Discussion of a Model and Correlation for the ISO 9705 Room-Corner Test

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ABSTRACT

New examinations of a predictive model for the ISO 9705 room-corner test have been made for a series of materials. The materials include many that melt and deform during combustion, and thus do not remain intact as wall and ceiling surfaces. Since the model cannot address these effects directly, the melting materials are represented by an adjustment to the total energy available per unit area. This effectively reduces the overall burn time to account for the material falling to the floor. Predictions for melting materials indicate that a significant reduction in the total available energy can provide reasonable fire growth predictions. Examples of materials that remain in place during combustion are also presented and appear to be predicted well by the model. An empirical correlation based on upward flame spread was also applied and indicates a direct relationship between the time to flashover and the heat release rate, times to ignition, and time to burnout.

KEY WORDS: material properties, room-corner test, modeling, flame spread, fire growth

INTRODUCTION

The ISO 9705 room-corner test subjects a material mounted to the walls and ceiling of a room to a 100 kW exposure from a 0.17-m square propane burner positioned in the corner. If

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flashover does not occur within the first 10 minutes, the heat output of the burner is increased to 300 kW for an additional 10 minutes. A model developed by Quintiere [1] uses derived material properties and simple equations that govern the physics of the fire dynamics to predict the ignition, upward and lateral flame spread, burnout, upper layer temperature, wall temperature, and heat release rate for materials tested in a room-corner configuration. Figure 1 shows a simple representation of the pyrolysis and burnout regions predicted by the Quintiere model.

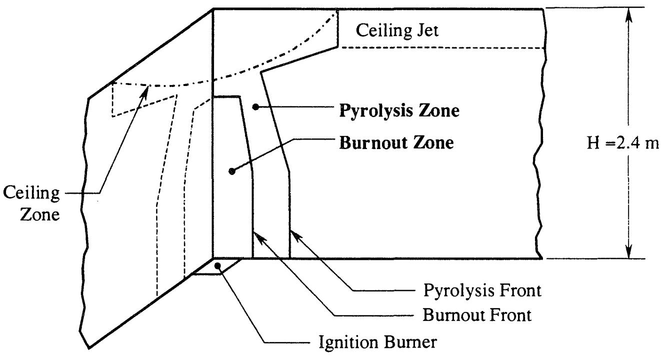

FIGURE 1: Representation of Quintiere's fire growth model for a room-corner test.

The twelve materials examined in this study include some that tend to melt and deform when exposed to the ignition burner and while burning. Traditional materials such as plywood were also included. Each of the materials was tested in the Cone Calorimeter five times at each of four incident heat flux levels—25, 35, 40 and 50 kW/m^2—as well as in the Roland apparatus by L. S. Fire Laboratories (LSF), Motano, Italy. The materials were also tested in accordance with the ISO 9705 room-corner test standard by the Swedish National Testing and Research Institute, Borås, Sweden [2]. Material properties were developed and used in the model to develop predictions of performance, which were then compared with the full-scale test results.

MATERIAL PROPERTIES

To predict fire growth in a room-corner configuration, Quintiere's model requires the input of the seven material fire properties presented in Table 1. These properties can be derived from small-scale test methods like the Cone Calorimeter and the Lateral Ignition and Flame Spread Test (LIFT) apparatus. A systematic method for determining these modeling properties has been developed by Dillon, *et al.*, [3, 4] and is summarized below. The properties for four of the twelve materials (untreated plywood, fire retarded plywood, extruded polystyrene and fire retarded PVC) are presented in Table 2.

Ignition properties ($k\rho c$ and T_{ig}) were based on the results from the Cone Calorimeter. In general the time to ignition (t_{ig}) can be expressed as

$$t_{ig} = C \cdot k\rho c \frac{(T_{ig} - T_{\infty})^2}{(\dot{q}_i'' - \dot{q}_{cr}'')^2} \tag{1}$$

where $\dot{q}_i''$ is the incident radiant flux from the Cone heater, $\dot{q}_{cr}''$ is the critical flux for ignition, and C is a constant that depends on $\dot{q}_i''$. For this analysis, C was taken to be $\pi/4$ for high incident heat flux values. In the model, t_{ig} is computed by a numerical method since the incident heat flux varies with respect to time, and the time to ignition for flame spread does not include $\dot{q}_{cr}''$. By plotting the inverse square-root of the time to ignition ($t_{ig}^{-1/2}$) with respect to the incident heat flux, $k\rho c$ and T_{ig} can be determined based on the critical heat flux and the slope of the linear fit through the data using Equation 1.

TABLE 1. Derived Material Modeling Properties.

Material Property	Symbol	Test Method
Ignition Temperature	T_{Ig}	Cone or LIFT
Thermal Inertia	$k\rho c$	Cone or LIFT
Min. Surface Temp. for Lateral Flame Spread	$T_{s,min}$	LIFT or Roland
Flame Heating Parameter	Φ	LIFT or Roland
Effective Heat of Combustion	ΔH_c	Cone
Effective Heat of Gasification	L	Cone
Total Energy per Unit Area	Q"	Cone

TABLE 2. Ignition, Flame Spread and Heat Release Properties of Materials.

Material	T_{ig} (°C)	$T_{s,min}$ (°C)	$k\rho c$ $(kW/m^2 \cdot K)^2 s$	Φ (kW^2/m^3)	ΔH_c (MJ/kg)	L (MJ/kg)	Q" (MJ/m^2)
Untreated Plywood	290	147	0.63	2.2	11.9	7.3	64.6
Fire Retarded Plywood	480	197	0.11	0.7	11.2	9.3	51.8
Extruded Polystyrene	275	77	1.98	1.2	27.8	4.0	38.7
Fire Retarded PVC	415	32	1.31	0.2	9.9	10.4	16.2

Flame spread properties (Φ and $T_{s,min}$) were determined by the procedures presented in ASTM E 1321 using data obtained from the Roland apparatus as opposed to the LIFT. Lateral flame spread velocity can be expressed using the following equation

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

The flame heating parameter, Φ, can then be determined by plotting the flame front velocity with respect to the incident heat flux. The location on the surface of the material at which lateral flame spread ceases can be used to extrapolate a value for $T_{s,min}$, based on the measured surface heat flux profile.

The ΔH_C and L values are based on a *peak average* rate of heat release per unit area of material burning in the Cone. It was desirable to determine these two properties based on the peak burning of the material without considering the peak heat release rate, which can be consistent with an instantaneous value. Therefore the *peak average* heat release rate is taken to be an integrated average of the measured heat release rates above 80% of the actual peak value. This was determined to be a heat release rate more consistent with actual burning during fire growth and flame spread.

The *peak average* heat of combustion, $\overline{\Delta H_{C\ peak}}$, was determined by taking a numerical average of the values measured in the Cone over the time interval that the *peak average* heat release rate was determined. ASTM E 1354 specifies that the heat of combustion, $\Delta H_C(t)$, be calculated based on the heat release rate per unit area, $\dot{Q}''(t)$, divided by the mass loss rate per unit area, $\dot{m}''(t)$, and that an effective value is then taken as an average of the values over the duration of the test. However, for this study, the measured $\Delta H_C(t)$ values are averaged over the time interval for which the heat release rate is greater than $0.80\,\dot{Q}''_{peak}$. Since the heat of combustion is typically considered to be a constant material property, the average values from the 20 Cone tests were averaged to produce an effective material property, $\overline{\Delta H_C}$. Figure 2 shows the average heat of combustion values plotted with respect to the incident heat flux with the horizontal lines indicating the effective value. Effective heat of combustion values were determined based on the actual peak (*peak*) as well as the ASTM E 1354 method (*overall average*); however, these were determined to be less consistent with "actual" values and were therefore neglected.

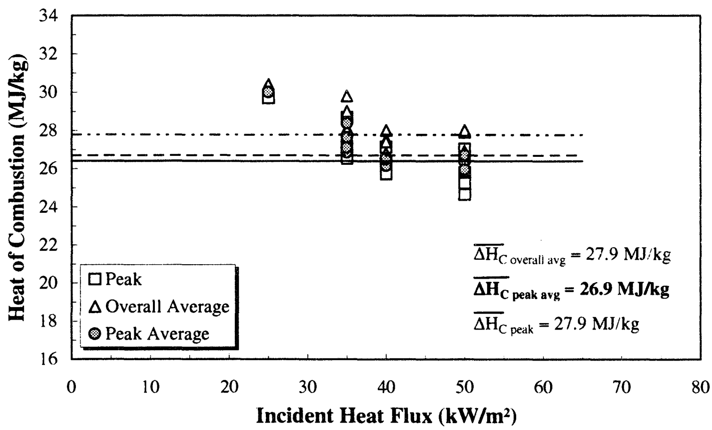

FIGURE 2. Typical $\overline{\Delta H_C}$ determination based on a numerical average of the ΔH_C values from 20 Cone Calorimeter tests: 3-layer, fire retarded polycarbonate panel.

The effective heat of gasification, L, was also determined using the *peak average* heat release rate. The heat release rate per unit area of material can be calculated by the following expression

$$\dot{Q}'' = \dot{q}''_{net} \frac{\overline{\Delta H_C}}{L} \quad (3)$$

where $\dot{q}''_{net}$ is the net heat flux to the material. In the Cone, the net heat flux represents the incident flux from the Cone heater, the flux from the flame, and re-radiation losses from the heated surface. It has been shown that the flux from the flames and the re-radiation losses are relatively constant over a range of incident heat flux levels [4, 5], and consequently $\dot{q}''_{net}$ and $\dot{Q}''$ vary linearly with the incident flux from the heater, $\dot{q}''_i$. This allows L to be determined by plotting the measured heat release rate $\dot{Q}''$ versus $\dot{q}''_i$ and taking the slope of the linear fit through data as being equal to $\overline{\Delta H_C}/L$ as shown in Figure 3. As with $\overline{\Delta H_C}$, the heat of gasification was determined based on the *peak* and *overall average* heat release rates, but these values were neglected.

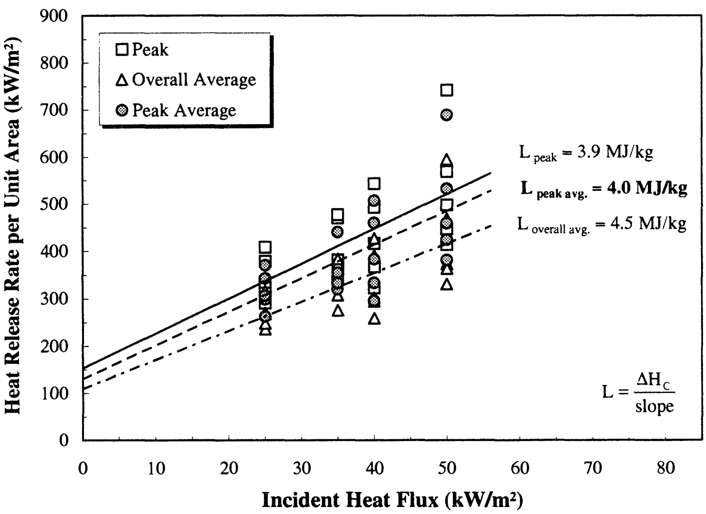

FIGURE 3. Typical determination of L using the slope of the linear fit of $\dot{Q}''$ data from the Cone Calorimeter plotted with respect to $\dot{q}''_i$: fire retarded extruded polystyrene.

The total energy that is available per unit area of material, Q", is determined by dividing the total energy measured in the Cone, Q, by the surface area of the sample. An effective Q" value for each material is then simply taken to be a numerical average of the values calculated for the 20 Cone Calorimeter tests.

MODEL PREDICTIONS

Using the derived material properties in Table 2, the heat release rate, $\dot{Q}$, for twelve materials was predicted using Quintiere's fire growth model. One useful way of ranking materials and determining the fire growth potential is by considering the time to flashover (t_{fo}) under the conditions specified by the test standard. Flashover is an altogether complex process and is associated with different characteristics of the fire compartment: heat flux to the floor of approximately 20 kW/m^2, an upper layer temperature of 500 to 600 °C and flames emerging from the doorway [6]. Based on the room geometry of the standard test, flashover conditions typically coincide with a measured $\dot{Q}$ of approximately 1,000 kW. This 1 MW criterion is for the most part independent of the material and only a property of the room geometry. Other factors can effect the overall performance of a material, but the time for the heat release rate to reach 1 MW will be used to indicate flashover and compare the predicted and full-scale test results. Therefore the predicted times to flashover were compared with ISO 9705 room-corner test data, and the results for four of the materials are presented below.

The heat release rate for materials that tend to remain in place (*i.e.* plywood) are reasonably predicted as can be seen in Figure 4. Examining the results for untreated plywood, it can be seen that the model predicts $\dot{Q}$ = 1 MW approximately 30 seconds before the actual test. However, it should be noted that the measurement of the heat release rate by oxygen consumption in the test appears to have a lag time of about 30 to 40 seconds—it takes about this long for the 100 kW from the burner to be measured. This lag may partly account for the differences in the flashover times. The figure also indicates that flashover did not occur for the FR plywood until the ignition burner was increased to 300 kW and that the test appears to be well predicted by the model.

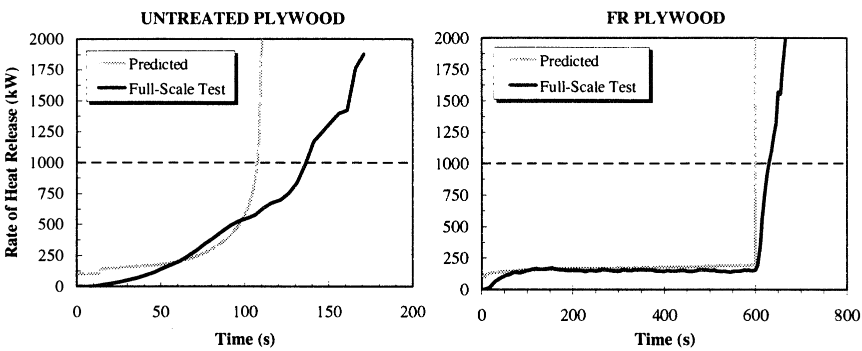

FIGURE 4. Comparison of the predicted and full-scale heat release rate in the ISO 9705 room-corner test: untreated and fire retarded plywood.

The extruded polystyrene was mounted in the room by gluing the sheets to a non-combustible board. In the full-scale room test, the 40-mm thick polystyrene board ignited 20 seconds after being exposed to the 100 kW burner. After 85 seconds, the material on the ceiling was melting and dripping onto the floor and 15 seconds later the heat release rate exceeded 1,000 kW. However, 2 minutes after the start of the test, the material had melted away, and the measured heat release rate reduced to the output of the ignition burner. Approximately 5 minutes later the heat release rate began to gradually increase. At 10 minutes the burner was increased to 300 kW, and the room went almost immediately to flashover.

The heat release rate predictions for the extruded polystyrene are presented in Figure 5. Using Q" from Table 2 provides a reasonable prediction (Prediction 1) of the material's performance and indicates flashover after 64 seconds. Since the material was melting due to the burner exposure, a reduced Q" value could provide a more accurate prediction of the material performance. This reduced value would effectively reduce the burnout time of the material (t_b) which can be calculated by

$$t_b = \frac{Q''}{\dot{Q}''} \tag{4}$$

The heat release rate per unit area of material is calculated using Equation 3 with

$$\dot{q}''_{net} = \dot{q}''_{ig} - \sigma T_s^4 \tag{5}$$

where $\dot{q}''_{ig}$ is the incident flux from the burner (taken to be 60 kW/m² over the height of the burner flame [1]); σ is the Stefan-Boltzmann constant (5.67 x 10^{-11} kW/m²·K⁴); and T_s is the surface temperature which is approximated as being equal to the ignition temperature, T_{ig}. This results in a heat release rate of $\dot{Q}'' = 380$ kW/m². It is difficult to determine exactly when the material began to melt since only the time when the material began to drip from the ceiling was reported. Using this time, 85 seconds, as an effective burnout time in Equation 4 results in a reduction in Q" to 32.3 MJ/kg which is 83% of the original value. Using the observed ignition time of 20 seconds results in a reduction of Q" to 20% of the original value.

Figure 5 indicates that a reduction in Q" down to even 30% of the original value provides the same heat release rate prediction as the original value for Q" used in Prediction 1. However, using 20% of Q" (Prediction 3), the model gives excellent agreement with the initial peak heat release. In order to simulate the second heat release peak, a value of 15% of Q" was used (Prediction 4).

The fire retarded PVC sheets were mounted in the room by screwing the sheets to a light steel frame. The PVC ceiling panels in the corner began to deform 30 seconds after the burner was ignited. After 85 seconds, the material in the corner began to melt and continued to melt until 9 minutes into the test, when most of the ceiling material had fallen to the floor. One minute after the ignition burner was increased to 300 kW, the remaining ceiling material had fallen to the floor. Throughout the 20-minute test, the heat release rate never reached the 1,000 kW associated with flashover. In fact, as Figure 6 indicates, the peak heat release rate never rose above 430 kW. At the conclusion of the test, the ceiling panels and most of the wall panels had melted and were lying on the floor in piles.

Using the Q" value for FR PVC provided in Table 2, the model prediction indicates a low heat release rate of approximately 100 kW during the early portion of the test, but after the ignition burner is increased, the model predicts flashover within about 2 minutes (Prediction 1). Equation 3 provides a heat release rate for FR PVC of $\dot{Q}'' = 45$ kW/m². Using the observed 30-second ceiling deformation time as an effective burnout time results in a Q'' of 1.35 MJ/m² which is approximately 10% of the original Cone Calorimeter derived value. Using this value in the model produces a similar heat release to that which was measured in the actual test (Prediction 2). The tremendous amount of deformation and melting that occurred may be a direct result of the method in which the PVC sheets were mounted—gluing the sheets to a non-combustible board may have significantly reduced the amount of melting and significantly affected the outcome of the test.

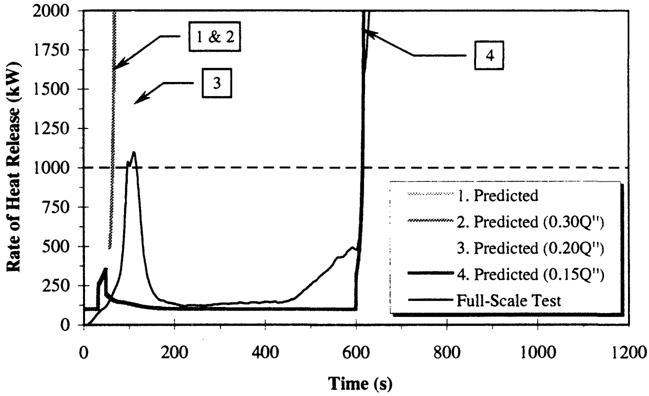

FIGURE 5. Comparison of the predicted and full-scale heat release rate in the ISO 9705 room-corner test: Fire Retarded Extruded Polystyrene Board.

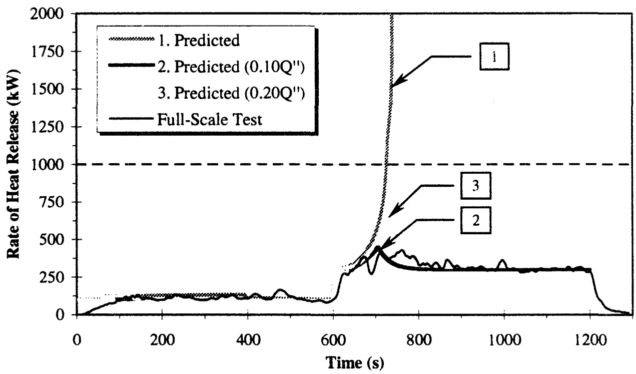

FIGURE 6. Comparison of the predicted and full-scale heat release rate in the ISO 9705 room-corner test: Fire Retarded PVC.

Based on this study, it appears that a rational reduction in the total energy per unit area, Q", can be used to improve the prediction of the heat release rate for thermoplastic materials and that this reduction may be directly related to the ignition time of the material. However, the methodology does need further development and a more rational theoretical basis.

As a further application of the model, blind predictions of the large-scale room-corner tests by Kokkala using EUREFIC materials [7] were made. The large-scale test room was 6.75 m by 9.0 m by 4.9 m high and follows the same ignition protocol as the ISO 9705 test standard. However, three 0.17-m square burners were used to provide a 900 kW ignition source after 20 minutes. The accuracy of the large-scale prediction results are mixed, and an example of one of the well modeled materials, Type B1 FR particle board, is presented in Figure 7.

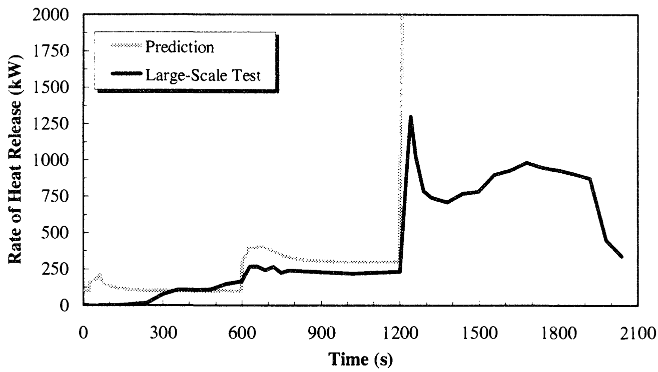

FIGURE 7. Comparison of the predicted and large-scale room-corner rate of heat release results: FR particle board, Type B1.

EMPIRICAL CORRELATION

Cleary and Quintiere [8] developed an empirical correlation that is based on upward flame spread in the standard ISO 9705 room-corner test. This correlation provides a dimensionless upward flame spread parameter, *b*, which depends on heat release rate as well as the time to ignition and burnout:

$$b = k_f \dot{Q}'' - \frac{1}{\tau_b} - 1 \qquad (5)$$

where k_f is an experimentally determined flame length coefficient (k_f = 0.01 m^2/kW); $\dot{Q}''$ is calculated using Equation 3 with a net heat flux, $\dot{q}''_{net}$ = 60 $kW/m^2 - \sigma T_{ig}^4$; and τ_b is the dimensionless burnout time, t_b/t_{ig}. The burnout time, t_b, is calculated using Equation 4 and t_{ig} represents the time to ignition for flame spread due to the heat flux from the wall flame, as opposed to initial material ignition expressed in Equation 1. This time can be expressed as:

$$t_{ig} = \frac{\pi}{4} k\rho c \left(\frac{T_{ig} - T_s}{\dot{q}''_{fl}} \right)^2 \quad (6)$$

where $\dot{q}''_{fl}$ is the flux from the extended wall flame which is taken to be $\dot{q}''_{fl}$ = 30 kW/m² [1].

The value of *b* indicates the likelihood of the flames to spread and cause flashover (*b* > 0) or decay until the material burns itself out (*b* < 0). Theoretically, values of *b* that are close to zero represent materials where small changes in either the material properties or the exposure conditions can affect the outcome significantly. The time to flashover, t_{fo}, from full-scale ISO 9705 experiments are plotted with respect to *b* in Figure 8, which represents a culmination of 45 different materials, including those from this study [9, 10].

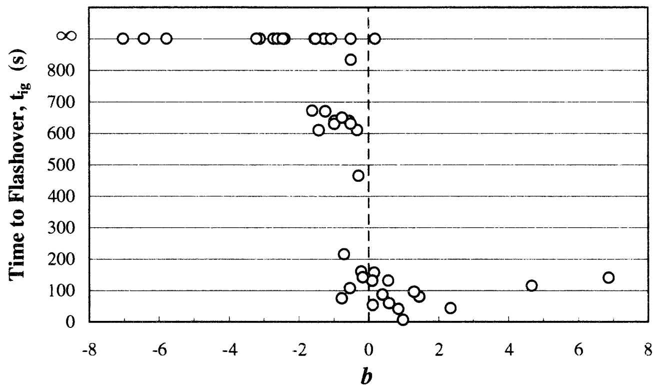

FIGURE 8. Time to flashover, t_{fo}, in the ISO 9705 room-corner test plotted with respect to the upward flame spread acceleration factor, *b* [9, 10].

Figure 8 indicates that the materials generally follow the empirical correlation. At low, negative *b* values, most of the materials do go to flashover ($t_{fo} \rightarrow \infty$). As *b* increases and eventually becomes positive, the time to flashover decreases and becomes asymptotic towards 0. The figure shows that for values close to *b* = -1, there is a significant change in the time for materials to produce flashover. It is in this region that material performance is very sensitive to the input parameters. This indicates that the critical value for *b* appears to be *b* = -1, as opposed to the theoretical value of *b* = 0. Nonetheless, different types of materials including woods, composites, thin materials, and thermoplastic materials are predicted well by the *b* parameter correlation. Thus it can be inferred that this empirical result gives a reasonable categorization of the flashover potential of materials in the ISO 9705 room-corner test.

Kim and Quintiere [11] show that the ratio between the heat release rate and the burner output, $\dot{Q}/\dot{Q}_o$, in Cleary and Quintiere's correlation is a function of the dimensionless flame spread parameters which are dependent on the derived material properties. According to the theory:

$$\frac{\dot{Q}}{\dot{Q}_o} \approx \frac{(a+1)}{a} e^{a(\tau-1)} \qquad \text{Before Burnout} \quad 0 < \tau - 1 < \tau_b \qquad (7a)$$

$$\frac{\dot{Q}}{\dot{Q}_o} \approx \frac{(a+1)}{a} \left(e^{a \cdot \tau_b} - 1\right) e^{b(\tau-1-\tau_b)} \qquad \text{After Burnout} \quad \tau - 1 \geq \tau_b \qquad (7b)$$

where $a = k_f \cdot \dot{Q} - 1$ and τ is time, t, normalized by the time to ignition (t/t_{ig}). A constant heat release rate of $\dot{Q}_{fo}$ = 1 MW at flashover results in a constant value for $\dot{Q}_{fc} / \dot{Q}_o$. This suggests several expressions for the dimensionless flashover time, τ_{fo}:

$$\tau_{fo} = \tau_{fo}(a) \qquad \text{Before Burnout} \qquad (8a)$$

$$\tau_{fo} = \tau_{fo}(a, \tau_b) \text{ or } \tau_{fo} = \tau_{fo}(b, \tau_b) \qquad \text{After Burnout} \qquad (8b)$$

However, $\tau_{fo} = \tau_{fo}(b, \tau_b)$ appears to provide the best results, and the dimensionless flashover time can be plotted with respect to b as shown in Figure 9.

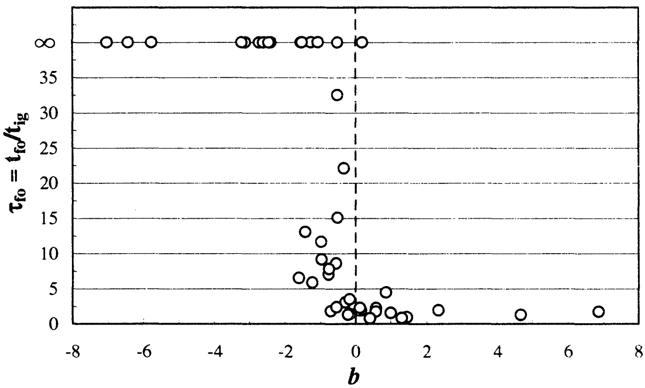

FIGURE 9. Dimensionless time to flashover, τ_{fo}, plotted with respect to the upward flame spread acceleration factor, *b*.

CONCLUSIONS

A systematic method for deriving the properties necessary for modeling has been developed and can be applied to most materials. Analysis shows that for materials like wood, which tend to remain fixed to the walls and ceiling, Quintiere's fire growth model does a good job of predicting the performance. Although the model was not developed to handle the effects of melting thermoplastics, a reduction in the total energy available per unit area can be used to predict actual performance. An empirical correlation has been presented and developed which indicates the dependence of the time to flashover on the time to material ignition, and the time to ignition for flame spread. The correlation provides a simple means for predicting the likelihood that flashover will occur for a wide variety of materials tested in accordance with the ISO 9705 room-corner test standard.

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REFERENCES

1. Quintiere, J. G., "A Simulation Model for Fire Growth on Materials Subject to a Room/Corner Test", Fire Safety Journal, Volume 18, 1992.
2. Thureson, Per, "Fire Tests of Linings According to Room/Corner Test, ISO 9705", SP, Swedish National Testing and Research Institute, Fire Technology, Report 95R22049, January, 1996.
3. Dillon, S. E., Kim, W. H. and Quintiere, J. G., "Determination of Properties and the Prediction of the Energy Release Rate of Materials in the ISO 9705 Room-Corner Test", Department of Fire Protection Engineering, University of Maryland, College Park, MD, June 1998 (submitted to NIST).
4. Dillon, S. E., "Analysis of the ISO 9705 Room-Corner Test: Simulations, Correlations and Heat Flux Measurements", M. S. Thesis, Department of Fire Protection Engineering, University of Maryland, College Park, Maryland, August 1998.
5. Rhodes, B. T., "Burning Rate and Flame Heat Flux for PMMA in the Cone Calorimeter", M. S. Thesis, nd, May 1994.
6. Drysdale, Dougal, An Introduction to Fire Dynamics, John Wiley & Sons, Chichester, 1994.
7. Kokkala, M., Göransson, U. and Söderbom, J., "Five Large-Scale Room Fire Experiments: Project 3 of the EUREFIC Fire Research Programme", Technical Research Centre of Finland, Espoo, 1992.
8. Cleary, T. G. & Quintiere, J. G., "A Framework for Utilizing Fire Property Tests", Fire Safety Science, Proceedings of the 3rd International Symposium, ed. G. Cox & B. Langford, Elsevier Applied Science, London, pp. 647 to 656, 1991.
9. Quintiere, J. G., Haynes, G. and Rhodes, B. T., "Applications of a Model to Predict Flame Spread Over Interior Finish Materials in a Compartment", Journal of Fire Protection Engineering, Volume 7, Number 1, pp. 1 to 13, 1995.
10. Quintiere, J. G. Heater, D. and Stege, S., "Ignition and Lateral Flame Spread: BRI/MOC Fire Project", Department of Fire Protection Engineering, University of Maryland, College Park, Maryland, February 1998.
11. Kim, W. H. and Quintiere, J. G., "Applications of a Model to Compare Flame Spread and Heat Release Properties of Interior Finish Materials in a Compartment", International Symposium on Fire Science and Technology, Seoul, November 12 – 14, 1997.