A Framework for Utilizing Fire Property Tests

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ABSTRACT

A complete approximate set of equations is developed to describe fire spread over a surface and its resultant energy release. Wall, floor, and ceiling orientations are considered. The needed model data are couched in terms of available test method results, e.g., Cone Calorimeter and LIFT apparatuses. Several applications are presented to show how energy release rates can be predicted and how well they represent real data from full-scale and model room lining experiments.

KEYWORDS: Energy release, fire property tests, linings, predictions, room fires.

INTRODUCTION

Theories of flame spread and new widely used test apparatuses capable of providing engineering fire property data make it feasible to construct a framework for fire hazard assessment. The test apparatuses include the Cone Calorimeter [1], and the Lateral Ignition and Flame Spread Test (LIFT) [2], both of which have been recently established as ASTM standard methods and are being considered in ISO. We shall formulate a model to compute the energy release rate of the fire as a function of time in terms of the material orientation and properties.

The model to be presented, we emphasize, represents only a framework for a more complete and precise solution to the appropriate characterization of materials through fire test methods. Our results and our model

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should serve as support for other analyses which have used similar property data to predict the flashover times for actual experiments [3-5]. However, we believe that our model is less empirical and more physically complete than these previous analyses [3-5].

THEORETICAL DEVELOPMENT

The essential elements of fire growth have been included; namely, ignition, energy release rate, burning time, and all relevant modes of flame spread for the surface orientation considered. Also, the effects of the ignitor and thermal feedback have been parametrically considered. Detailed transient characteristics and room smoke layering have been ignored, but their contributions eventually need to be assessed.

Fire Properties

The term "fire properties" will be used to describe the input material data for the model. Our "fire properties" will not necessarily be unique, but will depend on environmental conditions. These are described below:

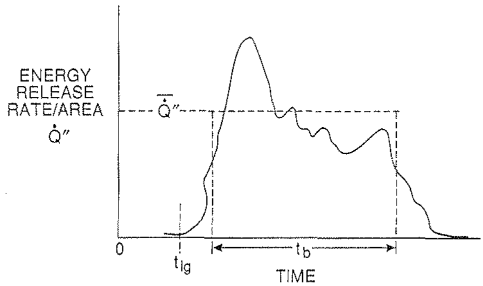

Figure 1 Energy release property data

1. $\bar{\dot{Q}}''$, average peak heat release rate per unit area. This value is derived from the Cone Calorimeter [1] for which the transient data have been averaged, and evaluated at a specified irradiance level. It is illustrated in Figure 1 in which the area under the actual curve is approximately equal to the area under the rectangle. We have not used a standardized prescription for determining the average energy release rate and burn time. This was done in a consistent manner by approximating the significant burning region of the curve by a square wave. We selected an average maximum for $\bar{\dot{Q}}''$ and then estimated t_b to maintain the total energy.

2. t_b, burn time. This value is the width of the approximating rectangle in Figure 1. This also corresponds to a given heat flux, and is derivable from the Cone Calorimeter.

3. t_{ig}, ignition time. This value is the time for piloted ignition at a given heat flux, specifically radiative. The heat flux level should be selected to correspond to the flame heat flux level appropriate to wind-aided flame spread.

4. Φ, flame heating parameter in opposed flow spread. This "property" is directly derivable from the LIFT [2,6] standard procedure. It represents the flame heat transfer and opposed flow velocity effects.

5. $T_{s,min}$, minimum temperature for flame spread. In opposed flow flame spread it is found that materials require a minimum heating level to achieve a surface temperature required for spread. Below this temperature spread is not possible. This temperature is also required but not available for, wind-aided or upward flame spread. For example, it appears

that a preheated surface temperature in excess of 80°C is necessary to cause sustained upward flame spread on wood particle board [7].

Equations

In developing the governing equations we shall consider all materials to be thermally thick, i.e. no effect of thickness, and laminated materials and substrates are treated as homogeneous, reflective of their bulk properties. The same corresponding equations will apply, without distinction, to horizontal (floor), lateral, and downward wall spread as opposed flow spread; and to upward wall and ceiling spread as wind-aided spread. One might argue with this lack of distinction but the opposed flow case for these different orientations has some support [8] whereas the extension of the upward spread theory to the ceiling is only a convenience for now which needs further study. For all orientations, as illustrated in Figure 2, symmetry is invoked, and the wind-aided coordinate is designated by y and the opposed flow coordinate by x. Spread on the floor (Fig. 2a), and ceiling (Fig. 2b) is radially symmetric, and on the wall (Fig. 2c) is approximated and as a region developed from two (x and y) spreads away from an initially ignited rectilinear zone of area $2x_o y_o$. The region between the extended pyrolysis wall fronts (x_p, y_p), and the burnout fronts (x_b, y_b) is formed by straight line approximations (Fig. 2c).

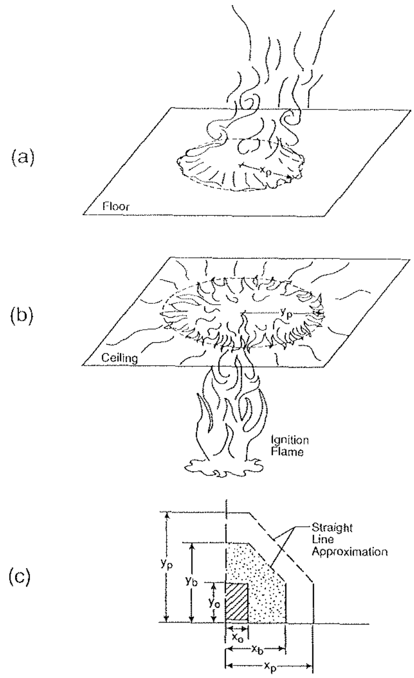

Figure 2 Model floor, ceiling, wall configurations

The objective of our analysis is to compute the energy release rate, $\dot{Q}(t)$, as a function of time for the orientation shown in Figure 2 or their combination. For energy release we write the following approximation based on Figure 1.

$$\dot{Q}(t) = \iint \dot{Q}'' \, dx \, dy = \overline{\dot{Q}''} A_p \tag{1}$$

where A_p is the pyrolysis or volatilizing area.

For the floor or ceiling cases it can easily be shown that

$$A_p = \pi (x_p^2 - x_b^2) \text{ or } \pi (y_p^2 - y_b^2) \tag{2}$$

For the wall case,

$$A_p = 2[y_p x_o + (x_p - x_o) y_o + 1/2 (y_p - y_o)(x_p - x_o)] \quad \text{for } t \le t_b \tag{3a}$$

or

$$A_p = 2\ [y_p x_o + x_p y_o + 1/2\ (y_p - y_o)(x_p - x_o)] \qquad \text{for } t > t_b \tag{3b}$$
$$\qquad -2\ [y_b x_o + x_b y_o + 1/2\ (y_b - y_o)(x_b - x_o)]$$

In order to formulate the rest of the analysis we write out and solve the equations for the pyrolysis and burnout fronts.

Wind-aided Solution

The upward or wind-aided solution is developed [9] from the equation

$$\frac{dy_p}{dt} = \frac{y_f - y_p}{t_{ig}} \tag{4}$$

where y_f is the position of the flame tip with $y_f - y_p$ defining the forward heat transfer region of the flame identified with heat flux, $\dot{q}_f''$. Equation (4) is a quasi-steady model which uses the steady-state flame spread result successively over time as the forward heat transfer region changes. Mathematically, this solution is continuous. This flame heat flux will be taken as 30 kW/m^2 in our analysis for all materials.

The ignition time is given as

$$t_{ig} = \frac{\pi\ k\rho c\ (T_{ig} - T_s)^2}{4\ (\dot{q}_f'')^2} \tag{5}$$

where T_{ig} is the ignition temperature, $k\rho c$ is the thermal inertia, and T_s is the surface temperature of the region $y \geq y_f$. As can be seen, the "property" t_{ig} can be related to more valid engineering materials properties ($k\rho c$ and T_{ig}) and other factors.

Finally, the flame length can be estimated by a linear approximation to wall fire data [9] as

$$y_f - y_b = k_f\ [\dot{Q}_o' + \bar{\dot{Q}}''\ (y_p - y_b)] \tag{6}$$

where y_b is taken as identically zero for $t \leq t_b$, and $\dot{Q}_o'$ is the energy release rate per unit width of the ignitor flame needed to start the process. This ignitor flame is assumed to provide a uniform heat flux ($\dot{q}_f''$) of 30 kW/m^2 over the region (x_o, y_o) which is taken to ignite at $t = t_{ig}$ in Eqn.(5), or corresponding to t_{ig} in Fig. 1. The value for k_f is approximately 0.01 m^2/kW. In Eqn.(6), the term $\dot{Q}_o'$ is set to zero when $t > t_b$. This is done after $t = t_b$ since the initial region as determined by the flame extent due to $\dot{Q}_o'$ is no longer burning, and subsequently the ignitor flame would become discontinuous from the material flame ahead of this region. This ignitor energy is continuously included in the overall heat release.

The burnout front can be approximated as

$$\frac{dy_b}{dt} = \frac{y_p - y_b}{t_b} \qquad \text{for } t > t_b \tag{7}$$

The initial conditions are given as:

$$t = 0\ ,\ y_p = y_o \tag{8a}$$
$$t = t_b\ ,\ y_p = y_p(t_b)\ ,\ y_b = y_o . \tag{8b}$$

The solutions to the above are given below:

$$\eta = \left(\frac{a+1}{a}\right) e^{a\tau} - 1/a \tag{9}$$

for $0 \le \tau \le t_b/t_{ig}$ where $\tau = t/t_{ig}$, $\eta = y_p/y_o$, $a = k_f\bar{\dot{Q}}'' - 1$, and $y_o = k_f\dot{Q}_o'$. This assumes that the initial pyrolysis length, y_o, is determined by the height of the ignition flame. For $\tau > (t_b/t_{ig}) \equiv \tau_b$. Eqns. (4) and (7) are subtracted and solved to yield

$$\psi \equiv \frac{y_p - y_b}{y_o} = c\, e^{b(\tau - \tau_b)} \tag{10}$$

where $b = a - 1/\tau_b$ and $c = \left(\frac{a+1}{a}\right)[e^{a\tau_b} - 1]$. From Eqn. (7) it follows that $\eta_b = y_b/y_o$ is given by

$$\eta_b = 1 + \frac{c}{b\tau_b}\left(e^{b(\tau-\tau_b)} - 1\right) \tag{11}$$

The parameters a and b must be greater than zero in order for the upward fire spread to accelerate. For values less than zero, the spread will eventually stop. This bimodal behavior is a distinct characteristic of upward flame spread which is conditional on the form of Eqn. (6). This clearly shows the role of the energy release rate per unit area and its duration in time, i.e., $\dot{Q}''$ and t_b.

Opposed flow solution

From the LIFT procedure [2,6] the governing equation for the pyrolysis position is

$$\frac{dx_p}{dt} = \frac{\Phi}{k\rho c\,(T_{ig} - T_s)^2} \qquad \text{for } T_s \ge T_{s,min}. \tag{12}$$

This can be rewritten as

$$\frac{dx_p}{dt} = \frac{\dfrac{\pi}{4}\dfrac{\Phi}{(\dot{q}_f'')^2}}{t_{ig}} \tag{13}$$

The dimensionless solution $\xi \equiv x_p/x_o$ follows as

$$\xi = \beta\tau + 1 \qquad \text{where } \beta = \frac{\pi}{4}\frac{\Phi\, x_o}{(\dot{q}_f'')^2} \tag{14}$$

The burnout solution analogously follows from Eqn. (7), i.e.

$$\frac{dx_b}{dt} = \frac{x_p - x_b}{t_b} \tag{15}$$

and it can be shown that $\xi_b = x_b/x_o$ is given by

$$\xi_b = \beta\,(\tau - \tau_b) + 1 \quad , \tau \ge \tau_b. \tag{16}$$

This completes the solution. These equations will now be applied to specific applications. For each case we shall appropriately apply the equations by accounting for the effects of geometry and thermal feedback as a parameter. For example, a corner wall and ceiling fire will be considered as an extended vertical wall representative of the actual corner wall and ceiling jet region plus a quadrant of a circular ceiling. To review, the procedure for implementing this solution is as follows:

1. Assemble material data namely, $\bar{\dot{Q}}''$, t_{ig}, t_b, Φ and $T_{s,min}$.
2. Prescribe the ignition source, $\dot{Q}_o'$.
3. Since no room fire model is coupled to this analysis, one must set T_s at a value representative of the particular room configuration.
4. Compute the pyrolysis area A_p for the surface configuration using the formulas for x_p and y_p.
5. Compute the fire product output rate, e.g. rate of any energy release, by multiplying A_p by $\bar{\dot{Q}}''$.

APPLICATIONS

Several applications of the analysis will be presented for cases where scenario results for total energy release exist along with a complete set of fire property data.

Full Scale Room - Corner Tests

A series of full scale room lining fire tests were performed at the Swedish National Testing Institute, Borås, Sweden [10]. The test scenario consisted of lining the walls and ceiling of the room (2.43 m by 3.66 m by 2.43 m in height with an opening 2 m by 0.9 m) with a given material. A 0.17 m by 0.17 m propane sand burner was placed in the corner of the room. Initially a 100 kW fire was allowed to burn in the corner. If this fire did not cause flashover in 10 minutes, then the burner output was increased to 300 kW.

Small scale fire test data were obtained by other researchers for the materials used in the Borås study [5,11,12] and were used to develop Table 1. These values are used for the model inputs. In the calculations, ceiling fire spread is accounted for by having the ceiling ignite when the pyrolysis front reaches the ceiling. The ceiling spread follows the wind-aided spread along the wall ceiling interface. Thus, the pyrolyzing ceiling area is given as the quadrant of the ceiling with a radius equal to the distance from the corner to the wall ceiling interface pyrolyzing front. Lateral spread was

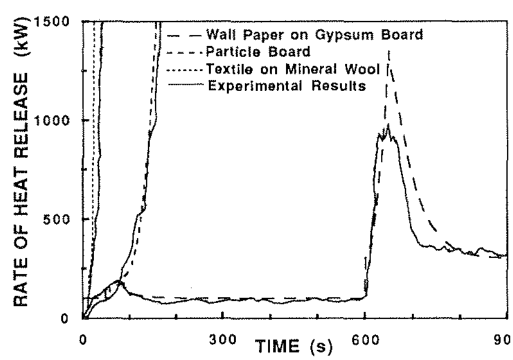

Figure 3 Energy release predictions for the Swedish data (T_s = 80°C, irradiance level = 25 kW/m^2).

allowed to occur only if the wall surface temperature is at the material's $T_{s,min}$ or greater. The model was run with T_s at 25°C and 80°C. While at the start of the test the surface temperature is uniform (about 25°C), allowing T_s to be an input parameter shows the sensitivity to feedback and the effects which increased lateral spread has on the results. This is justified because, while early on in the test T_s of 25°C is more representative of the room conditions, the upper layer temperature is always increasing and radiative feedback is raising wall and ceiling temperatures. We selected burner flame heights (y_o) of 1.3 m and 2.1 m for the 100 and 300 kW settings. We determined y_o values from an axisymmetric fire plume correlation realizing that corner flames would be taller and could interact with the ceiling. For cases that stopped propagating before 10 minutes, the analysis was restarted at t=600 s from a new origin at y_b(600 s). If y_b(600 s) is greater than 2.1 m, the ignitor flame height, we arbitrarily selected 0.3 m as a new y_o in order to initiate spread again. Also for t > 600 s, we selected T_s = 250°C based on the maximum gas temperatures measured [10]. Model predictions and experimental results for the time to a 1 MW fire are given in Table 2. Figures 3 and 4 show the experimental rate of heat release as a function of time (solid curves) and model calculations (dashed curves) with T_s = 80°C for six of the materials. The results are comparable to the calculations of Karlsson [5], but appear to be distinctly better than the results of Wickström and Göransson [3].

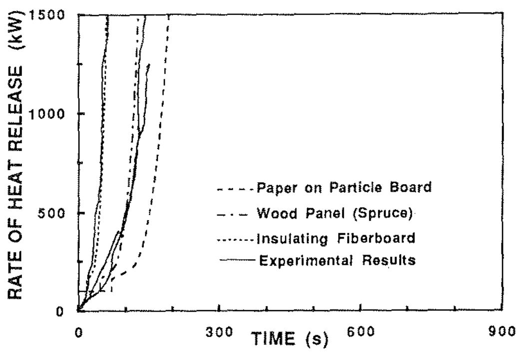

Figure 4 Energy release predictions for the Swedish data (T_s = 80°C, irradiance level = 25 kW/m²).

Table 1 Fire Properties of Swedish Fire Test Materials

Material	T_{ig} (°C)	$k\rho c$ (kW/m²K)² s	Φ (kW²/m³)	$T_{s,min}$ (°C)	$\bar{\dot{Q}}''$ (kW/m²) (25 kW/m²)	t_b (s) (25 kW/m²)	$\bar{\dot{Q}}''$ (kW/m²) (50 kW/m²)	t_b (s) (50 kW/m²)
Particle Board	405	0.626	8	180	140	>500	200	>500
Insulating Fiberboard	381	0.229	14	90	120	>500	150	>300
Medium Density Fiberboard	361	0.732	11	80	140	>500	170	>600
Wood Panel (Spruce)	389	0.569	24	155	140	>200	160	>400
Melamine on Particle Board	483	0.804	<1	435	-	-	115	>400
Wall Paper on Gypsum Board	388	0.593	0.5	300	100	40	200	20
PVC on Gypsum Board	410	0.208	25	300	105	20	160	20
Textile on Gypsum Board	406	0.570	9	270	200	30	300	20
Textile on Mineral Wool	391	0.183	6	174	250	30	375	20
Paper on Particle Board	426	0.680	13	250	140	>500	150	>500
Rigid Polyurethane Foam	393	0.031	3	105	110	60	180	60
Expanded Polystyrene Foam	482	0.464	-	-	-	-	300	100
Gypsum Board	469	0.515	14	380	-	-	100	20

\- Data were not taken

Table 2 Time to Achieve a 1 MW Fire for the Swedish Room Tests

Material	Experimental Time (s)	Model Calculations (25 kW/m²) (T_s = 25°C) (s)	(50 kW/m²) (T_s = 25°C) (s)	(25 kW/m²) (T_s = 80°C) (s)
Particle Board	157	198	143	145
Insulating Fiberboard	59	77	58	55
Medium Density Fiberboard	131	180	148	125
Wood Panel (Spruce)	131	165	143	117
Melamine on Particle Board	465	-	402	-
Wall Paper on Gypsum Board	640	632	616	641
PVC on Gypsum Board	611	619	606	622
Textile on Gypsum Board	639	615	613	615
Textile on Mineral Wool	43	33	28	24
Paper on Particle Board	143	237	220	177
Rigid Polyurethane Foam	6	11	6	7
Expanded Polystyrene Foam	115	-	122	-
Gypsum Board	*	-	*	-

- Data were not taken
* Did not reach 1 MW

Textile Wall Covering Room Tests

A series of textile wall fire tests was performed by the U.C., Berkeley for the American Textile Manufactures Institute [13]. In these tests, 0.31 m (1 ft) and 0.62 m (2 ft) wide strips of different textile wall covering materials were applied to a corner section and the wall portion of the wall-ceiling interface of a room with roughly the same dimensions of the room described above. A 0.31 m by 0.31 m propane sand burner was placed in the material lined corner approximately 10 cm from the walls. A small 40 kW fire was allowed to burn in the corner for 5 minutes, then the burner output was increased to 150 kW. The position of the burner and the size of the small 40 kW fire was such that in most cases it did not cause the textile material to ignite, but shortly after the burner output was increased to 150 kW, all wall lining materials ignited. The rate of heat release was obtained during each test. The data for input into the model is given by Harkleroad [14]. Here lateral spread was not included in the calculations since lateral spread is not expected with the 0.31 m wide strips anyway. It appears from the experimental results that the 40 kW fire only served to preheat the room, therefore we picked an initial surface temperature of 100°C based on the maximum gas temperatures measured during this preheating time. Table 3 shows the experimental and calculated results. By examining the 0.31 m and 0.62 m wide strip results, it appears in some cases lateral spread is significant. The model calculations were performed for the 0.31 m wide strip cases using Cone Calorimeter data at external irradiances of 30 and 50 kW/m². Ignition delay times for each of the materials were calculated from Eq. (5). For this calculation, we assumed T_s = 100°C and 60 kW/m² to represent the heat flux of the ignitor [15], and added the calculated ignition time to the model calculated time to reach the peak rate of heat release. The peak rate of heat release and the time interval from the start of the 150 kW fire for the 0.31 m strips are in fair agreement with the calculations. After the peak heat release was obtained a rapid decay was observed experimentally for most cases, this was predicted well by the model.

Table 3 Textile Wall Coverings Room Fire Tests

Material	Full Scale (0.31 m width) $\dot{Q}_p$ (kW)	Full Scale (0.31 m width) t_p^* (s)	Screening Tests (0.62 m width) $\dot{Q}_p$ (kW)	Screening Tests (0.62 m width) t_p^* (s)	Model Calculations (30 kW/m^2) $\dot{Q}_p$ (kW)	Model Calculations (30 kW/m^2) t_p^* (s)	Model Calculations (50 kW/m^2) $\dot{Q}_p$ (kW)	Model Calculations (50 kW/m^2) t_p^* (s)
(H) 85% wool 15% cotton	46	30	160	40	-		146	46
(C) 55% cotton 45% rayon	62	30	119	60	137	40	139	37
(G) 100% polyester	83	30	-		64	39	56	44
(B) 100% polyester	207	45	298	60	121	46	270	46
(Q) 100% polyester	207	40	480	40	145	50	293	55
(Qfr) 100% polyester	310	40	-		157	43	292	59
(R) 100% nylon	587	70	590	70	46	46	416	51
(AA) 70% acrylic 30% wool	684	30	-		725	109	744	106
(PPPF) polypropylene	-		337	50	271	45	450	48

\- Data were not taken $\dot{Q}_p$ = peak energy release rate
t_p^* = time interval from start of 150 kW burner to peak energy release rate

CONCLUDING REMARKS

We have presented evidence that an engineering approach utilizing "fire property" data from test methods can satisfactorily predict full scale energy release of room lining fires. The choice of the fire properties used is somewhat arbitrary until the fire heat transfer conditions can be related to the test method irradiance levels. The framework presented should serve as a basis for further analysis, but it could be used now to estimate the fire growth hazard of lining materials.

Acknowledgement

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Nomenclature

A	area
a	dimensionless parameter, Eq. (9)
b	dimensionless parameter, Eq. (10)
c	dimensionless parameter, Eq. (10)
$k\rho c$	thermal inertia
k_f	constant, 0.01 m^2/kW, Eq. (6)
q	heat transfer
Q	energy
t	time
T	temperature
x	opposed flow coordinate direction

Subscripts:

b	burnout
f	flame
ig	ignition
o	initial
p	pyrolysis

Nomenclature (continued)

y	wind-aided coordinate direction		Superscripts:	
β	dimensionless parameter, Eq. (14)		$(\bar{\ })$	average
τ	dimensionless time, t/t_b		$(\dot{\ })$	per unit time
ξ	dimensionless pyrolysis position, x_p/x_o		$(\ )''$	per unit area
ξ_b	dimensionless burnout position, x_b/x_o		$(\ )'$	per unit width
η	dimensionless pyrolysis position, y_p/y_o			
η_b	dimensionless burnout position, y_b/y_o			
Φ	flame heating parameter, Eq. (12)			

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