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PANEL ON FIRE RESEARCH AND SAFETY
MARCH 1-7, 2000**

VOLUME 1

Sheilda L. Bryner, Editor



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BALANCED APPROACH TO THE FIRE PERFORMANCE EVALUATION OF INTERIOR FINISH MATERIALS

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ABSTRACT

This paper describes a methodology for predicting the performance of interior finish materials in the ISO 9705 room corner test on the basis of material properties from small-scale tests (Cone Calorimeter and LIFT apparatus), and a relatively simple computer fire growth model (modified version of Quintiere's model). The heat release rate predictions are in good agreement with experimental room test data for a set of nine marine interior finish materials. The smoke predictions are in qualitative agreement with the measurements, but in some cases they err on the unconservative side. Therefore, additional work is needed to improve the smoke predictions.

INTRODUCTION

Room corner test procedures are now commonly used to evaluate the fire performance of interior finish materials. For example, U.S. model building codes specify acceptance criteria for textile wall coverings that are based on performance in the NFPA 265 or UBC 8-2 room test. The High Speed Craft Code (HSC Code) of the International Maritime Organization (IMO) allows for the use of combustibile interior finish materials on small ferries, provided they meet stringent ISO 9705 room test criteria. Such materials are referred to as "fire restricting materials." For the recent development of new reaction-to-fire classification systems in Europe and Japan, the ISO 9705 room test was chosen as the reference scenario.

A research program was conducted at Southwest Research Institute (SwRI) between August, 1997 and July, 1998. The program was funded by the U.S. Coast Guard (USCG), who is the Authority Having Jurisdiction (AHJ) enforcing IMO regulations in the U.S. The primary objectives of the program were to establish acceptance criteria to qualify materials as fire restricting based on performance in the ISO 5660 Cone Calorimeter test, and to determine whether the general IMO surface flammability and smoke and toxicity requirements for finish materials are consistent with and perhaps redundant to the requirements for fire restricting materials. Eight glassfiber-reinforced plastic resin composite materials and one textile wall covering (see Table 1) were tested in full-scale in the ISO 9705 room. These tests were conducted with test specimens on the walls and ceiling of the 2.4 x 3.6 x 2.4 m room, using the standard propane gas burner source specified in ISO 9705 (100 kW exposure for 10 min, followed by 300 kW for 10 min) The same materials were also evaluated in small-scale according to the test procedures of the Cone Calorimeter (ISO 5660 and ASTM E 1354), the IMO surface flammability test [IMO Resolution A.653(16)], the Lateral Ignition and Flamespread Test or LIFT (ASTM E 1321), and the IMO smoke and toxicity test (IMO FTP Code, Part2).

Table 1. Materials Tested.

Material No.	Generic Name
1	FR Phenolic
2	Fire-Restricting Material
3	FR Polyester
4	FR Vinylester
5	FR Epoxy
6	Coated FR Epoxy
7	Wall Covering Material
8	Polyester
9	FR Modified Acrylic

A follow-up research program was conducted at SwRI in 1999 for Hughes Associates Inc. in Baltimore, MD, as part of a larger program performed by Hughes for the USCG. The objective of this program was to evaluate different models of the ISO 9705 room corner test on the basis of the experimental data obtained during the previous program at SwRI, and possibly modify the models to improve agreement between predictions and experimental results. As a starting point we used the model developed by Quintiere in its original form, in conjunction with material properties obtained according to the procedures proposed in Quintiere's seminal paper [1]. Unfortunately, the resulting calculations were in poor agreement with the experimental room test data. Therefore, the procedures for obtaining material properties, as well as the model itself were modified to improve agreement with the experimental data. These changes are discussed in some detail below.

IGNITION PROPERTIES

Procedures to obtain material properties from piloted ignition data at different heat flux levels commonly assume that the surface heat losses partly involve Newtonian cooling which is characterized by a constant convection coefficient. Recent measurements at SwRI show that the convection coefficient in the Cone Calorimeter, for specimens in the horizontal orientation tested with the retainer frame, can be expressed as a linear function of the external heat flux from the Cone heater:

$$h_c \equiv h_0 + h_1 \dot{q}_c'' \quad (1)$$

where $h_0 = 11.8 \text{ W/m}^2\cdot\text{K}$ and $h_1 = 0.00034 \text{ 1/K}$ at heat flux levels below 50 kW/m^2 , and $h_0 = 25.5 \text{ W/m}^2\cdot\text{K}$ and $h_1 = 0.000065 \text{ 1/K}$ at heat flux levels equal to or greater than 50 kW/m^2 .

Consider a semi-infinite solid with constant properties k , ρ , and c exposed to a constant radiant heat flux, \dot{q}_c'' , with radiative and convective heat losses from the surface:

$$\rho c \frac{\partial T}{\partial t} = k \frac{\partial^2 T}{\partial x^2} \quad (2.a)$$

with

$$T = T_\infty \quad t = 0, \text{ and } x \geq 0 \quad (2.b)$$

and

$$\varepsilon \dot{q}_c'' = h_c (T_s - T_\infty) + \varepsilon \sigma (T_s^4 - T_\infty^4) \quad (2.c)$$

where T_s is the temperature at the surface ($x = 0$), and T_∞ is the initial and ambient temperature. The solution of Equations (2.a)-(2.c) can be expressed by the following relationship between the time, t_{ig} , to reach surface temperature $T_s = T_{ig}$, and the incident heat flux \dot{q}_c'' [2]:

$$\dot{q}_c'' = \sigma (T_{ig}^4 - T_\infty^4) + \frac{h_c}{\varepsilon} (T_{ig} - T_\infty) + \frac{0.71(T_{ig} - T_\infty)}{\varepsilon} \left(\frac{k\rho c}{t_{ig}} \right)^{0.5} \quad (3)$$

Substitution of Equation (1) into Equation (3), after rearranging, leads to

$$\left(\frac{k\rho c}{t_{ig}} \right)^{0.5} = C_1 \dot{q}_c'' - C_0 \quad (4.a)$$

where

$$C_1 = \frac{\varepsilon}{0.71(T_{ig} - T_\infty)} - \frac{h_1}{0.71} \quad (4.b)$$

and

$$C_0 = \frac{\varepsilon \sigma (T_{ig}^4 - T_\infty^4)}{0.71(T_{ig} - T_\infty)} - \frac{h_0}{0.71} \quad (4.c)$$

Equation (4.a) suggests that $(1/t_{ig})^{0.5}$ be plotted as a function of \dot{q}_c'' . The intercept of a straight line fitted through the data points is equal to C_0/C_1 , which can be used to determine T_{ig} . Once the surface temperature at ignition is known, $k\rho c$ can be calculated from the slope of the linear fit. Because h_0 and h_1 have different values for heat fluxes below and above 50 kW/m², the slope of the linear fit is slightly smaller at heat fluxes below 50 kW/m². This procedure was used to recalculate the ignition properties for the nine materials.

FLAME SPREAD PROPERTIES

The ASTM E 1321 LIFT data analysis procedure specifies that $1/\sqrt{V(x)}$ be plotted as a function of $\dot{q}_c''(x)$, and a straight line be fitted through the data points. The flame heating parameter ϕ is calculated from the slope C as follows:

$$\phi = \frac{k\rho c}{C^2 h_{ig}^2} \quad (5)$$

Since the ignition properties have changed, the flame heating parameter was recalculated.

HEAT RELEASE RATE PROPERTIES

The simulations with the original version of Quintiere's model generally underestimates fire growth. This is attributed, at least in part, to high heat of gasification values. To eliminate this problem, it was decided to use actual Cone Calorimeter heat release rate curves, instead of heat release properties derived from Cone data. The Cone Calorimeter data show that heat flux effects are not significant for most materials, and the experimental data at 50 kW/m² were selected for (an initial) analysis. Quintiere [1] uses an incident heat flux of 60 kW/m² for the ISO 9705 ignition burner flames and 30 kW/m² for a vertical wall flame. However, experiments by Dillon [3] and calculations by Janssens [4] indicate that a heat flux of 45 to 50 kW/m² may be more appropriate for the ISO 9705 burner with an output of 100 kW. Therefore, the selection of Cone Calorimeter data at 50 kW/m² is reasonable for this analysis. For materials that did not ignite at 50 kW/m², the Cone Calorimeter results at 75 kW/m² were used instead. The average heat release curve for all runs conducted at 50 (or 75 kW/m²) was approximated by an exponentially decaying function, as shown below:

$$\begin{aligned} 0 \leq t - t_{ig} \leq 30 & : \dot{Q}'' = HRR_{30,max} \\ 30 \leq t - t_{ig} \leq t_b & : \dot{Q}'' = HRR_{30,max} e^{-\lambda(t-t_{ig}-30)} \\ t - t_{ig} > t_b & : \dot{Q}'' = 0 \end{aligned} \quad (6)$$

The decay parameter λ is determined such that the area under the curve is equal to the average total heat release rate measured in the Cone Calorimeter experiments. The idea to use an exponentially decaying function was based on earlier work by Magnusson and Sundström [5]. The maximum 30-sec sliding average heat release rate was used instead of the peak, because the former has been proposed as one of the criteria to qualify fire-restricting materials on the basis of Cone Calorimeter data [6].

SMOKE RELEASE RATE PROPERTIES

A method was developed to obtain a rough estimate of the smoke production rate in the ISO 9705 room-corner test. The heat release rate of the wall material is divided by the heat of

combustion (based on Cone Calorimeter data obtained at 50 or 75 kW/m²). The resulting mass loss rate is multiplied with the specific extinction area, σ , measured in the Cone calorimeter to determine the smoke production rate.

MODIFICATIONS TO THE MODEL

The geometry of the burning area was simplified based on equations previously used by Janssens [2] in his QBasic version of the Quintiere model. The pyrolysis and burned out areas are represented by rectangular areas as opposed to complex trapezoids. Algorithms were also included that better describe the geometry and thermal environment created by the ignition source. The heat flux to the material in contact with the burner flame is determined based on the heat output of the burner and the temperature of the material, as opposed to simply using a constant flux.

Equations to estimate heat release rate on the basis of the heat of combustion, heat of gasification, and net heat flux were replaced with calculations on the basis of the exponentially decaying curve. The total heat release rate from the wall material at time t is given by

$$\text{HRR}(t) = \sum_{i=1}^t (A_i - A_{i-1}) \dot{Q}''(t-i) \quad (7)$$

where A_i and A_{i-1} are the burning areas at time i and $i-1$ seconds, respectively. As the flame front progresses, the pyrolysis area increases. At every incremental time step, a new area may ignite and start burning. The modified model tracks and sums the heat release rate from each incremental area based on the exponentially decaying heat release rate curve to determine the total heat release rate from the material. This method automatically accounts for burnout, i.e., an incremental area burns out when its heat release rate reaches the end of the exponential curve.

Routines were also added to estimate the smoke production rate, SPR, and the corresponding emissivity of the hot gas layer, ϵ_g . The smoke production rate is calculated as the heat release rate divided by the heat of combustion and multiplied by the specific extinction area measured in the Cone Calorimeter.

The emissivity of the upper gas layer is also calculated as a function of the specific extinction area. Quintiere's original model assumes $\epsilon_g = 1$, which appears to be overly conservative for low smoke producing materials. The emissivity of a hot and smoky gas layer can be estimated from [7]

$$\epsilon_g = 1 - \exp(-(0.33 + 0.47C_s)(H - Z_i)) \quad (8)$$

where C_s is the concentration of soot particles (g/m³), H is the room height (m), and Z_i is the layer interface height (m). The soot concentration can be estimated from

$$C_s = \frac{SPR}{k_m \dot{V}_o} = \frac{\sigma HRR(t)}{k_m \dot{V}_o \Delta H_c} \quad (9)$$

where $k_m = 7.6 \text{ m}^2/\text{g}$ based on data by Seader and Einhorn for flaming wood and plastics fires [8]. The layer depth was set equal to 1 m, based on observations in the ISO 9705 tests. To obtain a conservative (high) estimate of ϵ_g , a volumetric vent flow of $0.5 \text{ m}^3/\text{s}$ was chosen. The resulting ϵ_g estimates vary between 0.4 and 1.0.

MODIFIED MODEL SIMULATIONS

The heat release rate predictions are in good agreement with the measurements. Typical examples are shown in Figures 1 and 2. Table 2 compares measured and predicted flashover times, with flashover defined as the moment when the total heat release rate in the room reaches 1000 kW (except for material No. 5, for which 750 kW was used, based on visual observations during testing). For the materials with a flashover time less than 600 s (Nos. 3, 4, 8), the model predictions are very close to the measured heat release rate. For materials with flashover times between 600 and 1200 s (Nos. 5 and 9), the predicted flashover times fall within the same 300-kW exposure period. For the remaining materials, the model correctly predicted that flashover does not occur, and that the heat release criteria for fire restricting materials are not exceeded. However, two of the four materials (No. 1 and No. 6) marginally failed the smoke requirements for fire restricting materials, while the model predicted that all four materials would meet the smoke requirements.

Table A2. Comparison of Measured and Predicted Flashover Times.

Material No.	Experimental (s)	Model (s)
1	No flashover	No flashover
2	No flashover	No flashover
3	342	345
4	306	305
5	978	666
6	No flashover	No flashover
7	No flashover	No flashover
8	102	56
9	672	611

Bold Italic: Time to 750 kW

CONCLUSIONS

A modified version of Quintiere's fire growth model was developed to predict performance of wall and ceiling linings in the ISO 9705 room-corner test. Good quantitative agreement was found between the predicted and measured heat release rates for a set of eight marine composite materials and one textile wall covering.

Although the flame spread data were developed, it was found that lateral flame spread had an insignificant effect on material performance in the ISO 9705 test. Therefore, it is suggested that LIFT and IMO surface flammability test data are unnecessary for performing predictions by the method presented in this report. This can be advantageous due to the high cost of lateral flame spread tests in comparison with Cone Calorimeter tests.

A first attempt was made at estimating the smoke production rate on the basis of the specific extinction area measured in the Cone Calorimeter. The smoke predictions are in qualitative agreement with the measurements, but in some cases they err on the unconservative side. Therefore, additional work is needed to improve the smoke predictions.

A major benefit of the proposed procedure is that a minimal amount of small-scale data is needed to predict ISO 9705 room test performance. It is sufficient to test a material in the Cone Calorimeter at an heat flux level of 50 kW/m², provided the sample is instrumented with a thermocouple on the exposed surface to measure the surface temperature at ignition.

REFERENCES

1. Quintiere, J. G., "A Model for Fire Growth on Materials in a Room-Corner Test," *Fire Safety Journal*, Vol. 20, 1993, pp. 313-339.
2. Janssens, M.L., "Thermophysical Properties of Wood and their Role in Enclosure Fire Growth," Ph.D. Thesis, University of Ghent, Belgium, 1991.
3. Dillon S. E., "Analysis of the ISO 9705 Room/Corner Test: Simulations, Correlations and Heat Flux Measurements," NIST-GCR-98-756, National Institute of Standards and Technology, Gaithersburg, MD, August 1998.
4. Janssens, M., "Predictions of ISO 9705 Room/Corner Test Using a Simple Model," Interscience Communications Limited, Fire and Materials, Proceedings of the 4th International Conference and Exhibition, 1995, pp.73-83.
5. Magnusson, S. E. & Sundström, B., "Combustible Linings and Room Fire Growth—A First Analysis," *Fire Safety Science: Science and Engineering*, ASTM STP 882, T. Z. Harmathy, Ed., American Society for Testing and Materials, Philadelphia, 1985, pp. 45-69.
6. Janssens, M. L, Garabedian, A. S. & Gray, W., "Establishment of International Standards Organization (ISO) 5660 Acceptance Criteria for Fire-Restricting Materials Used on High-Speed Craft," Report No. CG-D-22-98, U.S. Coast Guard R & D Center, Groton, CT, 1998.
7. Quintiere, J., "Growth of Fire in Building Compartments", *Fire Standards and Safety*, ASTM STP 614, A.F. Robertson, Ed., American Society For Testing and Materials, 1977, pp. 131-167.
8. Seader, J.D., and I.N. Einhorn, 16th Symposium (Int) on Combustion, Pittsburg, PA, 1976.

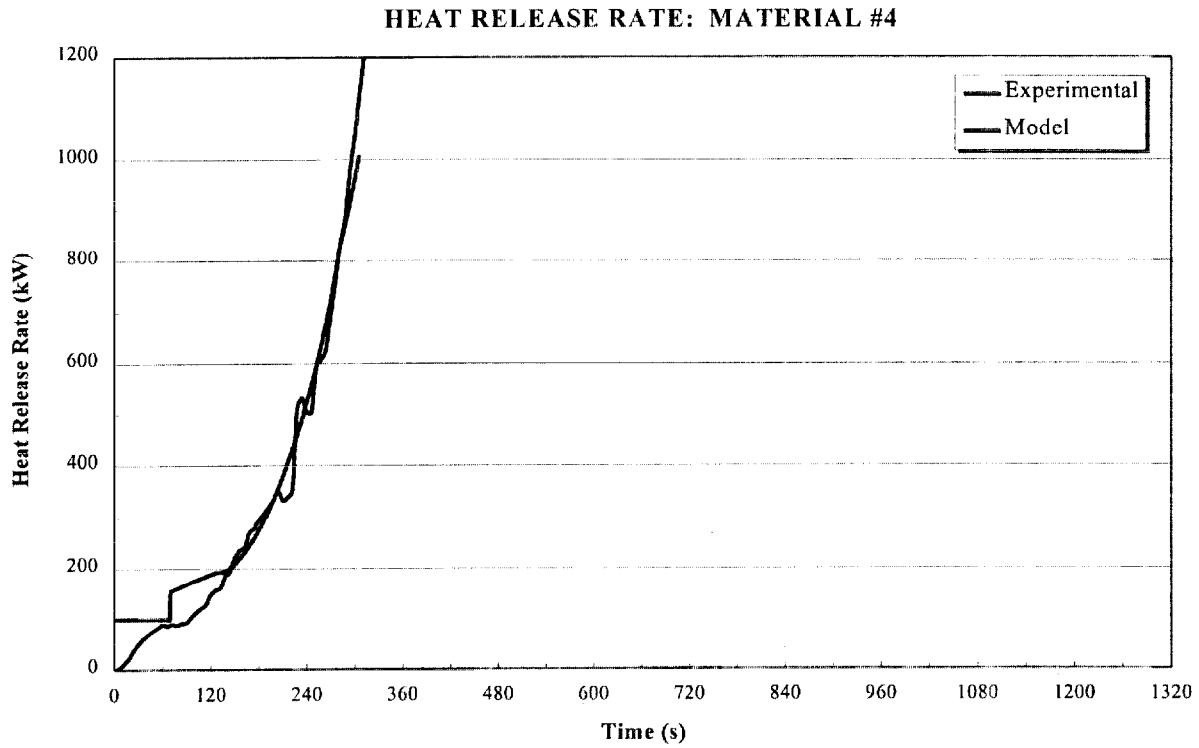


Figure 1. Best agreement between predicted and measured heat release rates

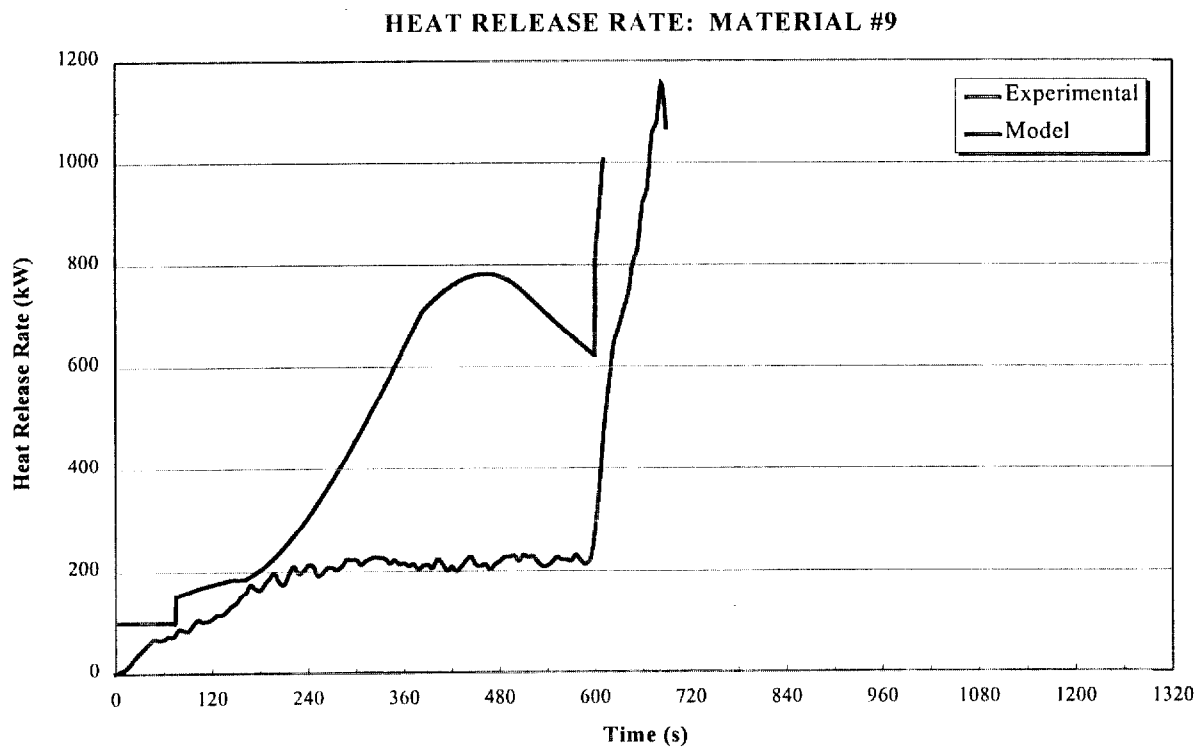


Figure 2. Poorest agreement between predicted and measured heat release rates