken to be 30 kW/m^2. Alternatively, where the minimum flux-time product method [6] is used to correlate the ignition data, the time to ignition expression used is:

$$t_{ig} = \mathrm{FTP_n}(\dot{q}''_{ff} - \dot{q}''_{cr})^{-1/p} \tag{19}$$

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:

$$y_f = K(\dot{Q}'_b + \dot{Q}''_p y_p)^n \tag{20}$$

where K is the flame area constant (=0.067), n is the flame length power (=2/3) and $\dot{Q}''_p$ is the peak 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 $K\dot{Q}_b'^n$.

The lateral pyrolysis front is given by equation 21 where Φ is a flame spread parameter. The equation only applies when $T_s \geq T_{s,\min}$, where Φ and $T_{s,\min}$ are determined from the LIFT test [7]. The surface temperature in this equation is taken as the average temperature of the wall in contact with the upper layer and is provided as output from the zone model.

$$\frac{dx}{dt} = \frac{\Phi}{k\rho c(T_{ig} - T_s)^2} \tag{21}$$

At each time step the total pyrolysis area and heat release from the ceiling material in the adjacent room is then calculated from:

$$\dot{Q}(t) = \Sigma(\dot{Q}''(t)\Delta A_p(t)) \tag{22}$$

$\dot{Q}''$ is the energy release per unit area for each incremental area and depends on the elapsed time of burning for each incremental area. This is determined from the available set of cone calorimeter heat release rate curves for the material determined for a range of external heat fluxes. The data set is interpolated using a cubic spline technique [8] to determine the applicable energy release rate given the elapsed time from ignition, and the imposed heat flux to the wall. Data is not extrapolated, so where the imposed heat flux is outside the range bounded by the cone calorimeter tests, data from the the nearest curve is used.

MATERIAL FLAMMABILITY PROPERTIES FOR FLAME SPREAD

Silcock and Shields [6] describe a method for correlating time to ignition data in the cone calorimeter which does not presume thermally thick behaviour, and is more generally applicable to a wide range of materials (cellulosic and polymeric). This Flux-Time-Product (FTP) method is used here to correlate ignition data and for estimation of an ignition temperature for the material.

Time to ignition data from cone calorimeter tests are correlated by plotting the external flux against t_{ig}^p. The power (p) is varied between 0.5 (thermally thick) and 1 (thermally thin) to determine which value provides the highest correlation coefficient for a straight line of the following form fitted through the data. $\dot{q}''_{cr}$ is the intercept of the straight line onto the $\dot{q}''$ axis. The slope of the line will give FTP_n^p from which FTP_n can be determined. Time to ignition was defined as the time for the heat release to reach 30 kW/m^2 and this was used in preference to the reported times.

$$\dot{q}'' = \dot{q}''_{cr} + \frac{\mathrm{FTP}_n^p}{t_{ig}^p} \tag{23}$$

The following equation is then solved (by iteration) for the surface temperature for ignition, T_{ig}, taking the convective heat transfer coefficient for the cone calorimeter $h_c = 0.0135$ kW/m^{2}K, and surface emissivity at ignition, ϵ, as appropriate for the material.

$$\epsilon\dot{q}''_{cr} = h_c(T_{ig} - T_\infty) + \epsilon\sigma\left(T_{ig}^4 - T_\infty^4\right) \tag{24}$$

APPLICATION TO A CORRIDOR LINED WITH PLYWOOD

To illustrate the application of the model, it has been used to model fire spread from an ISO 9705 standard room [9] into an attached corridor. The room is assumed to be lined with plasterboard (with no contribution to heat release) with a 1.5 MW gas burner located in the centre of the room. A door vent 0.8 m wide by 2.0 m high connects the room to a corridor 10 m long by 1.5 m wide by 2.4 m high, which is open to the atmosphere at the far end. The corridor is lined with a 12 mm thick birch plywood (Eurefic Material #2 [10]) for which cone calorimeter data at 25, 35 and 50 kW/m^2 was available.

Ignition data from the cone calorimeter was correlated using the flux time product method to yield estimated values of the critical heat flux, ignition temperature, and FTP_n. Thermal conductivity and specific heat were estimated from the literature [11] while the density was known [10]. The lateral flame spread parameter and minimum temperature for spread were also taken from the literature [12]. A summary of the thermal parameters for the plywood material for use with the model are summarised below.

k	ρ	c	$k\rho c$	ϵ_s	T_{ig}	$\dot{q}''_{crit}$	FTP_n	$T_{s,min}$	Φ
W/mK	kg/m^3	kJ/kgK	kW^{2}s/m^{4}K^2	–	^oC	kW/m^2	s(kW/m^2)$^{1/p}$	^oC	kW^2/m^3
0.14	600	2850	0.217	0.88	424	19.1	832	120	12.9

The model was successfully used to predict the heat release rate within the room for a standard ISO 9705 room corner test, with the above plywood fixed to the walls and ceiling ignited by a 100 kW propane burner located in the corner. A comparison for this case between the model prediction and the experimental measurements [10] is shown in Figure 5.

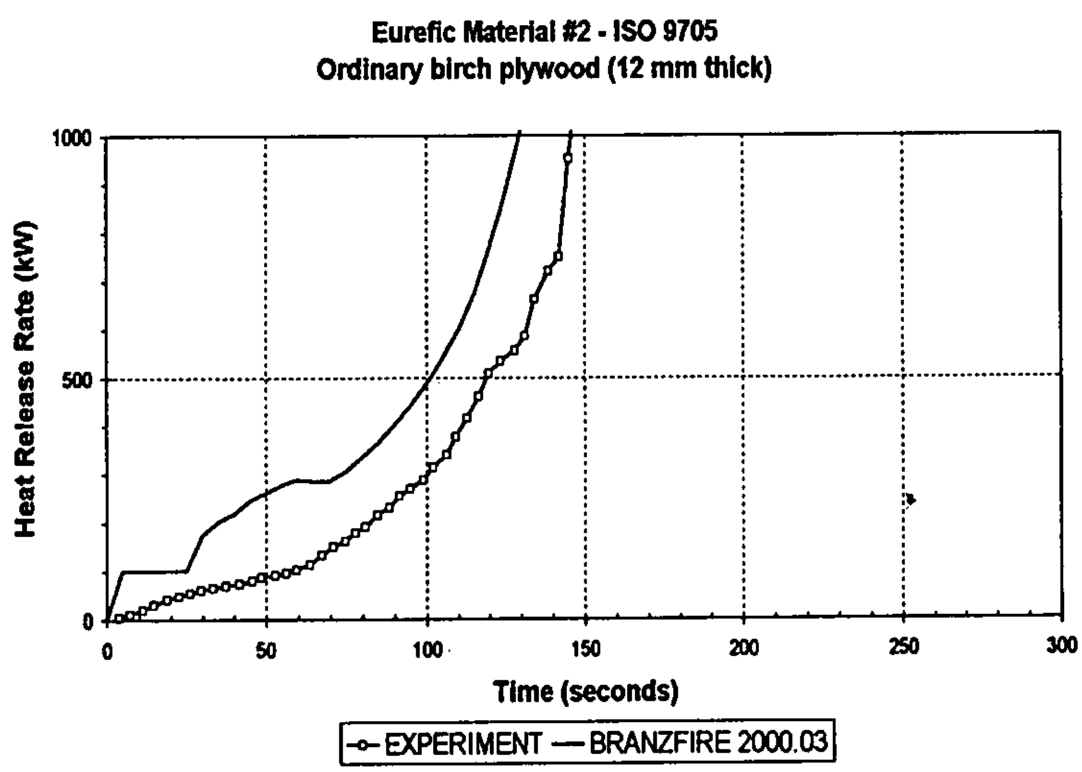

Figure 5: Heat release rate in standard ISO 9705 room corner test.

The model was then used to predict the heat release and fire environment for the room corridor configuration described above. Figure 6 shows the predicted heat release in the corridor and the size of the fire burning at the opening of the corridor to an outside space. It can be seen that the plywood linings in the corridor ignite at about 280 seconds, with some of the heat from the plywood linings resulting from combustion within the corridor (using oxygen present in the upper layer and oxygen entrained into the corridor upper layer via the room to corridor vent flow) and some of which burns in the vent to outside.

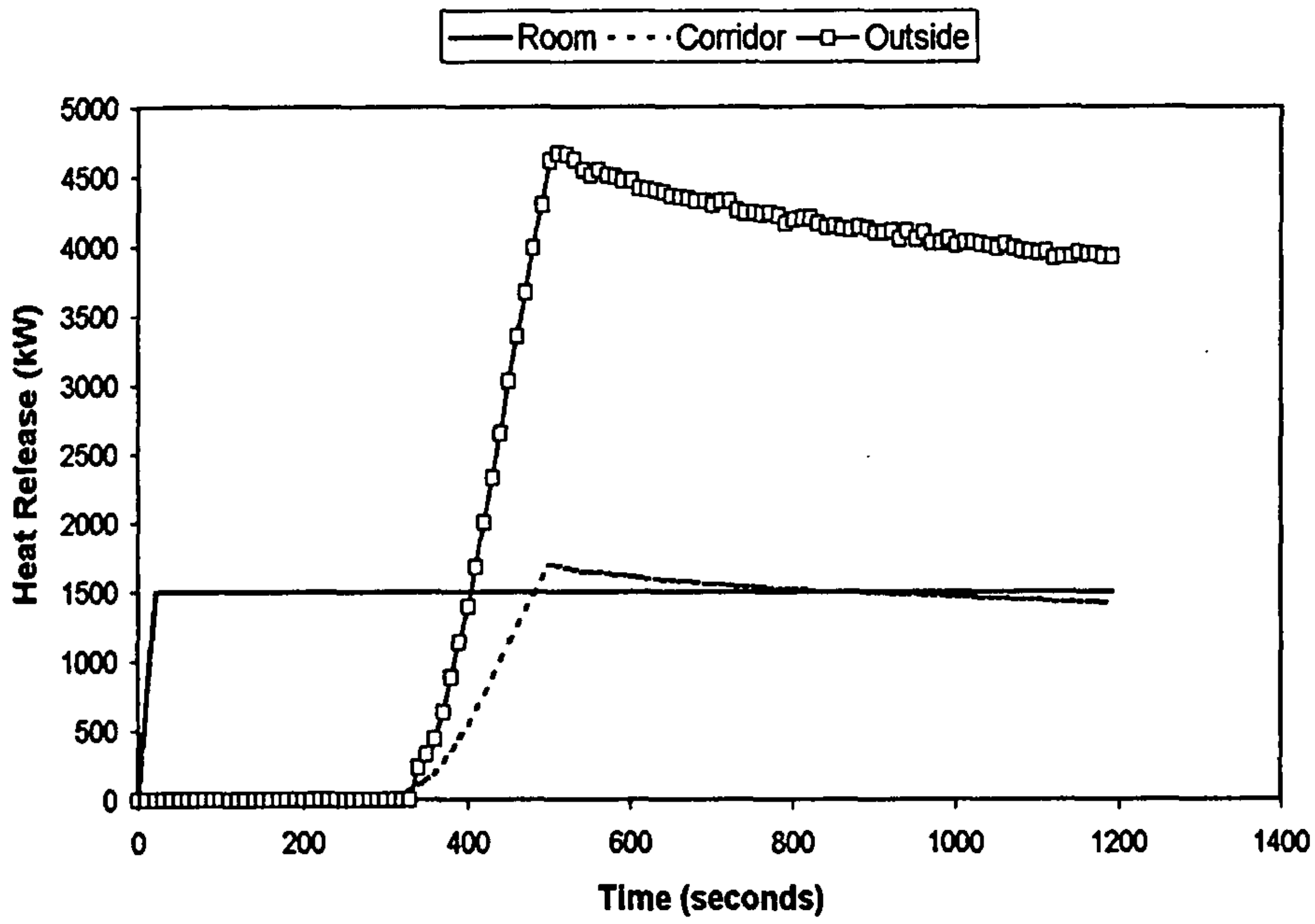

Figure 6: **Heat release rate in room and corridor.**

Figure 7 shows the predicted position of the upward pyrolysis front. Following ignition of the wall above the vent at 280 seconds, the flame spreads up the wall reaching the ceiling at 330 seconds and continues along the ceiling to reach the far end of the corridor at approximately 545 seconds. The flame spread rate is predicted to accelerate dramatically as the average surface temperatures in the corridor approach the ignition temperature of the plywood. This is also apparent in Figure 8. Figure 9 shows the predicted upper layer temperatures in the room and corridor.

FUTURE RESEARCH

A collaborative arrangement between BRANZ and the CSIRO, Australia will see a room-corridor test facility used to measure the heat fluxes on corridor surfaces resulting from the flow of gases through the door vent. These measurements will assist with the validation of some of the intermediate calculations in BRANZFIRE and subsequent prediction of flame spread rates and heat release.

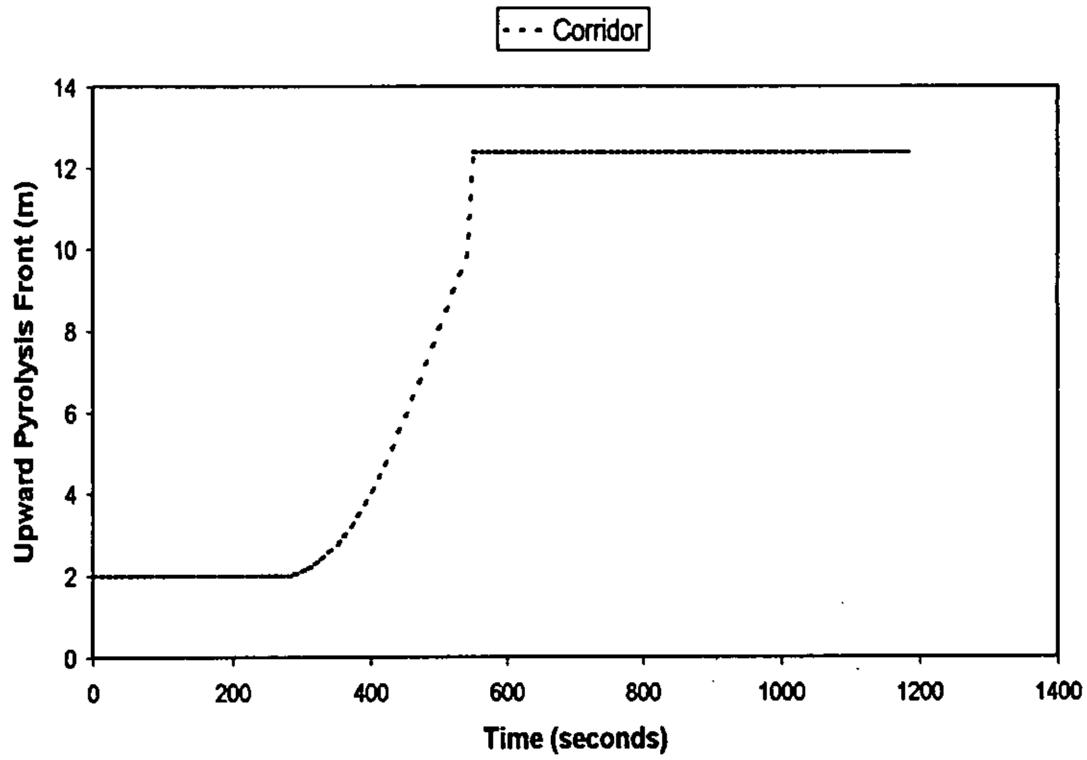

Figure 7: **Position of upward pyrolysis front in corridor.**

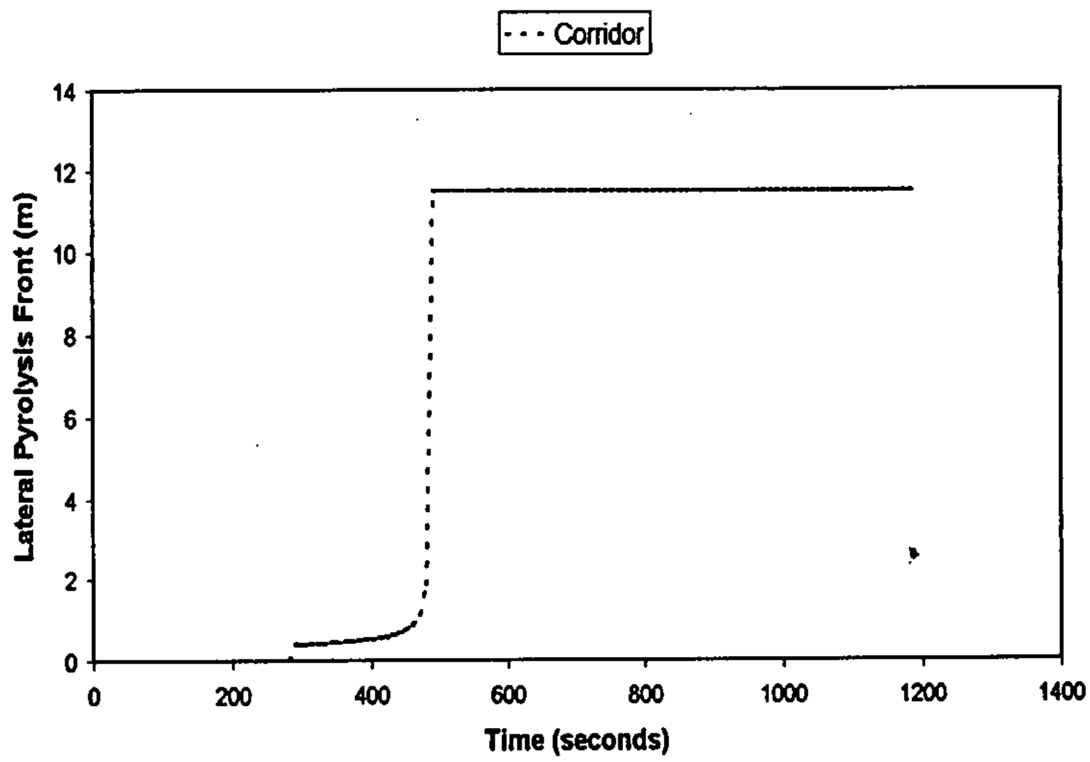

Figure 8: **Position of lateral pyrolysis front in corridor.**

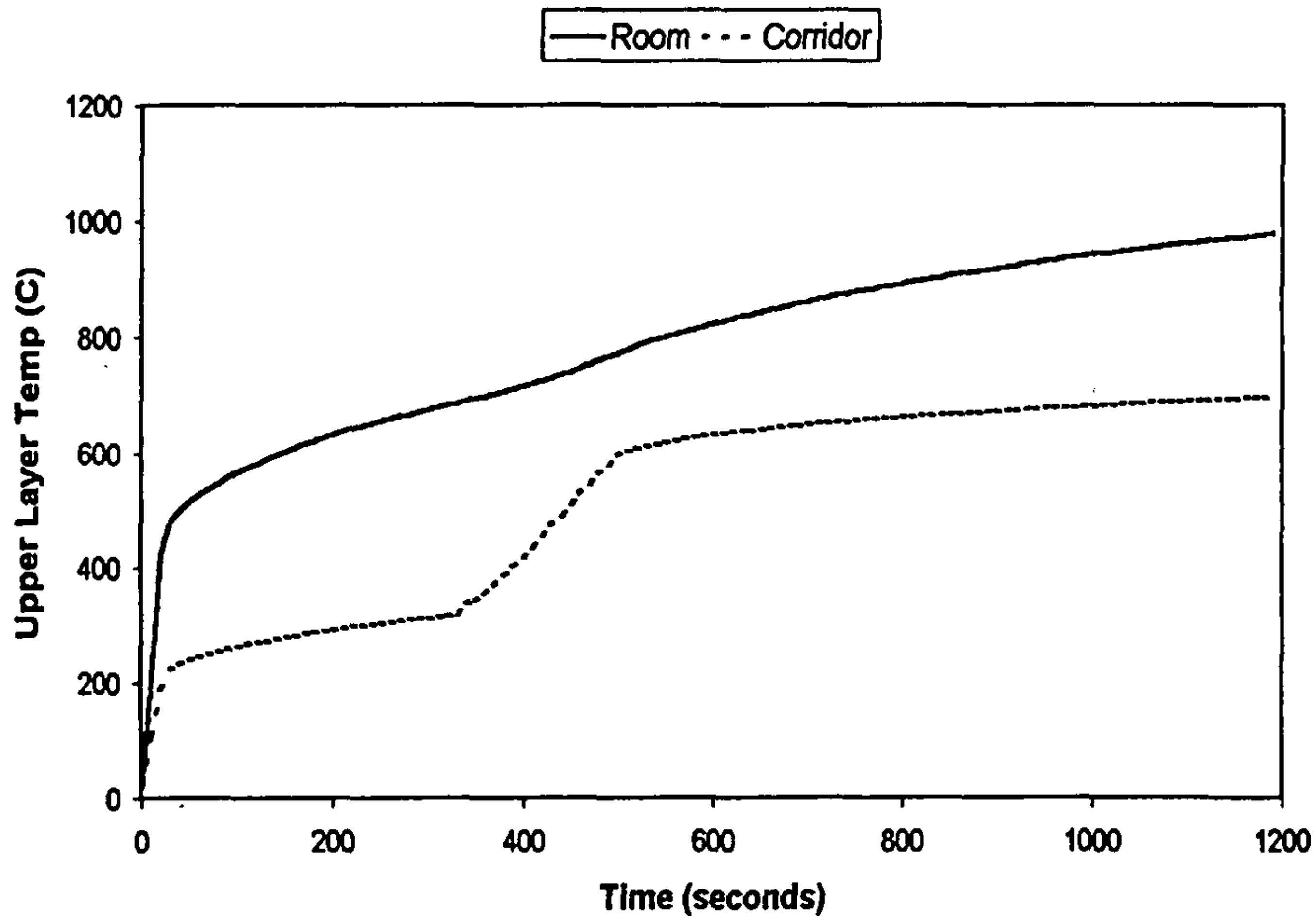

Figure 9: **Upper layer temperature in room and corridor**

SUMMARY

An algorithm has been described for modelling the spread of fire from a room of fire origin to combustible linings in a connecting room or corridor. The ignition source for the corridor linings is assumed to be the flow of hot gases through a connecting vent and/or a vent fire in conjunction with a hot layer developing in the corridor. On ignition, the pyrolysis area, upward and lateral flame spread rates and heat released by the wall and ceiling is determined, and these are integrated with the BRANZFIRE multi-compartment zone model calculations. Future work requires the theoretical model to be compared with experimental data.

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