

## Chapter 28

# Upward Flame Spread on Composite Materials

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Three existing models of upward flame spread were tested against intermediate-scale experiments on a vinyl-ester/glass composite. Characterization of rate of heat release per unit area, needed as input to the models, was obtained at external radiant fluxes below the minimum for ignition by adaptation of a method due to Kulkarni. There are several limitations on the accuracy of the material characterization when applied to composites. Each of the flame spread models has definite limitations as well. Nevertheless, all three models produced predictions of spread behavior in sufficiently quantitative agreement with the experiments that they should prove useful for engineering analyses of flame spread potential.

The U. S. Navy is investigating the use of composite materials for both ship and submarine compartment construction. Load-bearing compartment walls would consist of flat (or possibly more complex) panels of such material. The composite construction materials of interest consist of two components: long fibers of high tensile strength material which are the primary load bearing elements and a continuous organic resin which surrounds the fibers to protect them, hold them in place and transfer stresses between fibers (*1*). Typically the fibers are in several layers or plies, each of which may be woven into some fixed pattern and oriented to maximize resistance to load stresses in specific directions. Such composites offer a high strength-to-weight ratio and other advantages, such as corrosion resistance, which make them attractive for a wide variety of structural uses.

In any structural use of composites, one must be aware of two potential limitations brought on by the organic nature of the binder resin. Both are potential consequences of a fire in proximity to the composite. First, the key structural roles of the resin--to hold the fibers in place and transfer stresses among them--may be compromised as the temperature of the composite

approaches the glass transition temperature of the resin. The result is that the composite loses its strength, especially toward compressive loads. This is particularly a problem for certain relatively inexpensive thermoplastic resins (2). Second, the resins are typically flammable, to varying degrees, and thus may become involved in and contribute to the spread of a fire.

It is the second problem area which is addressed here. In particular, we are seeking a consistent way in which to characterize composite materials in small-scale tests so as to obtain the necessary data to predict their full-scale flammability behavior. The focus here is on upward spread of flames on the surface of a composite because it typically represents the fastest mode of fire growth. Three existing models of this spread process are compared with data obtained on a non-flame retarded vinyl ester/glass roving composite in an intermediate scale facility. As will be seen, certain modifications were necessary in the normal procedure for small-scale characterization of a solid fuel by means of heat release rate calorimetry.

## FLAME SPREAD MODELS

**Thermophysical Processes.** Experience with other materials indicates that surface flame spread can be treated with reasonable accuracy as the movement of an ignition front, with that front being represented by a fixed isotherm, the ignition temperature. As this front passes a given point the fuel pyrolysis rate goes from negligible to significant, i.e., the actual Arrhenius-like temperature dependence of the gasification process is approximated by a step function. The speed of this pyrolysis front movement or flame spread process can then be predicted by following the chemically-inert heating, to the ignition temperature, of successive fuel elements ahead of the front. In the case of upward flame spread, that heat-up process can be a result of two heat fluxes. The first is the convective/radiative flux from the flame which buoyancy causes to rise upward into contact with unignited portions of the fuel. The second, which is not always present, is the radiative flux from a nearby burning object or from hot combustion gases trapped by a compartment ceiling.

There are three key empirical elements to any model of upward flame spread based on the above idealization of the chemical behavior of the fuel: 1) the magnitude and spatial variation of the heat flux from the flame to the fuel surface as a function of distance above the pyrolysis front; this dictates how fast the inert fuel heats up; 2) the height of the flame as a function of the total heat release rate (kilowatts per unit width) below the flame front; this helps dictate the time over which the upward moving flame heats the fuel surface and thus it interacts with (1) to affect how rapidly the fuel heats-up to ignition; 3) the dependence of the heat release process from an element of ignited fuel (below the upward moving flame front) on both external flux and time; this also interacts with (1) and (2) to further complicate the time dependence of the heat flux which the flame provides to fuel surface above the pyrolysis front. The models examined here treat each of these differently.

It should be noted that when an external radiative flux is present (as it is in the experiments described here), that flux is typically below the minimum flux

needed to cause ignition of the material. Ignition then occurs during the spread process as the flames provide additional heat. This poses a problem for item (3) above, the rate of heat release rate from unit area of burning fuel, since the data needed are for external radiant fluxes below that needed to ignite the material. The normal technique for measuring rate of heat release from a material (in the Cone Calorimeter, for example) employs radiative fluxes above that needed to ignite the material. The real requirement here is that the heat release data input to the model reproduce (or be able to reproduce) that which is evolved in the full-scale flame spread situation. This essentially means that the net heat flux into the sample surface during its burning be the same in the small-scale and large-scale situations. This is discussed further below.

**Cleary and Quintiere Model.** The simplest model of upward flame spread to be considered here, that of Cleary and Quintiere (3), addresses the three empirical input requirements listed above as follows. It assumes the flame heat flux above the pyrolysis front to be spatially constant up to the flame tips (and zero above this), the flame height to be a linear function of total heat release rate below the front and the fuel heat release rate per unit area to be constant in time until complete consumption occurs at any given height on the fuel surface. The constant heat release rate is an average of that obtained in Cone Calorimetry; however, the proper value for the incident radiant flux to be used for this small-scale measurement is not well-defined for some situations. These simplifying assumptions allow an analytical solution for pyrolysis front position versus time.

**Mitler's Model.** The model of Mitler (4) is numerical in nature. It uses separate sub-models, grounded in data from gas burner experiments, to calculate the radiative and convective fluxes from the flame versus height. The flame height vs. heat release rate correlation is also based on gas burner results. A transformation procedure based on a balance of the various heat fluxes crossing the fuel surface during burning is used to take Cone Calorimeter heat release data obtained at an arbitrary external heat flux and convert it to any external flux for which the flame spread process is being predicted. In principle, these data could then be measured at fluxes above or below the minimum heat flux needed to ignite the material.

**Model of Brehob and Kulkarni.** The model of Brehob (4) and Kulkarni, *et al* (6), also numerical, uses an experimentally-fitted exponential decay law for flame heat flux as a function of height above the pyrolysis front and an experimental flame height vs. heat release rate correlation, also based on gas burner behavior, but different from that used by Mitler. Finally, this model uses experimental rate of heat release data at the specific external flux of interest for flame spread prediction; no means for interpolating or extrapolating heat release data to other fluxes is provided. Kulkarni, *et al* (6) used mass loss rate data obtained for a small sample in the presence of a turbulent gas burner flame (plus an external radiant flux (5)) and the heat of combustion to infer the needed rate of heat release inputs.

**Application to Composites.** In all of these models the chemistry of the fuel is present only implicitly, in the heat release behavior and in the ignition temperature. Such models can handle fuel composition variations only through substitution of new experimental data on these properties. That is a limitation but also an advantage in dealing with real materials for which detailed chemical parameters would be nearly impossible to obtain.

Composite materials have two features not found in other materials for which the above models have been tested. First, they have a high content of inert material (the glass fibers in this study). If the degrading resin does not liquify and wick through this residual structure, the fiber mats will perform a function similar to a char in a burning material such as wood. That is, as the outer layers of resin gasify, deeper layers will be somewhat insulated from the flame heat flux by the glass left behind and thus gasify more slowly, weakening the flame. If wicking does occur, this self-protective feature is lessened. In any event, the small-scale measurements of rate of heat release should capture this effect in a manner equally pertinent to the full-scale test.

The second feature peculiar to composites is the tendency to delaminate during intense surface heating as a result of gas generation between plies. This has at least two consequences. First, it implies that the thermal properties (particularly thermal conductivity) of the delaminated layers are changed appreciably. Second, when performing measurements on small-scale samples, one notes a tendency for the evolved gases to come out the sample edges, especially late in the burning process. This edge burning issue was examined to a limited extent in a previous study (7). Suppressing edge burning leads to rather erratic heat release behavior that may not be relevant to full-scale flame spread testing; it was not suppressed in the present study. The consequences of delamination for model/experiment comparisons are believed to lie mainly in the thermal property effects but this issue may need further study.

## EXPERIMENTAL

**Flame Spread Experiments.** The intermediate-scale experiments were performed with the facility sketched in Figure 1. A flat, 0.95 cm thick (13 ply) composite panel (vinyl ester/E-glass, plain weave, woven roving), 0.38 m wide by 1.22 m tall, was uniformly irradiated ( $\pm 5\%$ ) on one surface by a pair of electrically-heated panels. The flux was varied from test to test by changing the panel temperature, typically in the 325-600 °C range. Irradiation was started at time zero by removal of a shutter; at the same time a methane-fueled line burner, spanning the sample width at its base, was ignited. This burner proceeded to ignite the composite across its base, initiating upward flame spread. The location of the pyrolysis front was noted by an observer at frequent intervals, to an accuracy of a few centimeters; it was made visible by the tendency of the fuel gases to emerge in small jets from the highest permeability locations in the woven glass roving.

Heat flux gages were inserted through the sample (sensing surface flush with the front face of the sample) at three heights (1/4, 1/2 and 3/4 of sample

height) to aid in assessing flame fluxes and appropriate conditions for small-scale assessment of heat release rate; the gages were operated at a temperature of 100 °C or above to eliminate water condensation on their sensing surface. Flame spread rate was measured, in separate experiments, as a function of both incident radiant flux and igniter heat release rate. The hood above the apparatus is designed to catch all of the fire plume. Oxygen and gas flow rate measurements in the hood exhaust stream thus allow calculation of the time-dependent total rate of heat release from the burning sample (8).

**Heat Release Experiments.** A Cone Calorimeter was used to measure heat release rate per unit area on vertical, 100 mm square samples of the composite. Heat release rate is inferred from the same variable measurements as in the intermediate-scale experiments. As noted above, the desired data are for external radiant fluxes below that needed for sample ignition; these are the flux levels used in the larger-scale experiments. Recall that in the larger-scale tests, the flame spreads as a consequence of the flame heat flux and the external radiant flux, typically set at a value well below that needed to directly ignite the sample.

The Cone sample was pre-heated, typically 600 s, with an external flux comparable to that used in the above experiments; this mimicked the pre-heating the sample sees in the large-scale experiments before the flame arrives. (A pre-heat time of 400 s gave distinctly more erratic heat release behavior.) At the end of this interval a methane line burner below the sample was ignited. The function of this burner is not to produce upward flame spread but rather to produce a turbulent flame over the sample face resulting in a total heat input (flame flux plus external radiant flux from the Cone heater) to the sample surface comparable to the total in the above intermediate-scale experiments; in this way, the net heat input to the sample surface (flame plus radiative input minus surface radiative loss) should be the same in both situations. The heat release rate of the sample plus burner combination was recorded and the constant burner contribution subtracted to obtain the desired input data for the models. The accuracy was nominally  $\pm 5\%$  but the repeatability, especially at lower fluxes, was as poor as  $\pm 25\%$  in portions of the heat release history.

This rate of heat release measurement technique is unconventional; it is an adaptation of the mass loss procedure developed by Kulkarni, *et al* (6) to get heat release data at external radiant fluxes below that necessary to ignite a material. In previous work where the gas flame was not used (a high external radiant flux was used to yield ignition then reduced to a low value) the burning of the sample was erratic and unsatisfactory (7).

## RESULTS AND DISCUSSION

**Flame Heat Fluxes.** Measurement of the flame heat fluxes for this composite proved to be somewhat problematical. As noted above, the flux gage was inserted from the rear of the sample through a hole just slightly larger than the 6 mm gage diameter itself. This hole proved to be an intermittent relief hole for fuel gas pressure build-up between plies of the composite. When this happened

strong jets of flame in front of the gage falsified the flux data obtained. It was necessary to exclude the flux data obtained during jetting; videotapes of the tests made it possible to do this after the fact. Figure 2 shows the results of the flux gage measurements as a function of incident radiant flux in the intermediate-scale experiments. Note that these are the total fluxes (flame plus external radiation) seen after the pyrolysis front has moved above the gage location. Also included in this figure are data obtained with an unretarded polyester composite with the same type of fiber plies; this composite allowed flame spread in the absence of an external flux. It is apparent that the noise level in these data is high, in spite of exclusion of data from the times of visible jet flames around the gages. Apparently this is because of the inherently fluctuating nature of the flames emerging, as mentioned above, as small jets from high permeability points in the glass weave pattern. Extrapolation of the heat fluxes to zero external radiant flux indicates that the turbulent flame alone supplies a flux in the range of 25-40 kW/m<sup>2</sup>; the polyester composite, which burns without an external flux, has a flame flux in this range, as well. Analogous flux measurements in the Cone Calorimeter indicate that the flame flux there, a result of the commingled gas burner and sample flames, is about 40 kW/m<sup>2</sup>. This is at the high end of the full-scale range, probably because the gas burner flame in the Cone apparatus is not fully turbulent. (In order to make this flame fully turbulent, it would be necessary to increase its height (and thus its heat release rate); this in turn would decrease the accuracy of the measurement of the heat release contribution from the sample itself.) This comparison of small-scale and full-scale fluxes does indicate that the Cone data are being obtained at approximately the same flame flux conditions as exist in our intermediate-scale experiments. Thus this manner of obtaining heat release data at fluxes below that needed to directly ignite a material (in this case, below 15 kW/m<sup>2</sup>) appears to be reasonably satisfactory.

**Cone Calorimeter Measurements.** Figure 3 shows Cone data obtained in this manner for the vinyl ester composite at three external radiant fluxes. The curves shown for the lowest and highest external fluxes are averages of two to three tests; the curve at the intermediate flux is the result of a single test and is clearly more noisy. The qualitative behavior as a function of time resembles that seen for char-forming, non-fiber-reinforced materials. That is, the rate of heat release shows an immediate decay from its initial value due to consumption of resin at and just below the heated surface coupled with the insulating effect of the non-volatile residue (here, the fibers). This suggests (but does not prove) that wicking of liquified resin degradation products to the front surface is minimal. It should be noted that the raw data for this peak were corrected upward over the first 100 seconds or so because video tapes of the test showed that ignition was not uniform over the sample surface; thus the heat release rate per unit area from the area actually burning was greater than the raw data showed. After this initial peak, one might expect the increasing insulating effect of the depleted glass plies would cause the heat release rate to continue to drop. However, the thermal

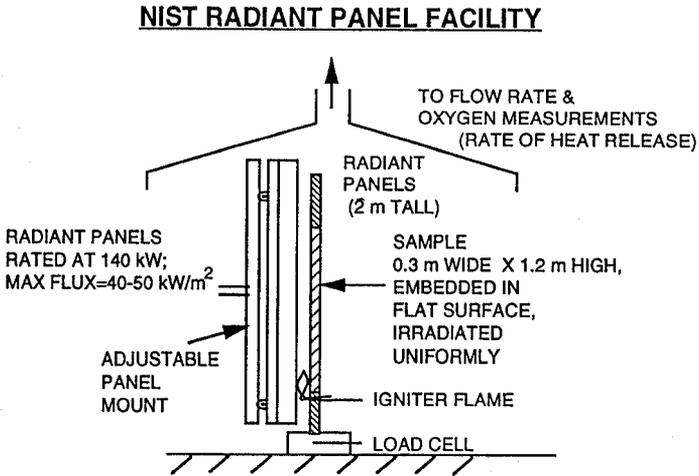


Figure 1. Radiant panel and heat release rate apparatus showing placement of sample in front of panels.

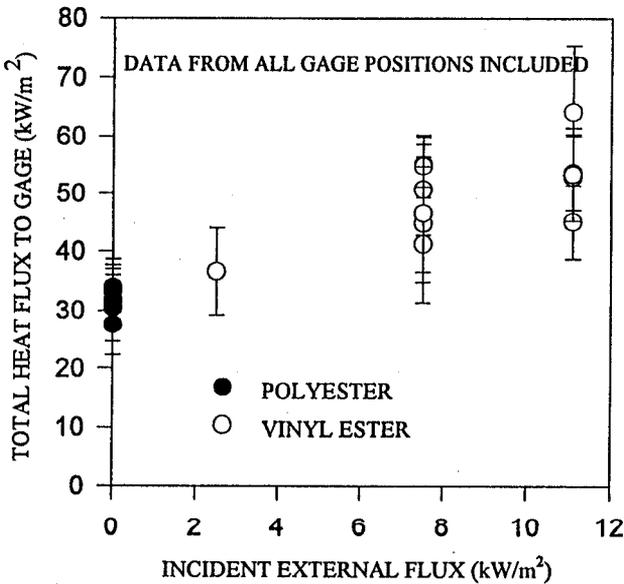


Figure 2. Total heat flux to gages embedded in sample surface.

wave in the sample soon reaches the insulated back surface and the sample becomes, in effect, increasingly pre-heated in depth. This causes the second, broad peak in the heat release curves. The effect of the external flux level is not very great in the range shown; data scatter nearly masks a rough upward trend of heat release rate with flux. This implies that one need not precisely match the net flux into the sample in small-scale and large-scale tests.

The source of the scatter in these tests appears to be largely the result of non-reproducibility in the ply-to-ply delamination during sample burning. Certainly this is evident during the pre-ignition heat-up and early burning process. Since these materials are the result of a hand lay-up process, there could also be local variations in the amount of resin present in a given ply layer. These types of small-scale variations tend to be averaged out in the behavior of the intermediate-scale samples cut from the same composite slabs.

These data were used in the models discussed above. Where the detailed heat release history was to be used, rather than a simple averaged value (as in the Cleary/Quintiere model), the data were fit with a polynomial or otherwise approximated by a smoothed curve to eliminate the noise seen in Figure 3.

**Comparisons of Intermediate-Scale Data with Model Predictions.** Figures 4, 5 and 6 show a comparison of typical upward flame spread data (circles) with the three spread models examined here. The data shown for each flux are the result of two replicate tests. The gas burner igniter was set at 6 kW for all of these tests; this provided a flame whose tips reached up to about 20-30 cm from the bottom edge of the sample. The upward spreading pyrolysis front was generally only roughly flat due to a distinct tendency for the buoyant flames to contract laterally as they moved upward on the sample face (in spite of vertical fins on the outer edges of the sample holder intended to inhibit lateral flow). Another contributing factor to non-two-dimensional behavior was occasional preferential ignition (by the spreading flames) of local regions along the front probably due to delamination bubbles which decreased the local thermal conductivity.

The rather ragged-looking plateau in the upward spread process was seen in both tests at an incident radiant flux of  $2.5 \text{ kW/m}^2$ ; doubling of the igniter gas flow rate shrank the duration of this plateau to less than 100 s. At an intermediate incident flux of  $7.5 \text{ kW/m}^2$ , two tests (with the 6 kW igniter) showed behavior that was essentially a somewhat slowed version of that seen at  $11.5 \text{ kW/m}^2$  (i.e., smoothly accelerating upward spread) but a third test again yielded a substantial plateau. These plateaus appear to be a result of delaminations which cause earlier than expected ignition on portions of the composite surface. When the resin burns out of the delaminated ply or plies the pyrolysis front stops and then gradually resumes a more normal upward pace for the given external flux.

The model predictions in Figures 4, 5 and 6 are shown as solid lines. The input data to the models, characterizing the composite, are the same for all cases. These data, particularly thermal properties, are problematical, however.

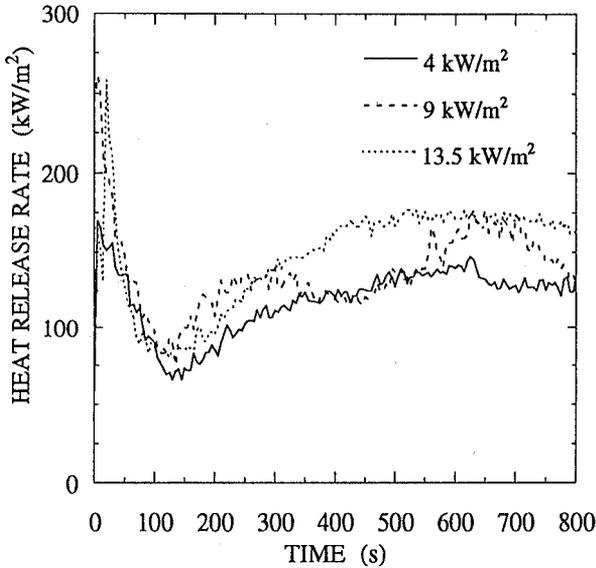


Figure 3. Rate of heat release per unit area of vinyl ester composite in Cone Calorimeter.

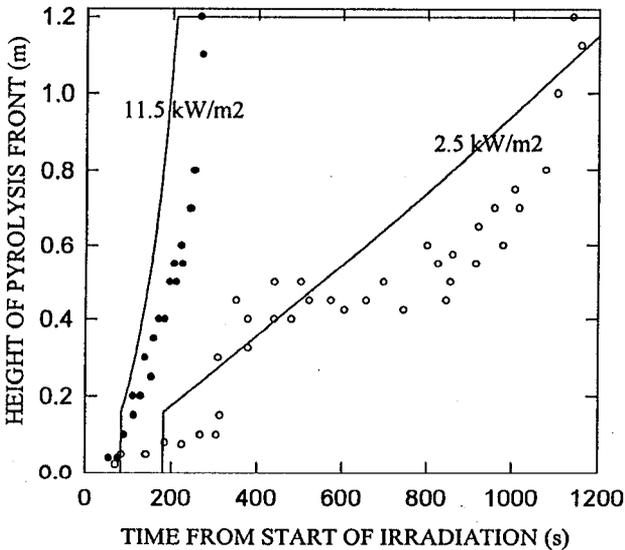


Figure 4. Measured pyrolysis front position as a function of time vs. prediction of Cleary/Quintiere model.

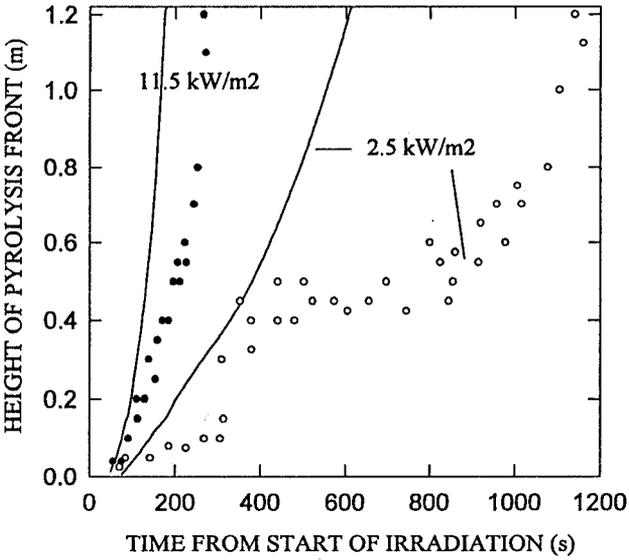


Figure 5. Measured pyrolysis front position as a function of time vs. prediction of Mitler's model.

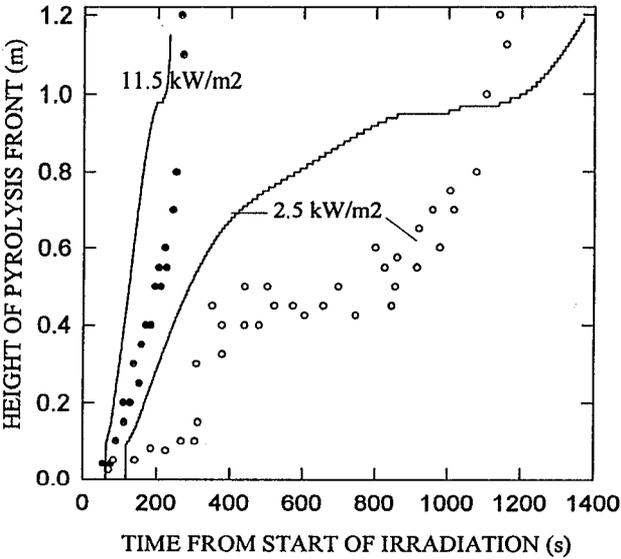


Figure 6. Measured pyrolysis front position as a function of time vs. prediction of Brehob and Kulkarni model.

The thermal conductivity was measured at about 100 °C for an undegraded composite sample and this is the value used here. One can readily argue that this value is approximate at best in this application. Ordinarily the conductivity is an increasing function of temperature but, as the resin begins to degrade and interply delamination occurs, the conductivity can be expected to drop. There are no quantitative data on these trends at present.

The effective, average heat capacity between room temperature and the ignition temperature also is not well-defined *a priori*; endothermic degradation reactions prior to ignition can increase it by an undetermined amount. Here this problem has been handled via an analysis of the ignitability behavior (ignition delay time vs. incident heat flux) of the composite as determined in the Cone Calorimeter. Ignition delay is dependent on the thermal inertia (product of conductivity, density and heat capacity). The effective value of thermal inertia is inferred by matching the experimental ignition data with a thermal model of the ignition process in the Cone Calorimeter. This model is based on constant thermal properties and a constant ignition temperature. It includes radiative and convective losses from the front surface and an adiabatic rear surface. The model is solved numerically to determine the time to reach the ignition temperature as a function of incident radiant flux; the results are compared to the experimental ignition data and the thermal inertia is adjusted to get a match. The effective thermal inertia obtained in this manner depends somewhat on the heat flux at which the match is made; this probably reflects the fact that the ignition temperature for a real material increases with heat flux. Here a value of 1.4 times the nominal room temperature value of thermal inertia is inferred from a match in the 20-25 kW/m<sup>2</sup> range. This multiplier is applied entirely to the input value of the heat capacity. However, since the spread process is one of successive ignitions, only the thermal inertia matters. The effective thermal inertia inferred here probably incorporates both heat capacity and thermal conductivity changes. The impact of delamination on a small sample in the Cone may not be as great as that on a full-scale sample (interply pressure is relieved more readily in small samples) so the thermal conductivity effects on the two scales may not be equal.

Figure 4 shows a comparison between the data and the model of Cleary and Quintiere (3). This model deals with sample heat-up in a simplified way and thus cannot correctly calculate the pre-heating of the sample as a function of height due to the external radiant flux. Instead we have calculated the pre-heat effect at mid-height using the numerical heat conduction model mentioned above applied for a time up to the experimental arrival time of flame at that height. This initial temperature is applied to the entire sample. The model also simplifies the ignition process induced by the gas flame igniter at the sample base. The flux is taken to be uniform over the igniter height and thus this full height ignites simultaneously yielding the vertical lines at the beginning of each model trace in Figure 4. This model uses a constant average of the rate of heat release data for the given external flux; the averaging time interval is that required for the pyrolysis front to reach mid-height. Here that time was found iteratively by

successive model solutions as follows. An initial guess for averaging time provided an average rate of heat release as the model input. The model was then solved and its predicted time for the flame to reach mid-height was used to obtain a corrected average heat release value. This cycle was repeated until it converged. In spite of these approximations (and others noted above), this model gives better quantitative agreement with the flamespread data than do the more mechanistically exact models discussed below. There is probably a fortuitous element to this.

Figure 5 shows a comparison of the data with the predictions of Mitler's model (4). With the thermal properties described above, this model clearly predicts somewhat faster upward spread than is seen experimentally. It should be noted that neither this nor the preceding model predicts the "plateau" behavior seen at the lowest flux. As noted above, the plateau appears to be associated with interply delamination and its effect on local thermal conductivity. Since this mechanism is not incorporated in any existing flame spread model, it is not surprising that no plateau is predicted (but see below).

Mitler's model starts out reasonably well for both fluxes but then overpredicts the speed of full upward spread. It uses heat release data from an intermediate external flux ( $4 \text{ kW/m}^2$ ) transformed to the actual flux of interest. The predictions are somewhat different if heat release data from another flux are used instead, implying that the transform method is only approximately applicable to this composite material. The transform is based on variations in the net heat flux to the sample surface, an approach that is plausible for a simple ablating material which leaves no residue on the surface. Here the increasing layer of glass fibers makes this method less accurate with increasing time.

Figure 6 shows a comparison with the model of Brehob (5) and Kulkarni, *et al* (6); note the extended time scale. The heat release data used as inputs are those measured at  $4 \text{ kW/m}^2$  and  $13 \text{ kW/m}^2$ ; data were not available at the run conditions of  $2.5$  and  $11.5 \text{ kW/m}^2$ . Such data would probably improve the agreement between model and experiment slightly. Also used as input data was an experimentally obtained correlation for this composite between total flame heat flux and distance above the pyrolysis front. The correlation is exponential in form as was that obtained by Kulkarni, *et al* (6) but the data were quite noisy; further work on this issue is being done.

This model does predict a plateau at the low flux though later than that seen experimentally. This model also predicts a peculiarly short plateau at the higher flux. Since the model does not account for delamination which appeared to be the actual cause of the experimental plateau, its plateau mechanism requires further study.

**Conclusions.** All of the models could probably be brought into better agreement with experiment by adjustments of the effective thermal inertia of the composite. This has not been done here because no further data on thermal properties of this composite exist now. In addition, one of the points of this study has been to see how accurate the models are with no adjustments to the inputs obtained from the small-scale tests in the manner described here. From the standpoint of an

engineering assessment of the potential hazard of fire growth on composite walls made of these materials, all of the models appear to be adequate and somewhat conservative for the limited conditions examined here. For the vinyl ester composite studied here, for example, all of the models indicate that it will contribute to fire growth in the presence of fairly minor ignition sources coupled with weak external radiant heating. Thus it would not take a very large nearby burning object for this material to participate in fire growth.

More assessment of model accuracy is certainly desirable. None of the models should be used to make fine judgements about the speed of flame spread. For use in a dynamic compartment fire situation, model extensions are needed so as to accept changing ambient oxygen levels and, except for Mitler's model which can already handle this, changing radiative inputs.

### ACKNOWLEDGMENTS

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