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ASSESSMENT OF MATERIAL FLAMMABILITY WITH THE FSG PROPAGATION MODEL AND LABORATORY TEST METHODS

by

P.K. Wu, L. Orloff and A. Tewarson
Factory Mutual Research Corporation
Norwood, Massachusetts, USA

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Assessment of Material Flammability with the FSG Propagation Model and Laboratory Test Methods

ABSTRACT

Full-scale tests to determine the flammability of new types of materials for various applications are expensive and time consuming. We have developed a technique, based on the combination of a small-scale flammability apparatus and a fire spread model, that has the potential to determine material flammability more efficiently. This technique involves the use of a numerical simulation of upward fire spread, the FSG model, and the FMRC Flammability Apparatus. The FSG model was constructed to be able to accept property inputs in terms of measurements from Flammability Apparatus experiments and was validated by a full-scale PMMA upward fire spread test. The measurements from small-scale Flammability Apparatus (e.g., time to ignition, heat of combustion and material response to heat flux in an inert environment) provide an effective first generation pyrolysis correlation to predict pyrolysis rates in fires. The combination of the model and the measurements eliminates the need to know the detailed components and configuration of the material. Hence, this technique is suitable for fire hazard assessment of complex fire retardant materials with unknown properties. The technique has been applied to various polymers and composite materials and the results are consistent with earlier evaluations performed using correlation techniques (e.g., by evaluating the Fire Propagation Index, or, FPI, from Flammability Apparatus measurements). The present method has the potential to provide a description of fire propagation for a wide range of configurations, as opposed to an index that correlates with only certain specific full-scale scenarios.

INTRODUCTION

The FMRC 50/500 kW Flammability Apparatus has been developed for many years (Ref.1) and effectively used for various applications (i.e., the influence of oxygen concentration on fire propagation, Ref. 2; the flame propagation for polymers, Ref. 3; and flame spread over Polymethylmethacrylate (PMMA) Ref. 4.). An upward fire spread simulation code (The FSG Model) was being developed. The FSG model was constructed with the physical understandings from small-scale laboratory experiments. Full-scale tests are needed for model validation. In validating the FSG model as well as providing badly needed full-scale heat flux data, an upward fire spread experiment was carried-out under the Fire Products Collector at the FMRC Test Center, West Glocester, Rhode Island with a 0.025 m thick PMMA wall, 0.58 m x 5 m high. The results from the full-scale test have been incorporated into the FSG model which provide excellent agreements with data.

The FSG Model assumes that the material is homogeneous and requires various chemical properties (i.e., density, thermal conductivity, heat of gasification, ...) of the material. However, materials of interest are usually composite with complex geometries and many components. A technique has been devised to test an unknown composite and provide some meaningful flammability assessment of the sample. The FMRC Flammability Apparatus is first used to carry-out the time-to-ignition and the mass loss measurements and the results then provide the needed inputs for the calculations with the FSG Mode. The FSG Model/FMRC Flammability Apparatus package was applied to various polymers and composites, and the results are not only consistent with the earlier Fire Propagation Index (FPI) evaluation but also providing a more comprehensive fire spread description than the FPI index alone.

In this paper, the FMRC 50/500 kW Flammability Apparatus is first reviewed for its main features. The essential characteristics of the FSG Model are then discussed with its' validation against a 5 m PMMA wall Fire Test. The technique is then applied to the flammability assessment of three complex composites (i.e., the E-701 Baseline Composite, S-2 Glass/Epoxy, and Graphite / Cyanate). The results clearly show the usefulness of the technique.

THE FMRC 50 kW FLAMMABILITY APPARATUS

The FMRC Flammability Apparatus (50 kW-scale) is shown in Fig. 1 and the 500 kW-scale Apparatus has similar features. Both Apparatus have a lower section and an upper section. The lower section is used for the measurements of time to ignition, mass loss rate during pyrolysis and combustion and other quantities (Ref.4). The upper section is used for the measurements of total mass and volumetric flow rates of chemical compounds - air mixture, temperature, concentrations of CO, CO_2, O_2 total gaseous hydrocarbons and others. From the species concentrations and volume flow rate, one calculates the chemical heat release rate and hence the heat of combustion. The Apparatus can provide the needed thermal properties and the mass loss (i.e., pyrolysis rate) history for the FSG model to carry-out the flammability assessments of a composite material.

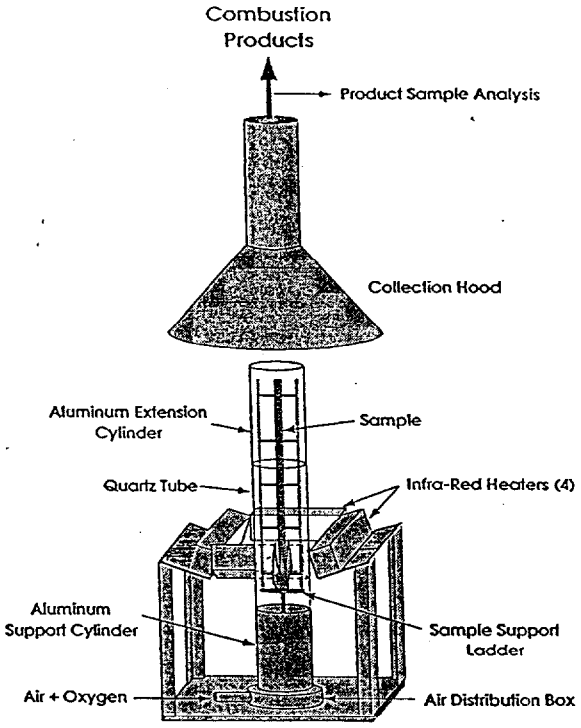

Figure 1. The FMRC 50 kW Flammability Apparatus

THE VALIDATION OF THE FSG MODEL

The FSG Model is clearly described in Ref. 5 and the details will not be repeated here. The model was constructed with the physical understandings of small-scale fires. When the model is extrapolated to full-scale fires, there are uncertainties in three areas of the model, i.e., the flame height correlation, the radiant fraction and the radiant (or total) heat flux distributions. The flame height Z_f was taken to be the 2/3 power of chemical heat release rate $\dot{Q}''_{ch}$ ($Z_f \sim \dot{Q}''^{2/3}_{ch}$). The radiant fraction was assumed to be a constant (Xr ~ 0.3) and the radiant heat flux distributions were taken to be triangular (Ref. 5).

A FULL-SCALE FIRE TEST

To validate the model with a full-scale test, an upward fire spread experiment was carried out under the Fire Products Collector at the FMRC Test Center, West Glocester, Rhode Island with a 0.025 m thick PMMA wall, 0.58 m wide x 5 m high. As shown in Fig.2, the PMMA wall was extended another 0.3 m on each side by Marinite panels. At the outer edge of the Marinite

panels, a perpendicular 0.6 m flow barrier (24 gauge steel) is used to minimize the effects of room drafts. On top of the wall, a 3 m extension provided a background for measuring the flame heights. Among many data acquisition instruments, seven total heat flux gauges and thermocouples were placed at various locations on the PMMA wall.

The measured total heat flux histories at various locations on the PMMA wall provide an important insight into the heat flux distributions in a upward propagating flame. As shown in Fig.3, the total heat flux histories at six locations were given. One gauge was destroyed in the test. Now, one can obtain the total heat flux distributions by cross plotting Figure 3. The results are given in Fig.4. The total heat flux is plotted as a function of vertical distance. The symbols are the data points and the lines are put in to aid visual interpretation of the trend. The pyrolysis height reached the top of the PMMA wall at about 1200 seconds and the steady state distribution from Orloff's study (Ref.6) was presented for comparison. When the measured total heat flux was plotted as a function of normalized vertical distance, Z/Z_f, the profiles are similar for Z/Z_f greater than about 0.8.

The heat flux distributions are clearly going through three phases. Initially, the flame starts with a triangle-like profile. As the flame races up the PMMA wall, the profiles have a top-hat distribution with peak values between about 30-40 kW/m2. Finally, after the pyrolysis zone reached the top of the PMMA wall, the profile evolves toward the steady state shape. The flame height result provides a flame height correlation, $Z_f = 0.048*Q'^{2/3}_{ch}$. Summing up the total energy gives a radiant fraction of about 0.26. After incorporating the new understandings into the FSG model, we repeated the calculations. The theory / data comparison was reasonable. The pyrolysis height history is given in Fig.5, while the chemical heat release rate history is plotted in Fig.6.

AN EXERCISE WITH THE FSG MODEL

After the validation, an upward fire spread calculation was carried out with the FSG model for a 5 meters PMMA wall. The mass loss and the net heat flux were traced at four locations, i.e., at heights of 1, 2, 3 and 4 meter. The results were plotted as a function of time modified by $\dot{Q}''^{2}_{net}$, Fig. 7 and 8. The mass loss and the net heat flux increase with height. However, when we differentiated the mass loss and normalized with the corresponding net heat flux, the results at four heights collapsed into a universal curve, Fig.9. This suggested that if we measured the distribution, it can be used everywhere at the surface.

APPLICATION OF THE FMRC APPARATUS / FSG MODEL TECHNIQUE

The technique of combining the small-scale test and the FSG model to carry out flammability assessments for complex materials have been applied to polymers and composites. The small-scale flammability measurements (i.e., time to ignition, heat of combustion and pyrolysis measurements in an inert environment) provide an effective pyrolysis correlation to predict mass loss rates in fires (i.e., the universal curve in Fig. 9). Sample results from the application of the technique to three widely different composites can demonstrate its usefulness. The composites are given in Table 1.

TABLE 1

	E-701 Baseline	S-2 Glass/Epoxy	Graphite/Cyanate
Critical Heat Flux (kW/m2)	10	15	20
TRP (kW-s1/2/m2)	382	400	1000
FPI	13	9	4

The pyrolysis measurements for these three composites are shown in Fig.10. The external heat flux for these measurements was 50 kW/m2. The unified mass loss rate curve does not depend on the external heat flux used in the pyrolysis measurement. As shown in Fig.10, the mass loss rate is highest for S-2 Glass/Epoxy. The FSG model used the pyrolysis rate to carry out an upward flame spread calculation for two parallel walls. The flame radiation flux to the surface and the re-radiation loss from the hot surface depend on the aspect ratio of D/W, where D is the separation distance and W is the width of the wall. When the two walls are far apart, the view factor for the radiation transport is zero. When the walls are close, the view factor is essentially one. When D and W are of the same order, the view factor is approximately 1/3. Calculations were carried out for all three composites with three view factors, i.e., 0, 1/3 and 1. The results of flame height and heat release rate histories are shown in Fig.11 and 12. The flame was ignited at about 100 seconds. For view factors of 0 and 1/3, the flame moves slow with heat release rate less than about 100 kW. However, the flame rapidly accelerates up the wall for view factor of 1. This implies that E-701 composite can not be used in confined space structure such as in vehicles. For comparison of the three composites, we choose the view factor of 1/3. As shown in Fig.13 and 14, S-2 Glass/Epoxy and E-701 composites are ignited at about 100 seconds while Graphite/Cyanate delays ignition to 600 seconds. Clearly E-701 composite is the worst one.

SUMMARY

The FMRC FSG Model has been validated for PMMA panels with height of up to 5 m. Full-scale data for other materials are needed to broaden our capability to carry-out confidently flammability assessment of various types of complex materials. The viability of combining the FSG Model and the FMRC Flammability Apparatus to test the fire hazard of a complex material has been shown by applying the technique to the PE/PVC cable tray, conveyer belts and composites. The results are encouraging. The FSG Model/FMRC Flammability Apparatus package offers the advantages of: (1) extrapolating the bench-scale flammability measurements to full-scale events with complex configuration (significantly reducing the testing cost) and (2) economically testing the effectiveness of fire retardants as passive fire protection agents to reduce thermal and nonthermal damages.

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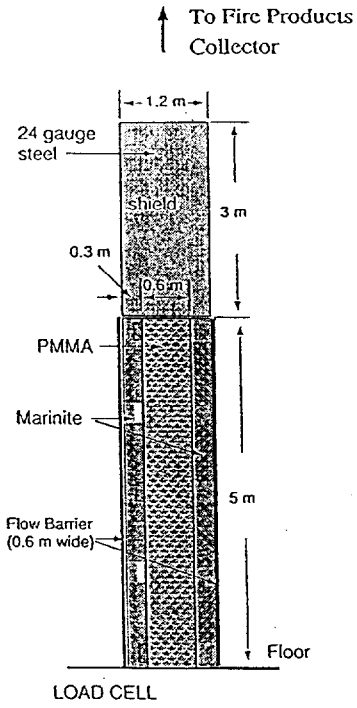

Figure 2. Full-Scale PMMA Wall Fire Test

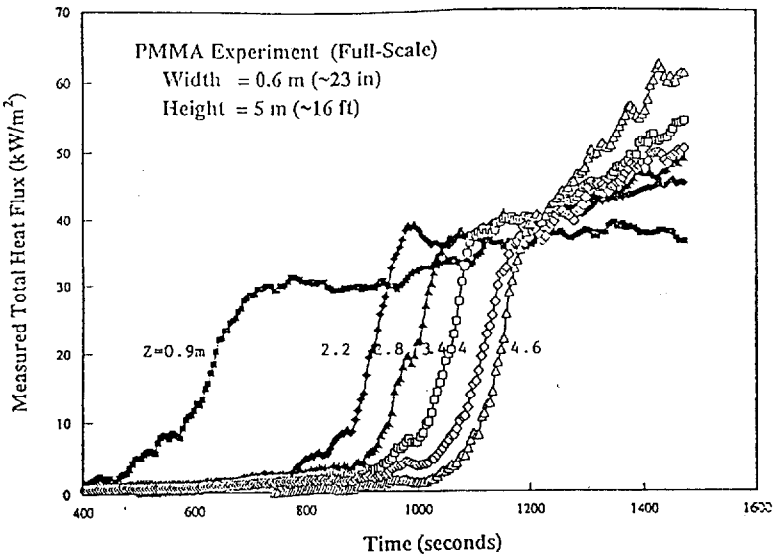

Figure 3. Total Heat Flux Histories At Various Heights

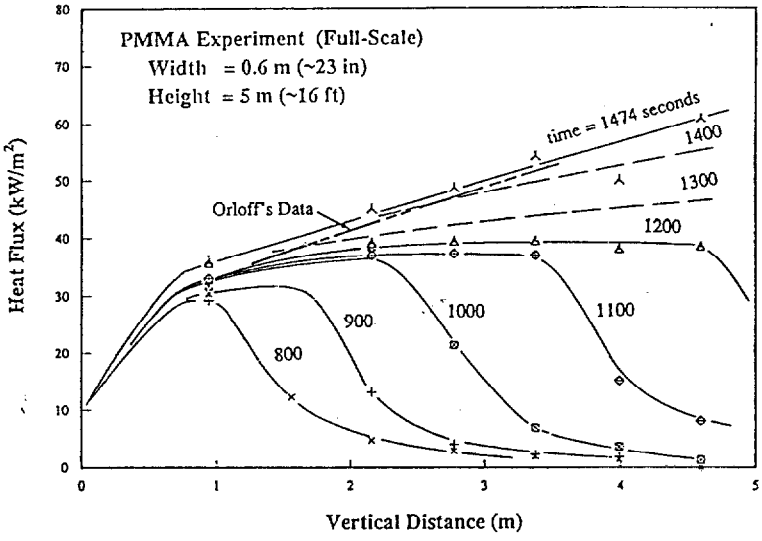

Figure 4. Heat Flux Distributions At Various Times

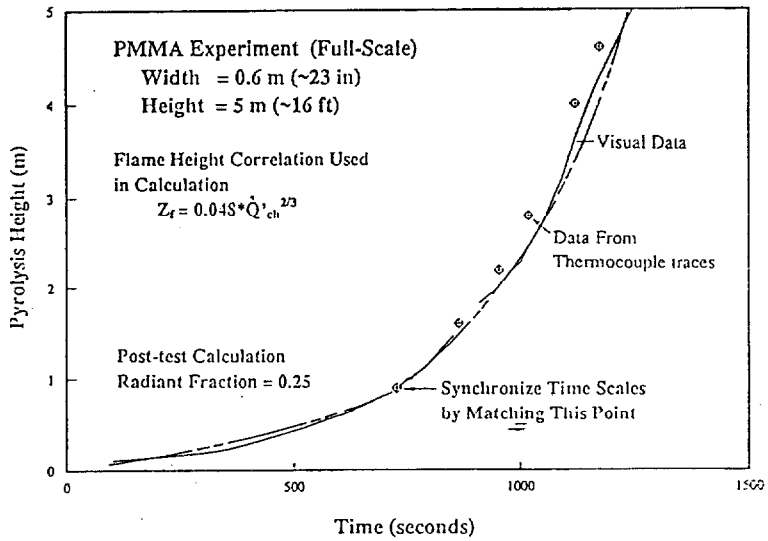

Figure 5. Model / Data Comparison On Pyrolysis Height History

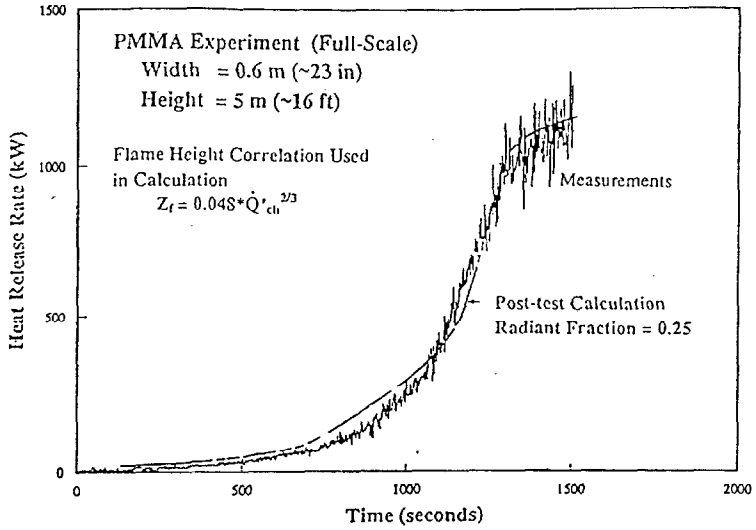

Figure 6. Model / Data Comparison On Heat Release Rate History

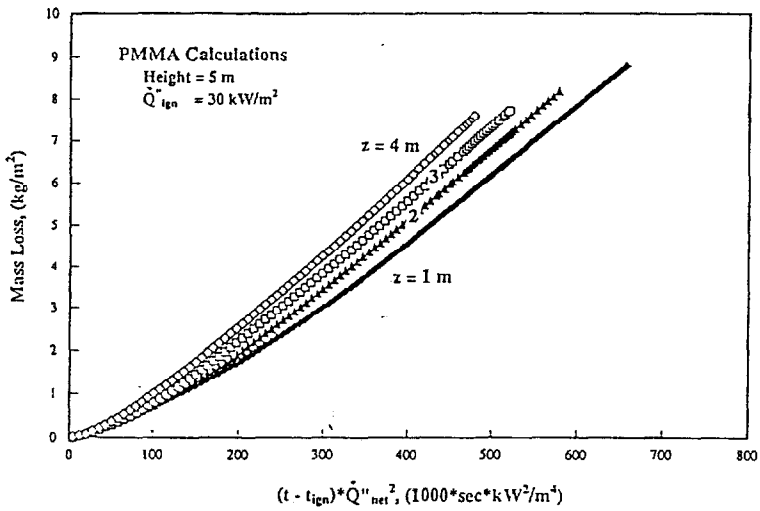

Figure 7. Mass Loss Rate Histories At Various Heights

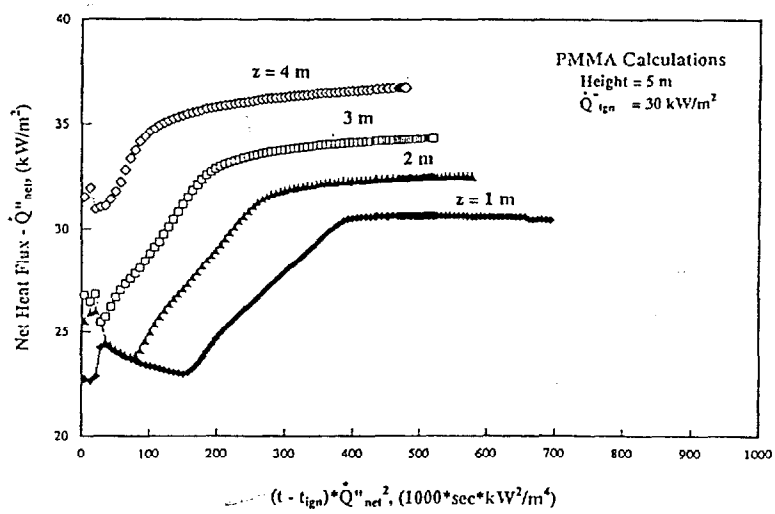

Figure 8. Net Heat Flux Histories At Various Heights

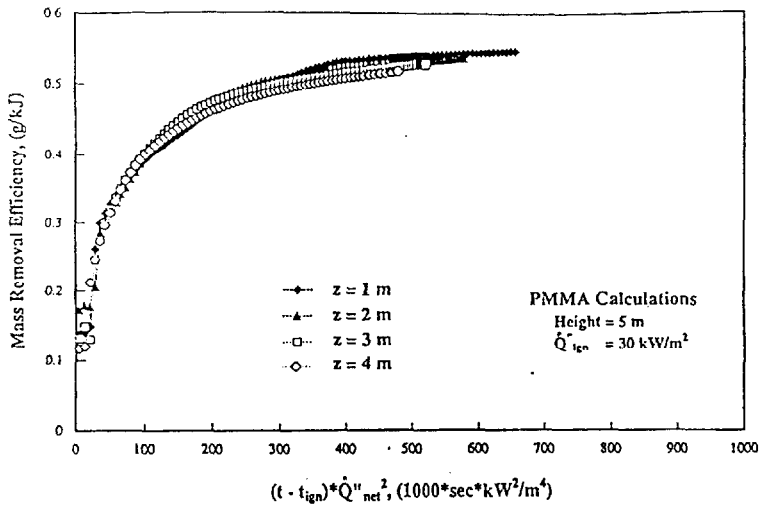

Figure 9. Mass Removal Efficiency Histories At Various Heights

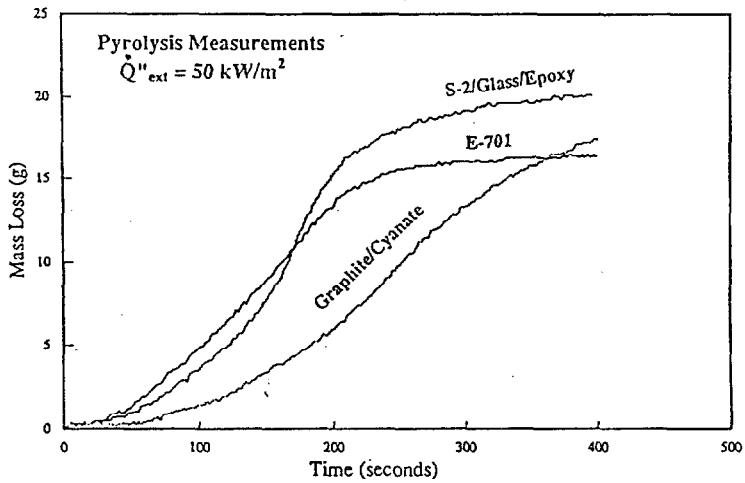

Figure 10. Pyrolysis Measurements For Three Composites

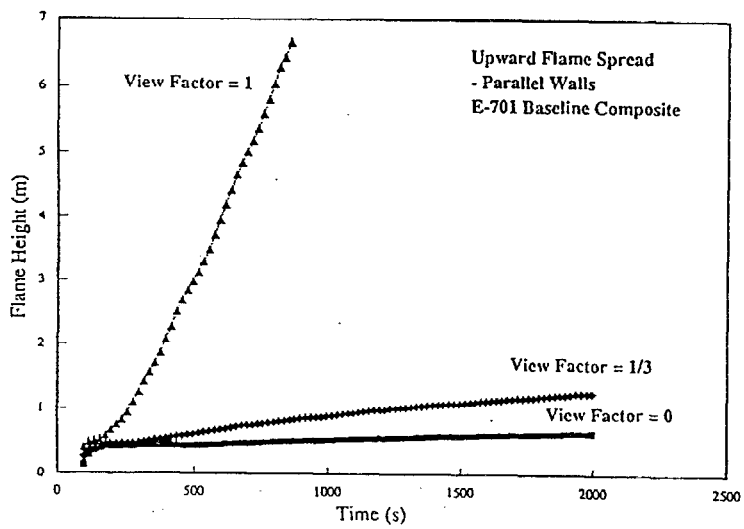

Figure 11. Flame Height Histories For Parallel Wall Fire

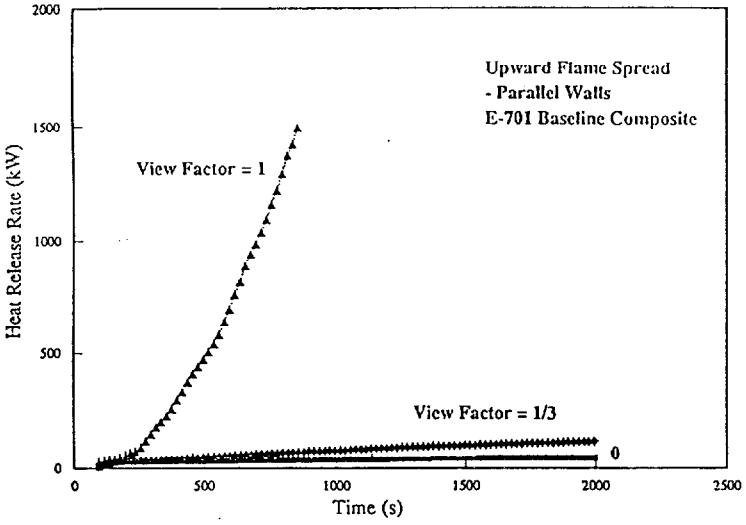

Figure 12. Heat Release Rate Histories For Parallel Wall Fire

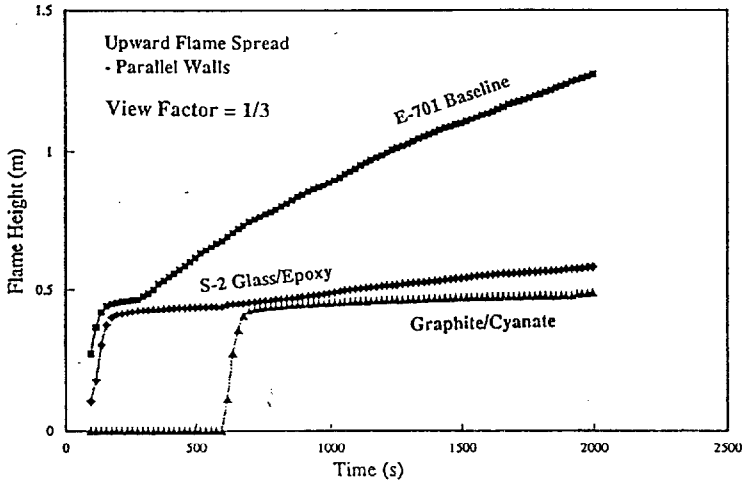

Figure 13. Comparison For Three Composites - Flame Height

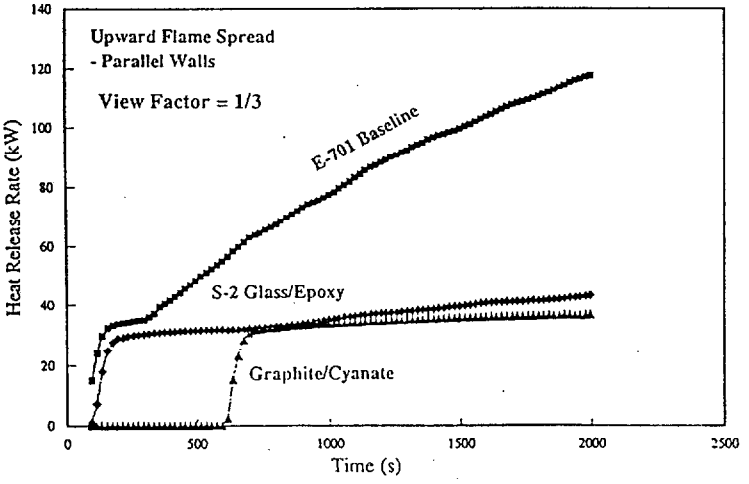

Figure 14. Comparison For Three Composites - Heat Release Rate

Discussion

Henri Mitler: The chronicled radiation fraction from PMMA was about 30%. Your colleagues have found 25% fitted better. I wonder if that could be explained by just noting that there is a substantial amount of radiation blockage?

Ronald Alpert: The answer is yes. Orloff and Markstein determined that there is roughly a 30% blockage factor of flame radiation back to the fuel surface. And I'm sure that has an effect.

William Grosshandler: I'm not an expert in this area, but I've observed for over a number of years, that so much is put on the results from either the FM flammability apparatus or the Cone Calorimeter results. Is there anything to be gained by doing a thorough analysis of those apparatus? That is, we have very sophisticated modeling methods, experimental measurement techniques. Is it useful to go back now and try to model what happens in these very fundamental laboratory apparatus to extract more information about pyrolysis and surface combustion?

Ronald Alpert: There are several organizations that are thinking about not necessary looking in more detail at these flammability apparatus, but in trying to determine more fundamental flammability properties going back to thermogravimetric analysis and differential scanning calorimeter. I know in particular, the FAA Technical Center is following this track.

Takashi Kashiwagi: Actually, when you look at a real sample, a lot of complicated things are happening, and these might be very important. The important questions is, can you include these phenomena? So far, the models are one-dimensional. Surfaces are flat, there is no swelling or bubbling, no cracking. These things actually happen. To model these requires a very basic scientific understanding. So my opinion is that, for now, if you want to model actual materials, we need to stay global. Meanwhile, we should look at the phenomena as deeply as we can.

Ronald Alpert: I agree. I prefer the global approach and that's what we are currently working with now with the University of Lund. We're trying to develop a global pyrolysis model that can be applied to real materials and develop parameters, equivalent flammability parameters, for real materials that can be used in these models.

Pravinray Gandhi: As you already mentioned, the problem arises when real materials are installed on real substrates. Many times, the burning behavior depends upon the distortion of the substrate. It may accelerate the burning because now the real surface gets exposed to fire. Would the model that FM is working on tackle the structure of fire problem together?

Ronald Alpert: Yes, I believe the global pyrolysis approach will, to some extent, take into account whatever the total material is as long as the total thickness is the sample is less than about 10 cm. Whatever happens will come out in the pyrolysis model. It will be reflected in the equivalent flammability parameter. I just want to emphasize the type of the variety of real materials that we see every day or week or month in our practice is truly amazing. There are different types of materials sent in from all over the world, and we have to deal with them, and it's a real challenge. You learn to appreciate the people that can deal with those materials when you see what they have to contend with.