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COUPLING THE FIRE BEHAVIOR OF CONTENTS AND INTERIOR FINISHES FOR PERFORMANCE FIRE CODES: EVALUATION OF A FIRE SPREAD MODEL

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SUMMARY

The role of combustible interior finish materials (CIFMs) in fire growth is often termed "flame spread" or "reaction to fire.".This phenomenon is inextricably tied to the heat release rate of the ignition source. Performance fire codes need to have a means of limiting the fire growth contribution of CIFMs and at the same time accounting for the expected role performed by contents. The concept of Critical Ignition Source Strength (CISS) is introduced as a possible performance criterion. Critical Ignition Source Strength links contents to CIFMs and focuses on the condition of flashover. The engineering level fire spread model of Quintiere is evaluated for its ability to predict CISS of a PVC foam wall lining. It is shown that improved opposed flow flame spread capabilities are needed, along with more directly applicable concurrent flow flame spread heat flux data. The lack of sufficiently detailed ignition source heat flux maps for common configurations is a current limitation. The importance of determining the "correct" finish material "properties" is demonstrated.

INTRODUCTION

The role of combustible interior finish materials (CIFMs) in fire growth is often termed "flame spread" or "reaction to fire." This phenomenon is inextricably tied to the heat release rate (HRR) of the ignition source, which drives the fire to and across the finish materials. The combustible contents of a space represent the potential ignition sources, and potential fire growth scenarios involving CIFMs are dependent on how the contents burn.

Performance fire codes need to have a means of limiting the fire growth contribution of CIFMs while accounting for the expected role performed by contents. Many buildings and other structures have well-defined interior contents. Seats are often fixed and other items of contents can be easily anticipated from the use of the structure. If the HRR of the expected interior contents is high, then little latitude remains for the contribution of CIFMs. In this case, they should be limited to essentially noncombustible materials and other materials such as gypsum wallboard which has a limited potential for flame spread. For situations where the HRR of the contents is limited, the allowable contribution of the CIFMs can be larger. The challenge is how to link the contribution of these two elements of possible fire growth scenarios.

This paper presents a framework based on the concept of Critical Ignition Source Strength (CISS) that can be used for fire safety design to evaluate potential fire growth scenarios involving CIFMs. Critical Ignition Source Strength links contents to CIFMs while focusing on the condition of flashover as a performance criterion. To evaluate potential scenarios, the fire protection

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engineer needs to have as his/her design tool a CIFM fire spread model that has been validated. Validation for a given class of CIFMs should be based on full-scale experiments. A series of full-scale experiments[1] involving a PVC foam wall lining which has a CISS of 64kW to 75kW will be used to evaluate an engineering level model's[2] ability to predict CISS. An important aspect of any design process is the information necessary to use the available design tools. The input data required to run the engineering model is discussed with particular attention to the availability and use of applicable data.

APPROACH

Criteria for performance fire codes[3-8] are currently undergoing rapid development. The Editor of *Fire Technology* recently published the procedure being followed by the group working on reformulation of NFPA 101®,[9] *Life Safety Code®*, into a performance fire code.[10] The procedure for this development consists of seven steps: (1) identify life safety objectives, (2) specify occupancy classification, (3) define appropriate fire scenarios, (4) establish performance criteria, (5) select suitable calculation methods, (6) update residual prescriptive requirements, and (7) designate documentation format. The process is not yet complete, but a preliminary draft of a performance *Life Safety Code®* has been proposed as an advisory appendix for the 1997 edition of the *Code*. This paper focuses on steps 3 through 5 in situations where CIFMs are present.

Fire growth scenarios which involve CIFMs usually have a source fire (ignition source) developing in interior furnishings and/or contents which are located near a wall or ceiling lining. The mode of fire growth involves the ignition and subsequent flame spread over the CIFM. If the source fire is not large enough to spread the fire on the wall or ceiling lining, then we have an "acceptable" fire performance for the lining material. On the other hand, the source fire may be so large and release heat so rapid that the contribution of the lining is small compared to the source fire. In this case, the contents are the *"villain"* and the wall and/or ceiling lining is the *"victim"* and not a significant factor in fire growth. However, between these two extremes there are fire growth scenarios in which the source fire is sufficiently large to *rapidly* spread the fire on the wall and/or ceiling lining. The traditional codes establish one or more standards which must be met by the lining materials, but there is little or no coupling of the "fire threat level" that a given wall and/or ceiling lining material would be expected to face without spreading the fire. Performance fire codes need to be able to distinguish between these three fire scenarios, and more importantly there needs to be a framework for classifying the particular situation which applies in each building. The approach described in this paper is to use the expected HRR of the source fire to predict potential fire spread on CIFMs.

Critical Ignition Source Strength[1] is the strength level which when exceeded causes CIFM fire spread sufficient to take a compartment to flashover. As performance fire codes are implemented, CISS is a candidate for use to regulate linings and contents items. Critical Ignition Source Strength is a performance criterion that couples both of these aspects of fire growth scenarios in a manner amenable for design by clearly identifying the critical condition of flashover. A performance code could be developed that specifies what CISS level a CIFM should have to be used in a building of a given type and in a given location in that building. Unlike the fixed ignition source exposure prescribed in standards such as *Uniform Building Code Standard #8-2*[11] (UBC 8-2), CISS encompasses a general ignition source exposure which can be readily related to existing and future real-world contents items.

For CISS to become a performance criterion, it must be modeled.[12] Modeling is required due to the prohibitive cost associated with full-scale testing to determine a CIFM's CISS. An approach to predicting CISS is to develop a model that is based on material "properties" that come from bench-scale standard tests such as the Cone Calorimeter[13] (ASTM E 1354) and the LIFT[14] apparatus (ASTM E 1321). When it is proven, based on full-scale validation, that a designated class of CIFMs can successfully be modeled based on Cone and LIFT results, then all new materials that fall into that class will only have to be tested in bench-scale to determine the new materials' CISS. If new CIFMs fall outside the validated classes of materials, then full-scale testing would still be required.

To model CISS, two issues must be addressed. (1) The insult from various ignition sources in corner, flat-wall, and ceiling configurations needs to be characterized. This means determining the heat flux distribution on the compartment walls and ceiling. Currently this is done experimentally by heat flux mapping.[15–18] The fire protection engineer would need to compile a database of heat flux maps to cover the various ignition source configurations involved in any fire growth scenarios to be modeled. (2) Ignition source driven concurrent and opposed flow flame spread needs to be simulated. Candidate models have been developed by Quintiere,[2] Karlsson,[19,20] Delichatsios,[21,22] Mitler,[23] and Grant and Drysdale.[24] To have a design tool that the fire protection engineer can use with confidence, the engineer needs to understand under what conditions and for what class of CIFMs a given model has been validated.

Model Evalutation

The full-scale experiments[1] which demonstrate that PVC foam wall lining has a CISS of 64kW to 75kW will be used to evaluate the model of Quintiere[2] (The Model). The Model was chosen for evaluation because it has both concurrent and opposed flow flame spread components, because the necessary bench-scale material "property" data is based on standardized tests,[13,14] and the ignition source provided is general in specification. None of the other models cited above have all of these features. The Model assumes one mode of concurrent flow for wall upward and wall-ceiling interface region flame spread. The Model assumes one mode of opposed flow for wall lateral and downward flame spread. This means that The Model effectively "unfolds" the corner and wall-ceiling interface to approximate flame spread as spread over an equivalent flat wall. The data set of these PVC foam wall lining experiments, though limited, captures some of the challenges faced when considering real-world wall lining materials. The PVC foam wall lining which looks like suede is a fire retarded thermoplastic material with a complex surface texture.

The experiments[1] were conducted in a "standard" fire test compartment conforming to UBC 8-2[11] specifications. The wall lining configuration used was the screening test protocol of UBC 8-2. A screening specimen is 0.61 m wide, and is installed on both walls of the corner, floor to ceiling, and at the top, along the full length, of both walls that make up the corner (see Figures 1 and 2). The ignition source used was a 0.30 m by 0.30 m propane fired sand burner with its top surface 0.30 m above the floor. The burner was placed in the corner with a 5 cm stand-off distance consistent with UBC 8-2. The experimental net HRR curves of the PVC foam are shown in Figures 3 to 6. As the strength of the ignition source was increased, the environment in the compartment "jumped" from preflashover to incipient flashover when the strength increased from 64kW to 75kW. The HRR necessary to flashover the compartment was 1200kW.[25] As can be seen from Figures 5 and 6, the peak net HRR is slightly lower than this value. The reason for the lower value is the limited area of the screening specimens. When a fully-lined compartment is evaluated at super-critical strength, the resulting net HRR easily exceeds the compartment flashover level.[1]

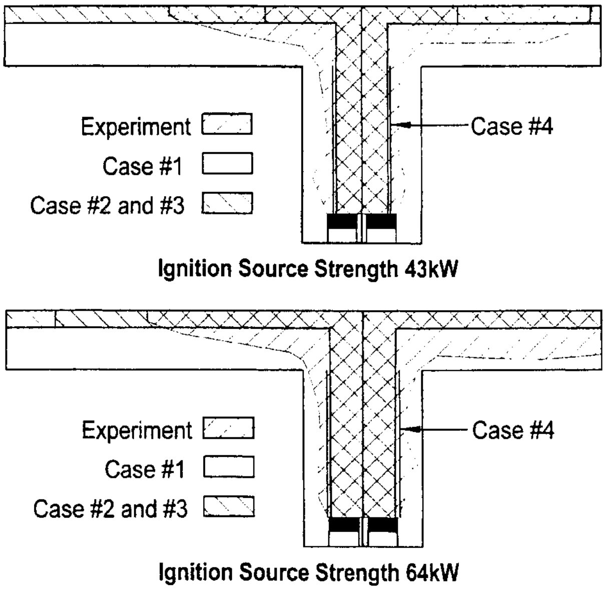

Figure 1. PVC Foam Wall Lining Final Burn Patterns — Sub-Critical Strength.

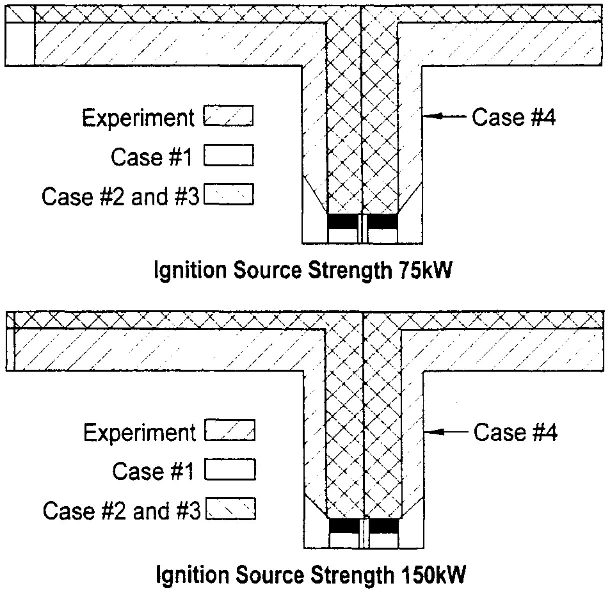

Figure 2. PVC Foam Wall Lining Final Burn Patterns — Super-Critical Strength.

The Model[2] requires that 33 variables be specified to define each fire simulation.

Related variables can be classified into five groups. Each group of variables will be discussed in terms of information available from the PVC experiments (design fire scenarios), the literature, and bench-scale tests. The Miscellaneous Group will not be discussed as these variables are primarily needed to run the program and/or program options.

The Room, Burner (Ignition Source), and Wall Lining Configuration Group are all variables that would readily be available based on design fire growth scenarios to be analyzed. These variables for the PVC experiments are considered fixed for evaluation of The Model. The variables are: room width = 2.4 m, room depth = 3.6 m, room ceiling height above burner surface = 2.1 m, surface area of room = 44.6 m^2, door height = 2.0 m, door width = 0.76 m, maximum lateral flame spread distance = 0.61 m, maximum concurrent flow flame spread distance = 5.1 m, and maximum downward flame spread distance = 0.44 m.

The Ignition Source (Burner) Strength Group are all variables that would be based on the assumed source fire and its location for the given fire growth scenarios. The values would come from the fire protection engineer's heat flux map database. Based on the PVC experiments, the values used for evaluation of The Model are assumed fixed. The variables are: height of the lining ignition region, $y_{p,o}$, half-width of the lining ignition region, $x_{p,o}$, HRR of the ignition source, $\dot{Q}_{ig}$, ignition source incident heat flux to the ignition region, $\dot{q}''_{ig}$, and ignition source HRR per unit width, $\dot{Q}'_{ig}$. The values used are listed in Table 1.

The $y_{p,o}$ and $x_{p,o}$ values were determined based on "high" heat flux regions identified from the final burn patterns in the PVC experiments, not shown in Figures 1 and 2, and data reported by Williamson

Table 1. Ignition Source Strength Group Variables.

$\dot{Q}_{ig}$	$y_{p,o}$	$x_{p,o}$	$\dot{q}''_{ig}$	$\dot{Q}'_{ig}$
kW	m	m	kW/m^2	kW/m
43	0.48	0.26	20	84
64	0.82	0.33	25	110
75	0.90	0.36	30	110
150	1.20	0.38	45	150

et al.[15] The $\dot{q}''_{ig}$ values used are area-averaged values based on the heat flux maps of Williamson *et al.*[15] and Kokkala.[17] The HRR per unit width of the ignition source is required to allow the concurrent flow flame spread model to properly account for the flame height of the ignition source. The HRR per unit width is calculated from $\dot{Q}'_{ig} = 100 y_{f,ig}$, where $y_{f,ig}$ is the flame height of the ignition source. The flame height of the ignition source in the corner was not measured in the PVC experiments. The authors did not find in the literature flame heights for a burner in a corner with a 5 cm stand-off distance. The flame heights were estimated using the mean flame height correlation, in the "open," of Zukoski.[26] Based on the work of Hasemi,[27] the error from using Zukoski should not be significant. The use of the final burn patterns from the PVC experiments and the correlation of Zukoski points to the lack of comprehensive heat flux map data in the literature for potential ignition source configurations. At this time, it is most likely that the fire protection engineer would need to supplement the heat flux map database with experiments addressing the specific ignition source configurations of interest. Having sufficiently detailed heat flux maps is a key set of information to accurately determine the initial conditions for a fire spread model.

The Flame Spread Mechanism Group are all variables that are particular to the flame spread mechanism. The values would either be provided as "defaults," or the fire protection engineer would have to find appropriate values in the literature. Based on the PVC experiments, the values used for evaluation of The Model are assumed fixed. The variables are: pyrolysis region net heat flux, $\dot{q}''_{f,net}$, and net flame heat - flux in spread (forward heating flux), $\dot{q}''_{f}$. The forward heating flux value used was 30kW/m^2, a conservative value, which is recommended by Quintiere.[2] This value is consistent with the work of Hasemi[28] involving wall fires in a corner configuration. The pyrolysis region net heat flux is $\dot{q}''_{f,net} = \dot{q}''_{f,p} - \sigma T_{ig}{}^4$, where $\dot{q}''_{f,p}$ is the incident flame heat flux over the pyrolysis region, T_{ig} is the ignition temperature, and σ is the Stefan-Boltzmann constant. To estimate $\dot{q}''_{f,p}$ the flat-wall correlation of Delichatsios[29] was used. Heat flux to a flat wall is consistent with the flame spread theory of The Model which effectively "unfolds" the corner and the wall-ceiling interface. A simple radiant heat transfer analysis of the corner, assuming both walls to be "covered" by a layer of flames, suggests that the error due to ignoring the enhancement of the incident flux should not be overly significant. To calculate an average heat flux over the pyrolysis region using the correlation requires that the HRR per unit width of a fire be known. To estimate the HRR per unit width of each experiment, the experimental peak net HRRs and the average widths of the final burn patterns were used. Based on the estimated HRR per unit width the correlation gave 44kW/m^2 as a typical value, which was used for $\dot{q}''_{f,p}$. Whether this process to estimate $\dot{q}''_{f,p}$ is reasonable is unknown. The use of the PVC experimental data and a flat wall heat flux correlation to estimate $\dot{q}''_{f,p}$, and the use of a conservative value for $\dot{q}''_{f}$ point to the lack of directly applicable heat flux data in the literature. This is an important limitation that the fire protection engineer currently faces. At this time, it is recommended that the most closely applicable literature values be used to estimate $\dot{q}''_{f}$ and $\dot{q}''_{f,p}$.

The Wall Lining "Properties" Group are all variables that are determined from Cone[13] and LIFT[14] testing. The fire protection engineer would either be able to look the values up in the literature for a given wall lining or have the wall lining tested. The variables are: thermal inertia ($k\rho c$), heat of combustion (ΔH_c), effective heat of gasification (L), total energy per unit area (Q''), ignition temperature (T_{ig}), lateral flame spread parameter (Φ), and minimum temperature for lateral spread ($T_{s,min}$).

Table 2. Wall Lining "Properties" Group Variables.

	T_{ig}	$k\rho c$	Φ	$T_{s,min}$	ΔH_c	L	Q''
Case #	°C	$(kW/m^2K)^2s$	kW^2/m^3	°C	MJ/kg	MJ/kg	MJ/m^3
1	363	0.35	25	300	11	4.4	8.7
2	322	0.16	25	300	14	4.4	10.9
3	322	0.16	25	300	14	4.4	5.2
4	322	0.16	4 and 25	90	14	4.4	5.2

The PVC foam used in the experiments was tested in the Cone[13] and the LIFT.[14] It was mounted to 13 mm gypsum wallboard using a water-based adhesive as was done in the experiments. From the LIFT, and the Cone testing a set of ignition data was compiled. In the Cone, HRR curves were measured at $25kW/m^2$, $50kW/m^2$, and $75kW/m^2$ incident heat flux, three curves at each flux level. In the LIFT no significant lateral spread occurred for the three flame spread samples tested. The lack of flame spread may be due to the "low" levels of external heat flux used[30] and/or the result of the chlorine and/or other fire retardants used in the PVC foam, as has been discussed elsewhere.[1]

The importance of material "properties" to The Model's ability to predict fire spread will be highlighted by consideration of four sets of "properties" (see Table 2), based on the test data, the PVC experiments, and typical literature values. Case #1 used the procedures of ASTM E 1321[14] to calculate T_{ig}, and $k\rho c$. For this case Φ and $T_{s,min}$ could not be calculated, and values for PVC covered gypsum wallboard (the only PVC CIFM values found) were chosen from the literature.[2] The material properties ΔH_c and Q'' are average values determined from the Cone HRR curves.[31] The procedure given by Quintiere[2] was used to determine L, where the average peak HRR values from the Cone for each incident heat flux are plotted versus the incident flux. The slope of the line between the points is $\Delta H_c/L$ which allows L to be calculated using ΔH_c.

The results of The Model predictions of the net HRR curves for the PVC foam at each ignition source strength level for Case #1 are shown in Figures 3–6. As can be seen, the times to ignition are too long and the initial fire spread rates are too slow, resulting in poor predictions from The Model. No opposed flow fire spread resulted in this case because the global wall temperature calculated by The Model did not exceed $T_{s,min}$.[2,31] The extent of concurrent flow fire spread for 43kW ignition source strength was underpredicted along the wall-ceiling interface, and for 64kW ignition source strength the concurrent flow spread was overpredicted along the wall-ceiling interface (see Figure 1). For the super-critical strength levels the extent of the concurrent flow spread reached to the ends of the specimen along the wall-ceiling interface as occurred in the experiments (see Figure 2).

Due to the poor predictions of Case # 1, an alternative set of the material "properties" were considered for Case #2 (see Table 2). Case #2 used the procedure of Janssens[32] to calculate T_{ig} and $k\rho c$ based on the ignition data. The "new" T_{ig} is somewhat lower, and the "new" $k\rho c$ is 54 percent lower. Additionally, ΔH_c and Q'' were increased 25 percent. The increase in ΔH_c and Q'' is consistent with the variation in these properties determined from the Cone HRR curves.

The Case #2 material "properties" greatly improve the net HRR predictions of The Model (see Figures 3–6). The times to ignition are slightly early, but the initial fire spread rates match to the experimental values

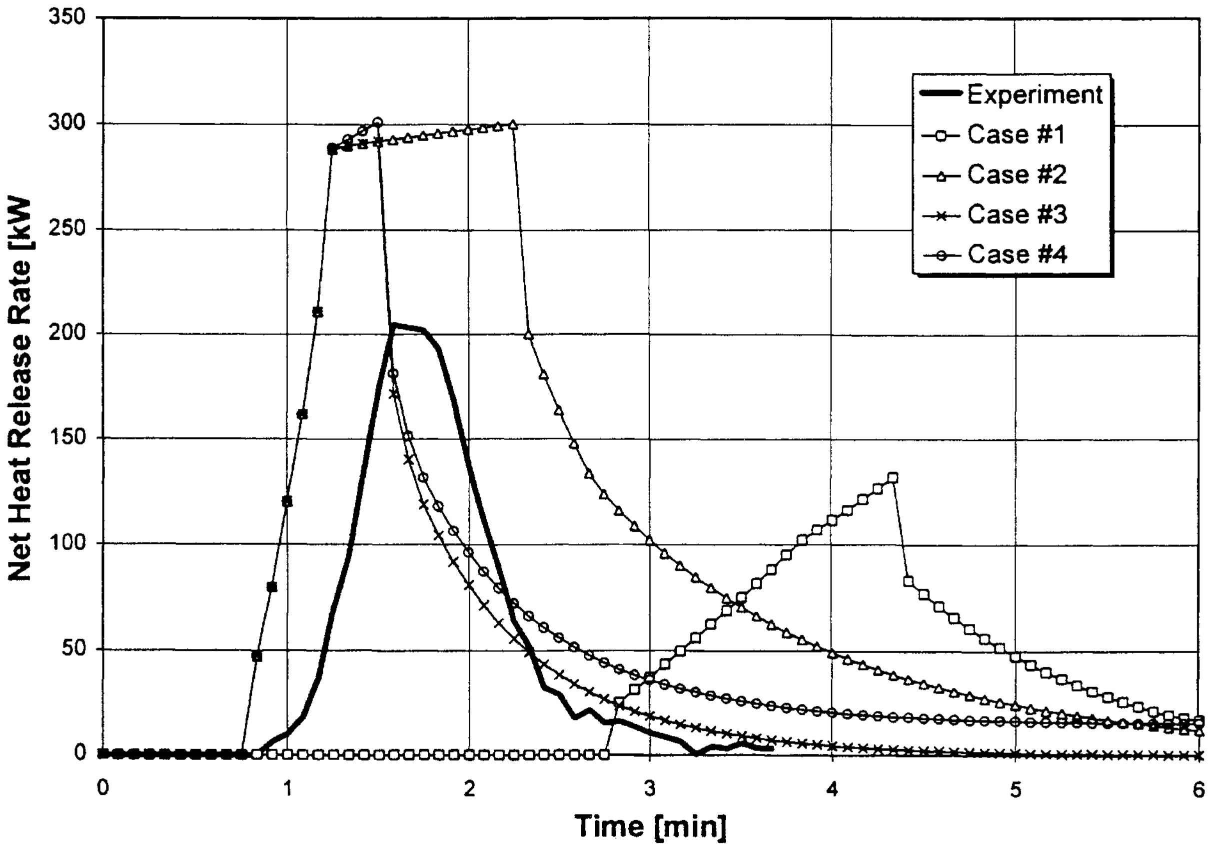

Figure 3. PVC Foam Net Heat Release Rate — Ignition Source Strength 43 kW.

quite well. However, the duration of the "flat-topped" peaks predicted by The Model indicate that burn-out of the PVC foam is taking too long. Again, no opposed flow fire spread occurs because $T_{s,min}$ is not exceeded. The lack of opposed flow spread causes the super-critical HRR curves to significantly under-predict peak net HRR. The extent of concurrent flow spread is over predicted for the sub-critical strength levels by reaching the ends of the specimens along the wall-ceiling interface (see Figure 1). This causes the over-prediction of the peak net HRR for 43kW strength. For 64kW strength, the close prediction of peak net HRR is somewhat fortuitous as the over-predicted concurrent flow fire spread is countered by the lack of opposed flow fire spread. For the super-critical strength levels, the concurrent spread extent matches the experiments (see Figure 2).

The Case #3 material "properties" change only Q'' to try to improve the shape of The Model's predicted net HRR curves. The value of Q'' used is the average value from the full-scale PVC experiments[1] which is a 40 perecent to 52 percent decrease over the Case #1 and #2 values (see Table 2). The Case #3 predicted net HRR curves are significantly improved by allowing burn-out to occur sooner, (see Figures 3–6). Otherwise, the Case #3 results are the same as for Case #2.

Case #4 was run to force opposed flow fire spread, which is very important to accurate HRR predictions for the super-critical strength levels. To allow The Model to "turn-on" the spread mechanism $T_{s,min}$ was changed to a "low" value.[2] The spread parameter Φ was also changed for the sub-critical strength levels (see Table 2). The lower Φ value was used to try to better match the final burn patterns. The extent of predicted lateral spread is shown with

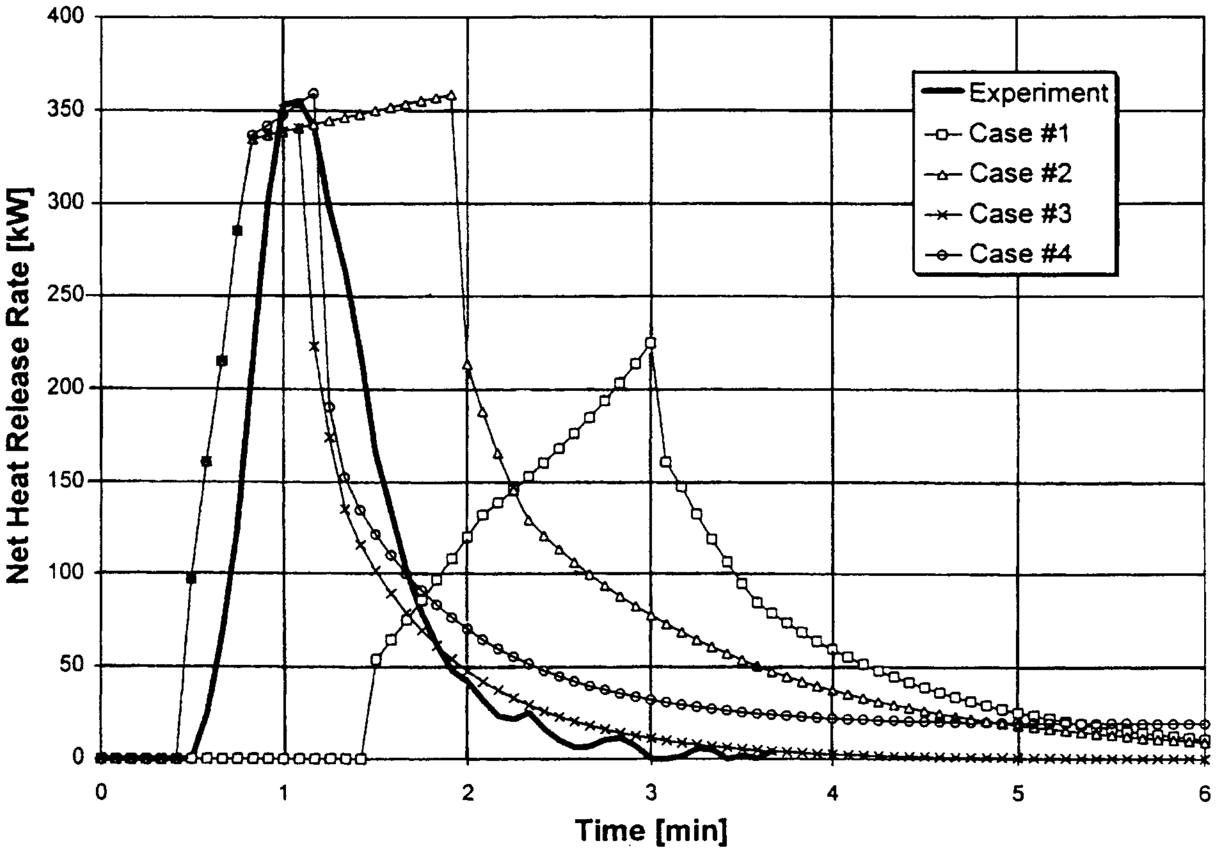

Figure 4. PVC Foam Net Heat Release Rate — Ignition Source Strength 64 kW.

the "heavy" lines in Figures 1 and 2. The predicted net HRR curves for the sub-critical strength levels are not significantly changed by the minimal lateral spread that occurs. For the super-critical levels, The Model gives a marginally better prediction at 75 kW and a reasonably good prediction at 150 kW. The fact that two Φ values appear to represent the experimental data indicates the Φ is not an independent material property.[33]

The PVC foam HRR curve predictions of the current version of The Model[2] indicate that CISS should be able to be predicted with a fire spread model of similar complexity. However, it will be necessary for a "new" model to better predict opposed flow flame spread. An alternative formulation for opposed flow spread based on explicitly accounting for the forward heat flux should be considered.[33] Additionally, more directly applicable heat flux data for concurrent flow flame spread will be important to validating any engineering level spread model. The fire protection engineer would like to have the appropriate heat flux data included in the validated model as "defaults" or options to be used at his/her discretion. This will provide consistency in the analyses between different design fire scenarios involving various configurations and CIFMs.

The initial conditions for fire spread, based on the ignition source heat flux map for a given design fire configuration will always be important for accurately accounting for the insult to the CIFM in the given scenario. As demonstrated by the four cases considered, determination of the "correct" material "properties" from bench-scale tests will be crucial for accurate fire spread model predictions. The ignition characteristics of the PVC foam are dependent on which method is used to reduce the igni-

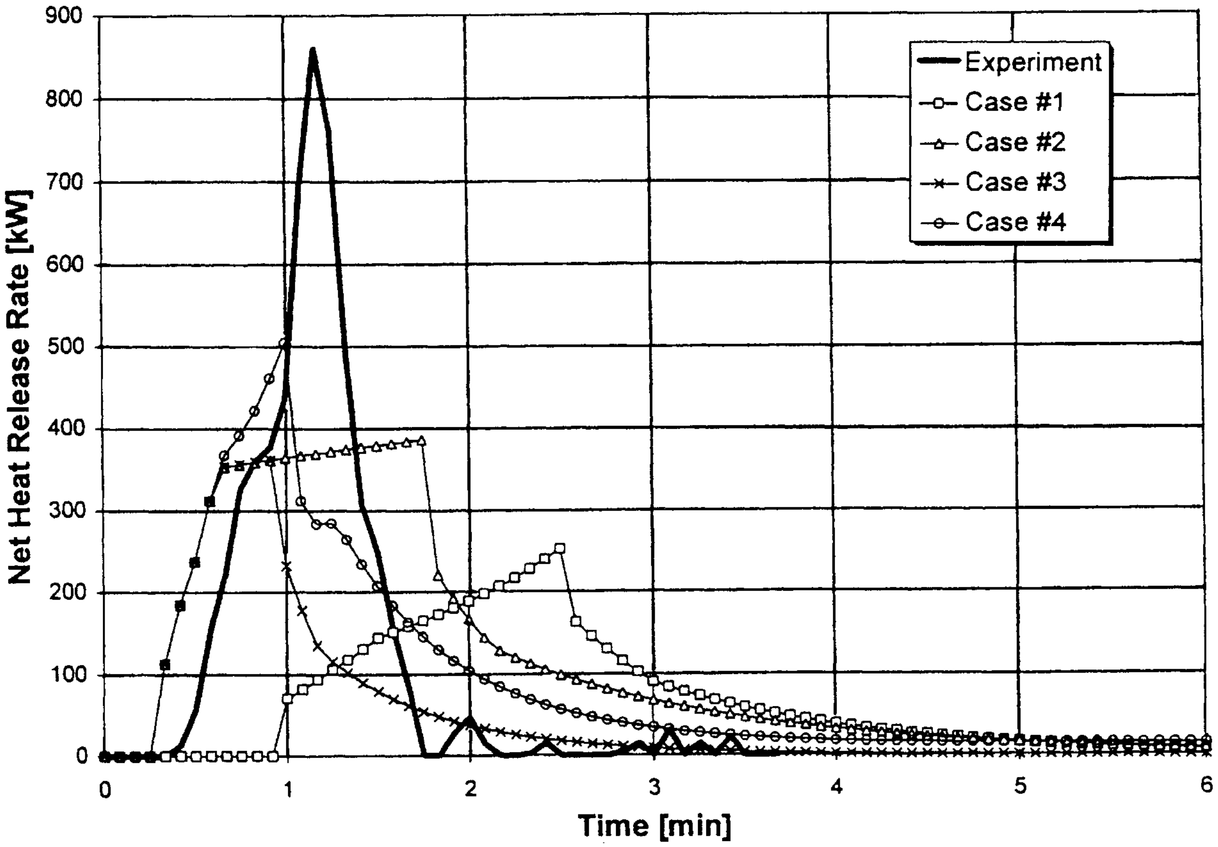

Figure 5. PVC Foam Net Heat Release Rate — Ignition Source Strength 75 kW.

tion data. For the PVC foam, the bench-scale tests and the full-scale experiments give some apparently contradictory results for Q″. This less than clear picture of what are the "correct" material "properties" to be used with The Model is of concern in the design process as accurate predictions of CIFM HRR behavior are not possible without knowing the "correct" material "properties." Uncertainty in how to determine the "correct" material "properties" of CIFMs will be compounded over the range of different type of CIFMs that the fire safety engineer may consider as candidate materials for any given design fire scenario. This uncertainty limits the flexibility of the fire protection engineer in choosing a candidate CIFM that will meet non-fire criteria as well as exhibit sub-critical behavior for a given design scenario.

CONCLUSION

The concept of Critical Ignition Source Strength[1] (CISS) has been introduced as a candidate criterion for use in performance fire codes to regulate combustible interior finish materials and contents items as a linked pair. Design fire scenarios involving this pair can readily be analyzed for performance with this criterion because the critical condition of flashover is clearly identified. For the fire protection engineer to be able to use CISS as a practical design criterion, the phenomenon must be modeled. The engineering level flame spread model of Quintiere[2] has been evaluated against full-scale experiments involving a PVC foam wall lining that has a CISS of 64kW to 75kW.[1] The predictions of the HRR behavior of the PVC foam indicate that an engineering level model of similar complexity should be able to predict CISS. A "new" model will have to be able to

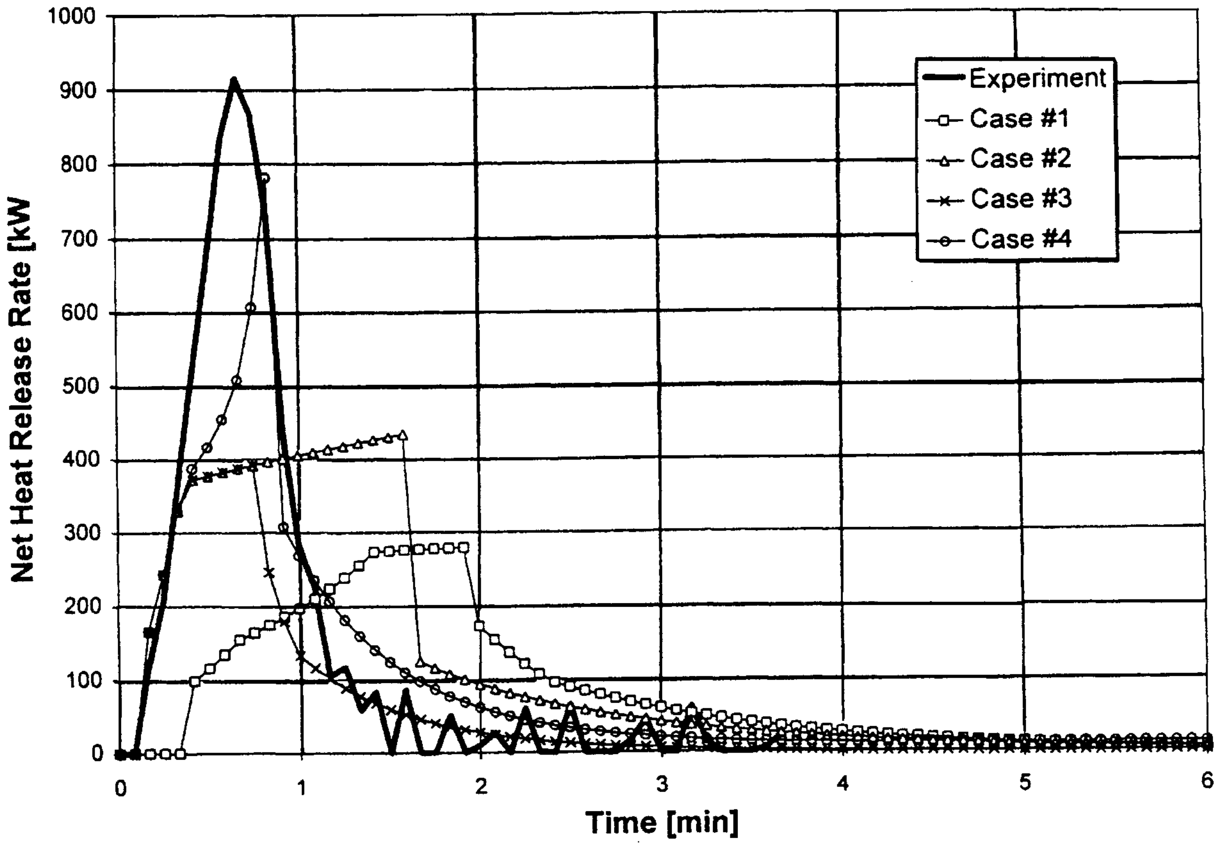

Figure 6. PVC Foam Net Heat Release Rate — Ignition Source Strength 150 kW.

better predict opposed flow flame spread to be able to clearly identify the CISS for a given finish material. The current lack of directly applicable heat flux data for concurrent flow flame spread is an important limitation to validating engineering level flame spread models and providing necessary consistency to the design process. Sufficiently detailed ignition source heat flux maps for various common configurations are still required to accurately define the insult to finish materials for a given design fire scenario. The lack of a clear procedure to determine the "correct" material "properties" from bench-scale tests[13,14] is a concern as accurate model predictions are not possible without the "correct" material "properties." Uncertainty in how to determine the "correct properties" limits the flexibility of the fire protection engineer in choosing a candidate CIFM that will exhibit subcritical behavior for a given design fire scenario.

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NOMENCLATURE

ΔH_c = heat of combustion [MJ/kg]

$k\rho c$ = thermal inertia [(kW/m²K)²s]

L = effective heat of gasification [MJ/kg]

$\dot{q}''_f$ = net flame heat flux in spread (forward heating flux) [kW/m²]

$\dot{q}''_{f,net}$ = pyrolysis region net heat flux [kW/m²]

$\dot{q}''_{f,p}$ = incident flame heat flux over the pyrolysis region [kW/m²]

$\dot{q}''_{ig}$ = ignition source incident heat flux to the wall lining ignition region [kW/m²]

$\dot{Q}_{ig}$ = ignition source heat release rate [kW]

$\dot{Q}'_{ig}$ = ignition source heat release rate per unit width [kW/m]

Q'' = total energy per unit area [MJ/m²]

T_{ig} = ignition temperature [°C, K]

$T_{s,min}$ = minimum temperature for lateral flame spread [C]

$x_{p,o}$ = half-width of the wall lining ignition region [m]

$y_{f,ig}$ = ignition source flame height [m]

$y_{p,o}$ = height of the wall lining ignition region [m]

Φ = lateral flame spread parameter [kW²/m³]

σ = Stefan-Boltzmann constant [kW/m²K⁴]

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