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FORMULAS FOR FIRE GROWTH PHENOMENA BASED ON MATERIAL PROPERTIES

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ABSTRACT

A review is presented of research conducted over the past decade to investigate models to predict material fire behavior. All of the models discussed are presented by analytical formulas derived to maintain what are believed to be the dominant phenomena. Ignition is based on an inert material with a fixed ignition temperature. Non-linear radiation effects are included. Expressions for the burning rate of non-charring and charring materials based on data from the Cone Calorimeter are given. The models are based on immediate conversion of solid fuel to fuel vapor and char, and on constant thermal properties and char fraction. A general formula for flame spread results in a correlation for flashover time in the ISO 9705 Room-Corner Test. The material properties needed, and their derivation is discussed. The level of accuracy of results show the practicality of this type of approach.

INTRODUCTION

The evaluation of the fire hazard of materials has been a challenging task that is based in empirical testing and a wide variety of regulatory practices. There is not a uniquely accepted technical consensus on how to approach this problem. Over about the last decade, we have investigated the feasibility of using the minimum amount of mechanisms in the formulation of analytical formulas to evaluate the various aspects of material fire behavior, namely: ignition, burning rate, flame spread and fire growth. Each fire process contributes new essential mechanisms, and therefore new properties that are needed in the formula. These properties, although modelling based, must have some universality or they are merely fitting parameters. The real answer for these "equivalent material properties" lies somewhere between meaningful science and mathematical coefficients.

Table 1. Material properties and Fire Process

PROCESSES→ PROPERTIES↓	Ignition	Flame Spread	Burning Rate Non-charring	Burning Rate Charring
Ignition, Vaporization Temperature	x	x	x	x
Thermal Properties, original material	x	x	x	x
Heat of Gasification	--	--	x	x
Char Properties	--	--	--	x
Flame Heat Flux, Length	--	x	x	x

For material properties to be practical in fire modeling they must not only produce accurate predictions, but they must be unambiguously deduced from test data. Keeping the number of properties to a minimum is also desirable. Since ignition precedes flame spread and burning, its properties feed into the latter two processes. The hierarchy of material properties with phenomena is shown in Table 1, and the relationship between phenomena and properties is implied by "x". We shall discuss these relationships and their basis in formulas for the processes.

IGNITION

The simplest model for *piloted ignition* that can be rendered is that based purely on heat conduction. We shall consider the case of a *thermally thick solid* exposed to a constant incident heat flux, $\dot{q}_i''$, under convective and radiative cooling to a fixed temperature ambient at T_∞. Assumptions of the model include:

1. inert semi-infinite solid with constant thermal properties, $k\rho c$,
2. constant ignition temperature, T_{ig}, and
3. blackbody surface conditions.

Assumption 1 requires minimal effect of energy sinks due to phase change and pyrolysis processes. To the extent these energy effects are important, they would be absorbed into an *effective kρc property.* Assumption 2 requires the same evolution of fuel gases at T_{ig} to always cause the lower flammable limit to occur at the pilot ignition source in a small time. Ideally, the pyrolysis kinetics must be very fast along with the time for mixing between the gaseous fuel and the air. Pyrolysis may play a significant role at low heat flux conditions near the critical flux for ignition, $\dot{q}_{cr}''$.

Since this problem is non-linear due to the radiation boundary condition, an exact analytical solution is not possible. An approximate integral solution yields the following dimensionless analytical solution for the time to ignite[1]:

$$\tau_{ig} = C\left(\frac{\dot{q}_{cr}''}{\dot{q}_i''}\right)^2 \tag{1}$$

$$\text{where } \tau_{ig} = \left(\frac{\dot{q}_{cr}''}{T_{ig}-T_\infty}\right)^2 \frac{t_{ig}}{k\rho c} \tag{1a}$$

$$\dot{q}_{cr}'' = \sigma\left(T_{ig}^4 - T_\infty^4\right) + h_c\left(T_{ig}-T_\infty\right) \tag{1b}$$

$$\text{and } C = \frac{\pi/2}{\left(2-\beta\right)\left(1-\beta\right)},\ \beta = \frac{\dot{q}_{cr}''}{\dot{q}_i''}. \tag{1c}$$

The coefficient, C, was modified by replacing 4/3 of the integral solution with π/2 so as to match the exact solution for purely convective heat loss. The exact solution for purely convective heat loss is

$$\frac{\dot{q}_{cr}''}{\dot{q}_i''} = 1 - e^{\tau_{ig}}\operatorname{erfc}\sqrt{\tau_{ig}} \rightarrow 2\sqrt{\tau_{ig}/\pi} \ \text{ as } \tau_{ig} \text{ becomes small.} \tag{2}$$

For the high flux limit or small time limit, both Eqns (1) and (2) give the well known limit where C is $\pi/2$. Approximate solutions to the non-linear problem have also been given for the purely radiative heat loss case by Delichatsios et al. [2]. Their linearized results are

$$\frac{1}{\sqrt{\tau_{ig}}} = \sqrt{\pi}\left(\frac{\dot{q}_i''}{\dot{q}_{cr}''} - 1\right), \text{ for } \frac{\dot{q}_i''}{\dot{q}_{cr}''} \le 1.1 \qquad (3a)$$

$$\frac{1}{\sqrt{\tau_{ig}}} = \frac{2}{\sqrt{\pi}}\left(\frac{\dot{q}_i''}{\dot{q}_{cr}''} - 0.64\right), \text{ for } \frac{\dot{q}_i''}{\dot{q}_{cr}''} \ge 3.0. \qquad (3b)$$

Eq. (1) can also be put in the same form as Eq (3b) for $\dot{q}_i'' / \dot{q}_{cr}'' \ge 2$ with the intercept of 0.64 replaced by 0.76, and for Eq. (2) the intercept replaced as 0.80. Figure 1 shows a comparison of

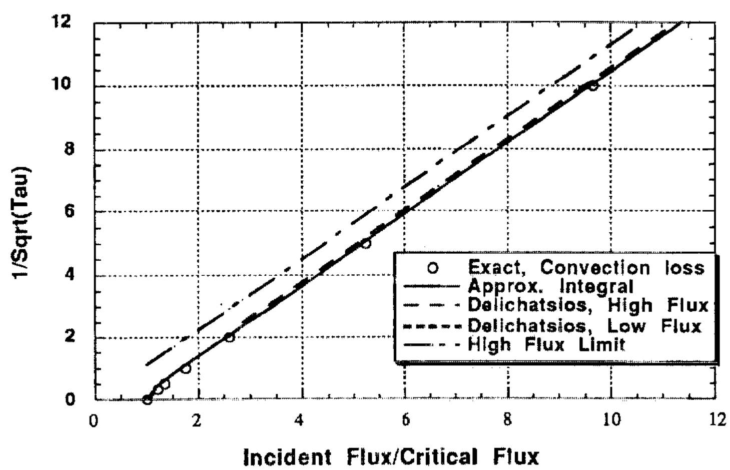

Figure 1. Comparison of Ignition Solutions

these solutions, and demonstrates the accuracy of Eq. (1). The more simple limit solution with C as $\pi/2$ under-predicts the dimensionless time as the dimensionless heat flux decreases toward 1. The limit solution might give an acceptable estimate for $\dot{q}_i'' / \dot{q}_{cr}'' \ge 2$ where $t_{ig,limit}/t_{ig}$ ranges from about 0.5 to 1.

Any of these equations offer a means to compare experimental data. They can also be used to fit experimental data by appropriately selecting the material properties: kρc and T_{ig}. However, there can be operational difficulties in implementing this property derivation since the simple conduction theory may not always apply. A plot of the ignition data in the form of $t_{ig}^{-1/2}$ versus $\dot{q}_i''$ offers a means to determine the critical heat flux from the intercept on the x-axis by using Eq. (3b), T_{ig} from Eq. (1b), and kρc from the slope of the graph. Since the slope depends on $(T_{ig}-T_\infty)\sqrt{k\rho c}$, any inaccuracy in determining $\dot{q}_{cr}''$ affects T_{ig} and therefore kρc, accordingly. Figure 2 gives an example of a dimensionless plot of ignition data for a variety of wood species, and the tightness of the data to a linear fit following the theory shows the appropriateness of the derived properties and the theory. Table 2 shows the derived wood properties.

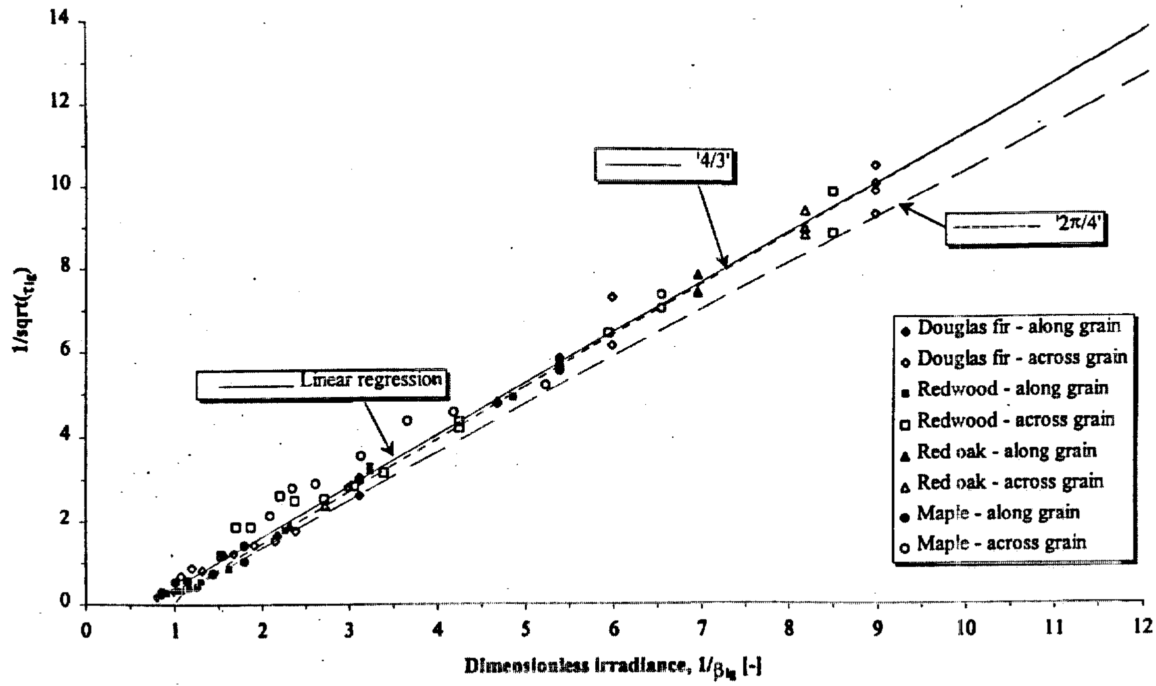

Figure 2. A comparison of dimensionless ignition data for wood species with the integral theory.

Table 2. Derived Material Properties [1,5]

Material	ρ kg/m³	T_{ig} °C	kρc $kJ^2m^{-4}K^{-2}s^{-1}$	Δh_c kJ/g	L kJ/g_{lost}	L_o kJ/g_{orig}	Char Fraction,ϕ –	Cone Flame Heat Flux kW/m^2
Redwood,L*	354	375	0.22	11.9	9.4	2.83	0.12-0.41	35
Redwood, X*	328	204	2.07	9.0	7.5	3.18	0.17-0.45	33
Douglas fir,L	502	384	0.25	11.0	12.5	1.57	0.27-0.62	17
Douglas fir,X	455	258	1.44	9.1	6.8	2.93	0.16-0.42	46
Red oak,L	753	304	1.01	12.3	10.0	2.34	0.21-0.49	35
Red oak,X	678	275	1.88	12.1	4.5	2.33	0.00-0.39	33
Maple,L	741	354	0.67	13.0	4.4	1.70	0.41-0.71	16
Maple,X	742	150	11.0	12.1	6.3	3.53	0.06-0.39	36
PMMA(Plycst)	1190	180+	2.1	--	2.8	2.8	0	37
Nylon	1169	380+	0.87	--	3.8	3.8	0	30
Polyethylene	955	300+	1.8	--	3.6	3.6	0	25
Polypropylene	900	210+	2.2	--	3.1	3.1	0	14

L, cut along the grain; X, cut across the grain; +, underestimated.

BURNING RATE

The simplest model to represent the mass loss rate of a solid due to an incident heat flux is to consider it as a steady state evaporating liquid at an original temperature, T_∞. For this idealization, the mass loss rate per unit area, $\dot{m}''$, is given in terms of the net heat flux, $\dot{q}''$, as

$$\dot{m}'' = \dot{q}'' / L \tag{4}$$

where L is the heat of gasification given as the sum of the heat of vaporization, ΔH_v, and the sensible energy needed to bring the solid fuel from its original temperature to its vaporization temperature, T_v, i.e.

$$L = \Delta H_v + c(T_v - T_\infty). \tag{5}$$

As long the solid fuel will vaporize without leaving a char residue, there is relatively no ambiguity on how to define L as a material property. For a charring material, an appropriate definition for L to obtain mass *loss* rate might be taken as

$$L = L_o/(1-\phi) \text{ in kJ/g fuel lost} \tag{6}$$

where L_o is based on the original mass of material as given by Eq. (5), and ϕ is the char fraction. Table 2 gives some typical results for L and L_o and shows the effect of the char fraction giving $L>L_o$ for a given polymer. A solution which tries to take into account the transient burning behavior, is more complex, especially for a charring material.

The transient solution is found from an approximate integral model based on studies we conducted [1,3-5] and is nearly identical to a formulation by Moghtaderi et al. [6]. The approximate solution has been shown to be in good agreement with more exact numerical solutions for the same equations. Therefore, the integral solution offers the prospect for analytical results to more clearly display the importance of properties and variables needed. The specific transient burning rate problem considered is a thermally thick solid with a constant incident heat flux composed of external radiative and flame components. The problem addresses the initial preheating up to ignition, and the potential development of a char layer. The significant modeling assumptions include:

1. the ignition temperature is the vaporization temperature,
2. the solid vaporizes at a fixed temperature with a constant heat of vaporization, ΔH_v,
3. the flame heat flux and the char fraction are constant, and
4. all thermal properties are constant.

The integral solution is described below:

The net heat flux to the surface for the burning problem is given as

$$\dot{q}'' = \dot{q}''_- \equiv \dot{q}''_i - \sigma(T_{ig}^4 - T_\infty^4) - h_c(T_{ig} - T_\infty),\ t \le t_{ig} \tag{7a}$$

$$\dot{q}'' = \dot{q}''_+ \equiv \dot{q}''_i - \sigma(T_{ig}^4 - T_\infty^4) + \dot{q}''_f,\ \ t \ge t_{ig} \tag{7b}$$

where $\dot{q}''_f$ is the total flame heat flux. This step change in heat flux produces a step change in the mass loss rate of the model when combustion occurs. This modeling approximation produces an instantaneous burning rate when the flame appears, and is given as

$$\dot{m}''_{ig} = \frac{(1-\phi)}{\Delta H_v}\left(\dot{q}''_f + h_c(T_{ig} - T_\infty)\right). \tag{8}$$

Non-Charring Result (ϕ=0)

The transient non-charring burning rate can be given as [5]:

$$\frac{\dot{m}''L}{(1-\phi)\dot{q}''_+} = \left(\frac{L}{\Delta H_v}\right)\left(1 - \frac{c(T_{ig}-T_\infty)}{L}\left(\frac{1}{\Delta}\right)\right) \tag{9}$$

with

$$\frac{1-\Delta}{1-\Delta_{ig}} = \exp\left(-(\Delta-\Delta_{ig}) - 6\left(\frac{L}{\Delta H_v}\right)(\tau-\tau_{ig})\right)$$

where here $\tau \equiv \frac{\left(\frac{k}{\rho c}\right)t}{\delta_s^2}$ is a dimensionless time, and

$\delta_s \equiv \frac{2kL}{c\dot{q}''_+}$ is a thermal conduction length needed to achieve steady vaporization.

Δ is a dimensionless thermal length, δ/δ_s, and Δ_{ig} is its value at ignition.

At steady state Δ=1, and the left-hand-side of Eq. (9) is also equal to 1. Table 2 gives the values of L for several non-charring plastics derived from steady state data indicative of Figure 3. In addition to the ignition derived properties, specific heat information is also needed and was selected from the literature. Figures 4a and 4b show typical predictions of transient burning compared to measured data in the Cone Calorimeter. Table 2 also gives needed corresponding values for the flame heat flux in the Cone heater for horizontal burning.

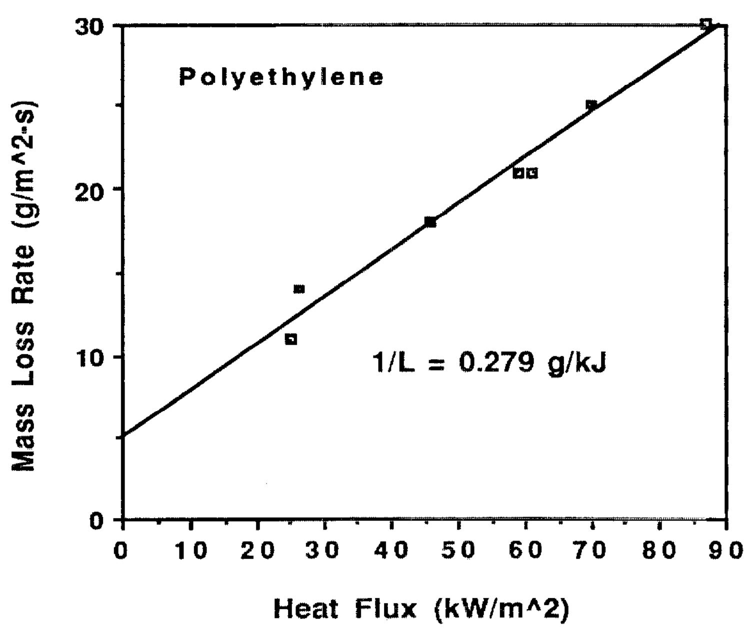

Figure 3. Steady mass loss rate for polyethylene [5].

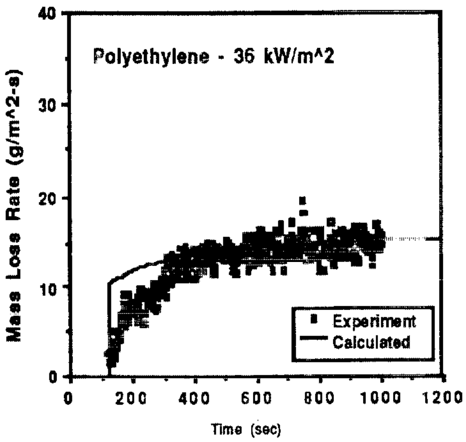

Figure 4a. PE in Cone Cal. At 36 kW/m2.

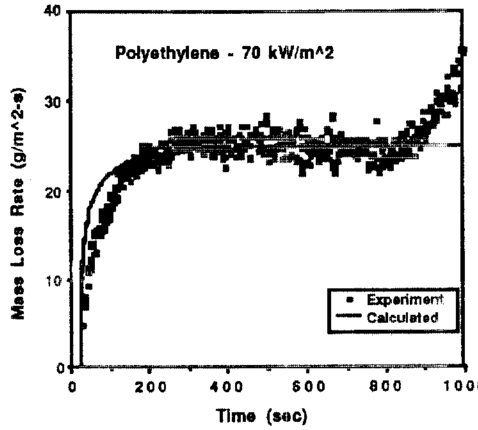

Figure 4a. PE in Cone Cal. At 70 kW/m2.

Charring Result

The corresponding equations that arise from an approximate integral solution are highly nonlinear, and an analytical solution is not directly possible. However, approximate analytical solutions can be produced for small and large time, and their combination produce reasonable results (Fig 5). The solutions are summarized below:

Small Time: The small time charring result follows the non-charring case with a given ϕ up to a peak burning rate after which the long time solution begins. The short time burning rate solution is given from Eq. (9) as

$$\frac{\dot m'' L_o}{(1-\phi)\dot q''_+} = \left(\frac{L_o}{\Delta H_v}\right)\left(1-\frac{c(T_{ig}-T_\infty)}{L_o}\left(\frac{1}{\Delta}\right)\right) \qquad (10)$$

$$\text{where } \Delta \approx \Delta_{ig} + 6\left(\frac{L_o}{\Delta H_v}\right)\left(1-\Delta_{ig}\right)\left(\tau-\tau_{ig}\right).$$

It can be shown that the char depth is initially linear in time and in heat flux:

$$\delta_c \approx \frac{\dot q''_f}{\rho \Delta H_v}\left(1-\frac{\dot q''_-}{\dot q''_+}\right)\left(t-t_{ig}\right). \qquad (11)$$

The surface temperature, $T_s \approx T_{ig}$.

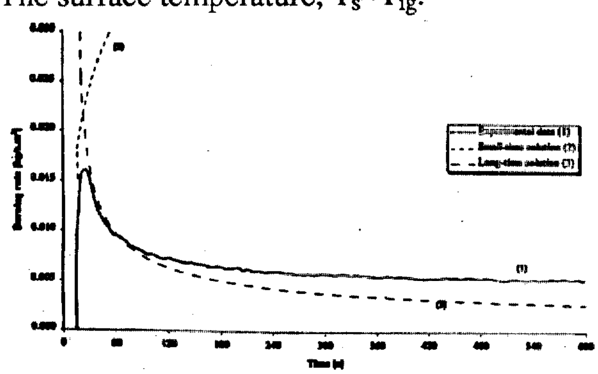

Figure 5a. Burn Rate for Douglas fir

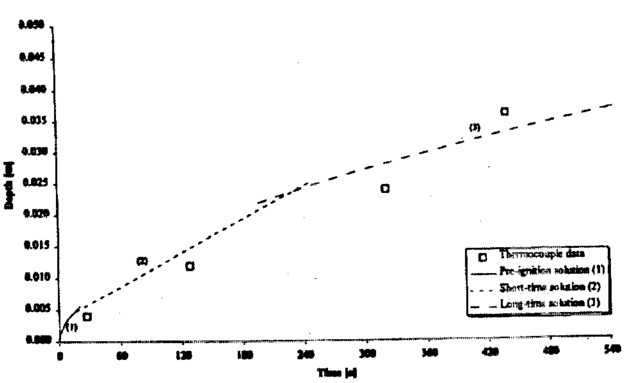

Figure 5b. Thermal depth, Douglas fir

Large Time: The long time solution is given as follows:

$$\delta_c \approx \sqrt{\frac{2k_c(T_s - T_{ig})(t - t_{ig})}{\rho \Delta H_v}} \tag{12}$$

$$\dot{m}'' = (1-\phi)\rho \frac{d\delta_c}{dt} \approx (1-\phi)\sqrt{\frac{\rho k_c (T_s - T_{ig})}{2\Delta H_v (t - t_{ig})}}, \tag{13}$$

and

$$T_s \approx \frac{\left(\dot{q}_f'' + \dot{q}_i''\right)^{1/4}}{\sigma}. \tag{14}$$

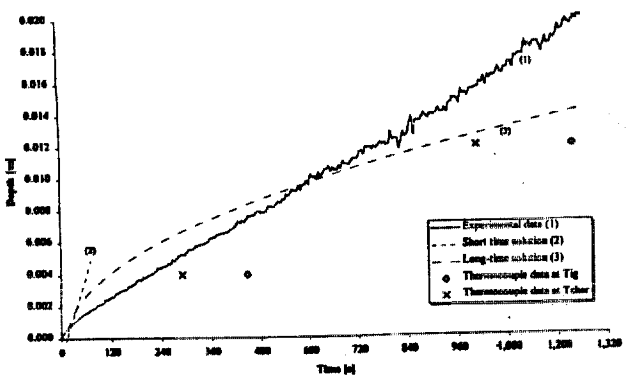

Figure 5c. Char depth, Douglas fir

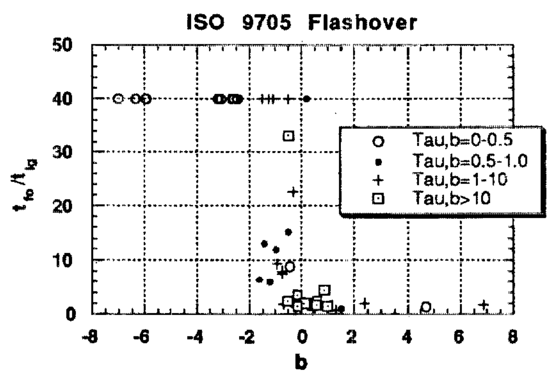

Figure 6. Flashover in ISO 9705

FIRE GROWTH

A criterion for flashover in the ISO 9705 Room-Corner Test can be derived from flame spread principles, and shown to correlate data for over 40 individual tests on a variety of materials. The results are shown in Figure 6. The parameter,b, can be derived from a flame spread model [7] as

$$b = 0.01\dot{m}''\Delta h_c - 1 - 1/\tau_b,\ \tau_{FO} = \frac{t_{FO}}{t_{ig}} \text{ and } \tau_b = \frac{t_b}{t_{ig}}. \tag{15}$$

The dimensionless burning time, τ_b, is also a small factor. Thus, we have tried to show the degree of prediction capable for a range of fire phenomena from derived property data.

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