ELSEVIER

Fire Safety Journal 31 (1998) 331–344

FIRE SAFETY JOURNAL

Effect of ignition conditions on upward flame spread on a composite material in a corner configuration[1]

T. Ohlemiller*, T. Cleary, J. Shields

National Institute of Standards and Technology, Building and Fire Research Laboratory, Gaithersburg, MD 20899, USA

Received 4 September 1997; received in revised form 9 April 1998; accepted 2 May 1998

Abstract

This paper focuses on the issue of fire growth on composite materials beyond the region immediately subjected to an ignition source. Suppression of this growth is one of the key issues in realizing the safe usage of composite structural materials. A vinyl ester/glass composite was tested in the form of a 90° corner configuration with an inert ceiling segment 2.44 m above the top of the fire source. The igniter was a square propane burner at the base of the corner, either 23 or 38 cm in width, with power output varied from 30 to 150 kW. Upward flame spread rate and heat release rate were measured mainly for a brominated vinyl ester resin but limited results were also obtained for a non-flame retarded vinyl ester and a similar composite coated with an intumescent paint. Rapid fire growth to the top of the sample was seen in replicate tests for the largest igniter power case; the intumescent coating successfully prevented fire growth for this case. Published by Elsevier Science Ltd.

1. Introduction

A fire adjacent to a composite structure poses two types of threat. First is the local thermal degradation of the composite with its attendant loss of strength in the heated structural elements. This issue is termed fire resistance. The second threat is the

[1] This work was sponsored in part by the US Navy Surface Warfare Center, Annapolis, MD. It is a work of the US Government and is not subject to copyright protection in the United States.

* Corresponding author.

0379-7112/98/$–See front matter. Published by Elsevier Science Ltd.
PII: S0379-7112(98)00019-8

possibility of fire involvement and fire growth on the composite surface. The organic nature of composite binders renders them flammable in some conditions and thus a small fire could, in a worst-case situation, lead to the total destruction of a composite structure. It is this second issue, fire growth on composites, which is addressed here.

This fire growth threat for composites is fundamentally similar to that for any flammable solid material. However, composites could bring new complications. Fire growth is largely a heat transfer process in which flames heat adjacent material causing it to ignite. Ignition occurs when the temperature of the material reaches a level where rapid degradation produces an ignitable mixture of fuel gases. The heat-up to ignition depends strongly on the thermal properties of the solid. For composites, with their typically lamellar structure, the heating process prior to ignition can cause delamination and thereby an alteration in the thermal properties. In principle, this tendency to delaminate could be aggravated by a compressive structural load in the plane of the fiber plies. Thus, a complete accounting of the thermal response of composite structures could necessitate the coupled treatment of heat flow and mechanical stresses. One of the goals of the research program, of which the current study is a part, is to determine if the fire growth problem of composites can be adequately addressed without consideration of such coupling. Thus, the case being examined at present does not involve mechanical loading on the composite, though future tests must do so. This is an important potential simplification, since the quantitative understanding of fire growth on ordinary materials such as wood, in the absence of load interactions, is still evolving.

The approach to quantifying fire growth for other materials, which is being adopted in this research program for composites, involves a combination of small-scale testing and models which use these test results to predict full-scale behavior. Ignitability and heat release rate information (as a function of incident radiant heat flux) are obtained on small-scale (10 cm square) samples in the Cone Calorimeter (ASTM E 1354). In full scale, the focus is on upward flame spread on the fuel surface, since this is typically the fastest mode of fire growth in natural convection conditions. Lateral fire spread on vertical or horizontal surfaces, which may be significant in some cases, can be assessed in the LIFT apparatus (ASTM E 1321) with the results applying directly to full scale.

Previous work examined the upward spread of flames on flat vertical wall surfaces, primarily of vinyl ester/glass composites [1, 2]. The test conditions were somewhat idealized to conform to the assumptions of existing models of upward flame spread. Thus, 1.2 m tall composite panels were uniformly irradiated with fluxes from zero to 15 kW/m^2 to simulate heat input such as might be encountered in an enclosure fire. Flame spread was initiated by applying a linear igniter flame along the bottom edge of the panel. The results of such tests were compared with predictions of three upward flame spread models which differed in their simplifying assumptions. None of the models was able to predict quantitatively the spread behavior seen over a range of incident fluxes and igniter sizes but all were sufficiently close to the real behavior to be potentially useful in judging the type of fire insult that a composite could withstand without exhibiting rapid fire growth. For an unretarded vinyl ester/glass composite, the results implied a substantial hazard since fire growth occurred under nearly all conditions examined. Data (as yet unpublished) for a brominated vinyl ester/glass composite showed a somewhat enhanced fire growth resistance, in that higher external fluxes were required to give equivalent growth behavior.

It has long been recognized that a vertical 90° corner configuration constitutes a greater hazard than does a flat wall with regard to fire growth potential. There are two reasons for this. First, the walls (and flame volumes) can exchange radiation; this enhances the local burning rate and, in turn, this accelerates fire spread. Second, the plume of hot gases is diluted less rapidly because the air inflow is partially blocked by the second wall; this allows the plume to transfer more of its heat to the wall surfaces, again enhancing the flame spread process. Such a corner is most relevant to a compartment fire scenario; thus, it pertains to the possible use of composite deckhouse structures aboard naval ships, for example. The corner configuration is also potentially of broader interest for infrastructural uses of composites but here it is not clear that it constitutes any sort of worst case.

A fire in the corner of a compartment soon becomes coupled to the entire compartment through accumulation of hot gases in the upper part of the room. In order to avoid this added complication at this stage of the research, an open corner configuration has been selected. To keep it similar in behavior to a real compartment corner, a triangular, inert ceiling section tops the corner. Fire growth in this corner is studied as a function of initiating fire size.

The immediate goals in examining this configuration are several. First, the results provide direct information on the size of initiating fires that a particular composite can withstand without exhibiting runaway fire growth. The composite is brominated vinyl ester/glass which the Navy is considering for deckhouse and mast applications. Second, the results constitute a basis for testing potential models of fire growth in this configuration; see below. Third, the tests provide an opportunity for a very limited assessment of the potential for fire growth suppression by means of an intumescent surface coating.

Room corner tests have been codified for the purpose of assessing the flashover potential of room lining materials. In ISO 9705, for example, a standard room lined with a material of interest is subjected in one corner to a gas burner that is held first at a 100 kW level then raised to 300 kW. The standard ignition source is so narrow in width (0.17 m) that, even at 100 kW, the continuous flame height exceeds the 2.4 m height of the room. Thus, this test involves mainly concurrent flow flame spread on the ceiling and opposed flow spread on the walls. Existing models of corner flame spread [3–5], which are based on Cone Calorimeter characterization of the wall material, have for the most part, been tested against data generated in this test. Their ability to predict upward growth in the corner, as in the present situation, is less clear. Saito and his students [6–8] have studied this growth process extensively for simple materials like PMMA. They have not developed a general model of the corner spread process but their results suggest that appropriate modifications to available flat wall models may be adequate for this purpose. A test of this is planned in this study but is not yet completed. The present report focuses on the experimental results.

2. Experimental

The principal composite was composed of a brominated vinyl ester resin and woven roving glass mat (0.82 kg/m^2; 24 oz/yd^2) prepared by the SCRIMP process (a vacuum-assisted resin infiltration process that minimizes voids). The panels were 1.27 cm thick. The supplied panels (91.4 cm by 122 cm) were cut in half in the long direction to facilitate formation of a corner test configuration, with minimal material requirements (see below). A second composite, used in the tests to assess a surface coating, was composed of non-fire retarded vinyl ester and the same woven roving glass mat. These panels were 0.95 cm thick with the same lateral dimensions as the flame-retarded panels; they were cut in half for mounting in the same manner.

The intumescent surface coating used was a commercial paint product sold explicitly for fire protection of organic materials. It was selected from four coatings that had been tested in the Cone Calorimeter, both for reduced heat release rate and ability to stay bonded to the composite under high heat loadings. It incorporates standard intumescent components plus ceramic fibers. The material was applied as several successive coats with a paint roller to the sanded surface of the composite, at a thicker than normal level of approximately 1.5 mm. It was given three days to dry after the last coat was applied.

Figure 1 is a schematic of the corner configuration showing the burner placement at its base. To minimize the cost of the tests, the composite panels occupy only that portion of the corner likely to be involved in upward or lateral flame spread. Note that there is a juncture between separate panels at mid-height. Any gaps around the periphery of the panels that were greater than about 2 mm were filled with ceramic felt to minimize the tendency for air or fire gases to pass through them. The sample panels were held in place by peripheral, spring-loaded clips, attached to a metal framework that touched the panels only along their outer edges and along the corner vertex. The only vertical load on the panels was due to their own weight. The panels showed some tendency, in some tests, to bow outward as much as 5–6 mm during the transient thermal loading from the burner but this did not appear to affect the test results in any significant way. The panels were insulated on the back with R-11 fiberglass batts.

Two square propane gas burners were used as the fire initiation sources. The smaller source, 23 cm in width, was constructed and filled (with gravel and sand) in the manner of the standard ISO 9705 burner. The larger source, 38 cm in width, followed the design of the alternate source specified in ISO 9705. Note that neither source is of a width specified in ISO 9705 because the goal here was to define the conditions that yield upward spread in the corner, not on the ceiling, of a compartment. In all tests the burner was immediately adjacent to the vertex of the corner with no air gaps. Propane flow was measured with a dry test meter and corrected for deviations from normal temperature and pressure conditions.

The smaller burner was run (in separate tests) at nominal power levels of 30 and 60 kW. The larger burner was run at three nominal power levels: 30, 60 and 150 kW. In all cases the burner was on steadily throughout the test, being shut off only well after the result of the spread process was evident. For a perspective on the size of these fires, it is noted that a plastic wastebasket fire can reach 50 kW; an upholstered chair

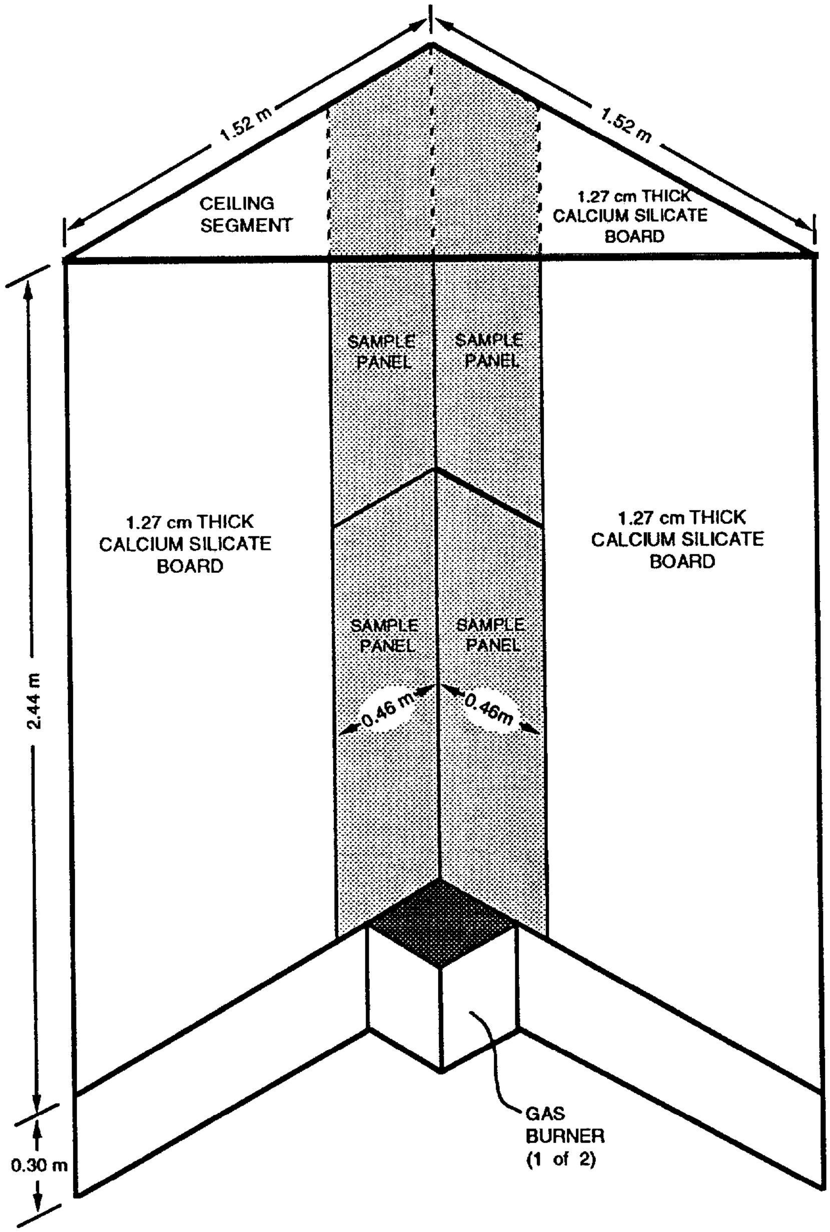

Fig. 1. Schematic of corner burn configuration used in this study.

can reach 1 MW. Thus, these burner power levels are near the low end of what might be provided by a burning object within a compartment. The choices of burner dimensions and fire sizes were guided by the corner burner characterization results of Kokkala [9] and by two preliminary tests done here. The goal was to choose a set of conditions which, ideally, spanned the range from little upward flame spread to full height spread.

All test conditions with the brominated vinyl ester were run in duplicate. One test each was run with the unretarded (coated and uncoated) vinyl ester; both were at a nominal burner power of 150 kW.

The tests were run under a flow collection hood equipped with oxygen and mass flow sensors to allow rate of heat release measurements from the fires. The system was designed for much larger fires but by running it at a reduced flow rate and calibrating with propane fires before each test, adequate measurements were possible.

Prior to the fire tests, the steady-state heat fluxes from the burner to one side wall were measured at sixteen points using a set of four Schmidt–Boelter total heat flux gages. This was done for each burner at each power level to quantify the thermal insult. These 6 mm diameter gages were inserted from the rear through holes, so that the sensor surface was flush with that of the 1.27 cm thick calcium silicate board used in place of the composite samples. These gages measure the total heat flux to the gage surface, which in this case was kept at 80–85°C to prevent water condensation. Soot deposition on the sensor surface was problematical during these tests; the gages were pulled just prior to each local measurement and dusted off to avoid a calibration shift. The same set-up was used to measure incident heat fluxes at four locations during the actual fire tests (holes were drilled through the samples). Tar condensation from the degrading vinyl ester could not be prevented in these circumstances but separate tests have indicated that its deposition does not shift the flux gage calibration; it does slow its response time, however. Soot deposition during the fire spread tests did not appear to be a problem.

The fire tests were videotaped by a close-up observer, with narration as to the flame front location. This location, which here proceeds up fastest in the region near the corner vertex, is difficult to discern precisely with most materials due to obscuration by the buoyant fire plume. It was previously found that with this particular type of composite the flame front can be seen intermittently as the highest set of small (several mm), bright flame jets attached to the wall [1, 2]. The jets seem to be issuing from a grid-like pattern of the highest permeability points on the composite surface, each corresponding to some specific locus on the woven roving glass fiber weave. Here the jets were more difficult to spot, possibly due to the much narrower nature of the leading flame front [6] and the slower air entrainment rate. Observing these jets proved adequate except for the fastest spread case (uncoated, non-fire retarded vinyl ester). This spread information was supplemented by videotapes taken with an infrared imaging camera using a flame filter at 10.6 μm to peer through the flames at the sample surface. By calibrating the camera against cases where the spread front could be followed visually, it was possible to use it to find the flame front in the case where the visual tracking was inadequate.

3. Results and discussion

3.1. Incident heat flux patterns

Figure 2 shows examples of contour plots derived from the incident heat flux data. Only the shortest and tallest burner fires are included, both with the 38 cm burner.

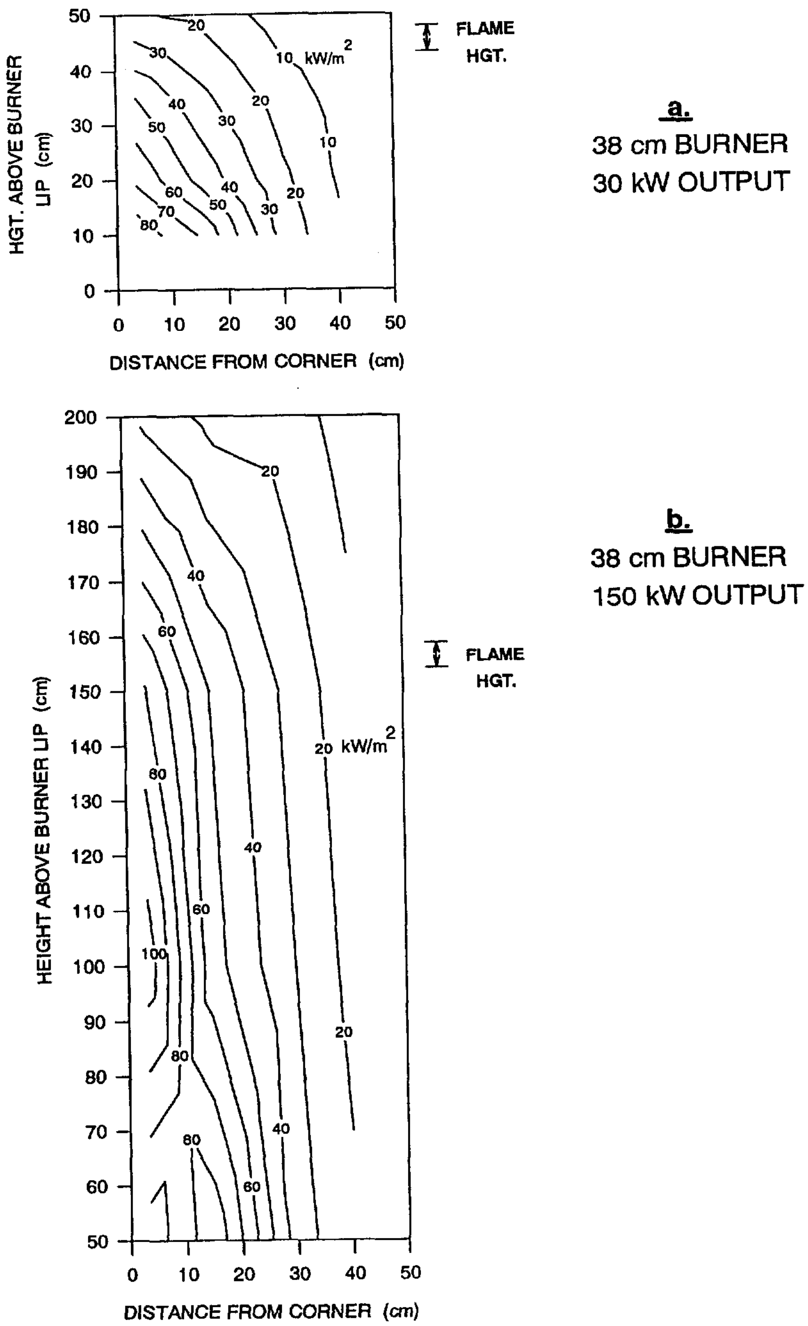

Fig. 2. Contours of constant heat flux on inert wall after extended exposure to (a) 38 cm burner operated at 30 kW; (b) 38 cm burner operated at 150 kW. Flame height is average level of attached flames.

It is important to realize that the smaller burner (23 cm width) yields, at the same propane flow rate (and thus at the same burner power level) a flame height roughly twice as high as does the 38 cm burner. At the same time, the smaller burner yields a more narrow flux distribution.

Note that the flux distributions grow narrower at the top. This is a consequence of the plume of hot gases being diluted by engulfment of ambient air after the fuel gases are consumed. The burning fuel gases behave similarly when they emerge during fire growth on the composite surface. Thus, the heating is most intense near the vertex of the corner where this dilution occurs most slowly and the flame front proceeds upward most rapidly. Radiative exchange is most effective near the vertex, further adding to this tendency.

It is not at all evident from Fig. 2 but it should be noted that the burner flame height fluctuates up and down quite substantially at about 1 Hz due to a well-known vortex shedding process for pool-like fires. Mean visible flame height measurements were made on the 23 cm burner, by averaging over about 90 successive video frames, the height of flames continuously attached (without a break) to the burner. The results agreed very well with Kokkala [9] at 80 kW but were about 25% higher at 30 kW. (Note: Kokkala did not report his flame height definition very precisely; the definition here could differ.) The peak incident heat flux levels appear to be in general agreement with Kokkala as well (ca. $\pm 15\%$). There are no exact matches in conditions against which to compare the overall heat flux profiles.

It is of interest to compare the peak flux levels here to those seen with the line ignition source used in the flat wall upward spread studies [1, 2]. The peak incident flux level for those thin flames was about 40 kW/m^2. Here, even for the 23 cm burner operating at 30 kW, the peak flux exceeded 80 kW/m^2. Much of the difference may be due to enhanced radiation from the substantially deeper flame volumes which square burners provide. These higher fluxes increase the local heat release rate from the composite subsequent to ignition and this, in turn, makes upward flame spread more likely. This, plus the corner flame spread enhancing aspects described above, help compensate for the lack of an external radiation source like that used in the flat wall tests.

3.2. *Upward flame spread behavior*

Results from the 12 flame spread tests are summarized in Table 1. They will be discussed in three separate groupings.

3.2.1. *Full factorial group*

The first eight tests in Table 1 comprise a full factorial two-level experiment with replicates. This makes it possible to generalize the results by means of an empirical equation which includes linear terms and a two-way interaction term [10]. Thus, for example, using the average net (total minus burner power) peak sample rate of heat release for each for the first four distinct test conditions in Table 1, one obtains the following result.

$$\text{Peak Net RHR (kW)} = 4.83\text{P} + 4.00\text{W} - 0.104\text{WP} - 154 \qquad (1)$$

Table 1
Summary of corner test results for vinyl ester/glass composites

Burner width (cm)	Burner power (kW)	Maximum spread Hgt (cm)	Time to reach top (s)[a]	Average spread rate (cm/s)[b]	Peak RHR (kW) (total, net)	Time of RHR peak (s)
23	31	187	∞	0	—	—
23	31	190	∞	0	45, 14	1250
23	63	244	410	0.60	152, 89	1100
23	62	244	410	0.60	152, 90	1350
38	31	116	∞	0	42, 11	1000
38	31	114	∞	0	71, 40	1200
38	61	244	1280	0.19	112, 51	1100
38	62	244	1390	0.175	ca. 116, 54	1200
38	145	244	167	1.46	271, 126	375
38	148	244	168	1.45	266, 118	650
	148					
38	Non FR, coated	Minimal	—	—	162, 14	1600
38	147 Non FR	244	120	2.0	576, 429	175

[a] Time from start of significant burner flame to estimated time flame front reaches top.
[b] (Total height of wall)/(Time to ignite and spread, bottom to top).

This allows one to estimate the net rate of heat release from the burning vinyl ester composite for any burner width, W(cm) or burner power output, P (kW) within the range covered by this experiment and, cautiously, somewhat outside this range, as well. Use at higher burner powers is discussed below

It is interesting to note that the behaviour is not quite what one might intuitively expect; the maximum net heat release rate from the composite does not occur for the combination of the bigger burner at the higher power. Instead, it occurs with the smaller burner at the higher power. As noted previously, the smaller burner provides roughly twice the flame height at a given propane gas flow. This yields a much more rapid spread to the top of the corner and thus more closely approaches a worst case condition in which all of the burn area is ignited simultaneously. After the flame front reaches the top, the taller burner flames appear to act as a more effective pilot flame for the retardant-weakened sample flames, thus yielding a greater heat release rate per unit area burning (the two burners ignite comparable burn areas).

Similar to the above empirical equation, the maximum height of flame spread can be calculated from the following:

$$\text{Max. Spread Hgt (cm)} = 358 - 1.84P - 9.80W + 0.16\ WP \qquad (2)$$

This equation cannot be used quantitatively to estimate flame spread length on a flammable ceiling (e.g., if the calcium silicate board in Fig. 1 was replaced with the vinyl ester composite) because the flow and thus, the heat transfer rates on a ceiling are significantly different than in the corner. However, this equation could be used to estimate maximum spread height for a ceiling higher than that used here (though, again, one cannot push this too far). It could also be used, for example, to find the relation between burner power and burner width for igniter fires which cause fire growth no more than halfway up the height of the corner, if this were deemed an acceptable maximum fire response from the composite. Note that for this particular composite, in spite of its flame retardant, the fire size which would cause fire growth to half the corner height is small (ca. 30 kW for a 38 cm burner). Thus, this criterion is quite demanding with regard to permissible ignition sources (e.g., other burning objects in the compartment whose walls are made from this composite) because of the relatively high flammability of this composite.

The 60 kW fires show behaviour that is strongly dependent on burner width. For the 38 cm burner, the fire requires more than 20 min to reach the top of the corner. For the 23 cm burner, it requires less than 7 min. The former case could offer quite adequate time to suppress a fire, while the latter case could be marginal. Thus, one might also develop an acceptability criterion on this basis, fitting an equation of the above type to the spread time data in Table 1. (Of course, this dependence of the fire behavior on two parameters, igniter power and dimensions, makes it more complex to relate this back to the allowable burning of real objects in a compartment.)

Any other parameter of interest in Table 1 can be fitted to an equation of this type to permit interpolation and some extrapolation of the data for other fire conditions. Of course, these are not mechanistic equations. In particular, they offer no insight as to how all of these results would change if a different composite were used to line the corner. Answering this sort of question, preferably on the basis of simple Cone Calorimeter characterizations of the composites of interest, is the province of a true flame spread model.

The reproducibility of the upward spread behavior shown in Table 1 is generally quite good. The net heat release rate values show some tendency to vary, particularly at the low end. This is due, at least in part, to the fact that the facility used for these measurements is intended for much larger fires and thus the system noise is a substantial fraction of the heat release signal for the smallest fires (see Fig. 3a).

Another potential contributor to the variability of the various data in Table 1 is ply delamination. This erratic phenomenon can, as noted previously, alter the apparent thermal properties of the composite and cause variation in the upward flame spread rate. Deep delamination bubbles were indeed visible from the back surface of the samples after the tests. They did not appear to play a significant role during upward spread; the good reproducibility of spread behavior is consistent with this. The last test in Table 1 is a possible exception with regard to delamination influence; see below. This result implies that, at least for this material in a no-load situation, a composite need not behave in a manner any more complex than traditional materials.

3.2.2. *Extended burner power range*

Two additional tests were performed on the flame-retarded vinyl ester composite with the larger burner run at a nominal power of 150 kW to extend the conditions to more serious fires. One might expect this to reveal a non-linear dependence of peak

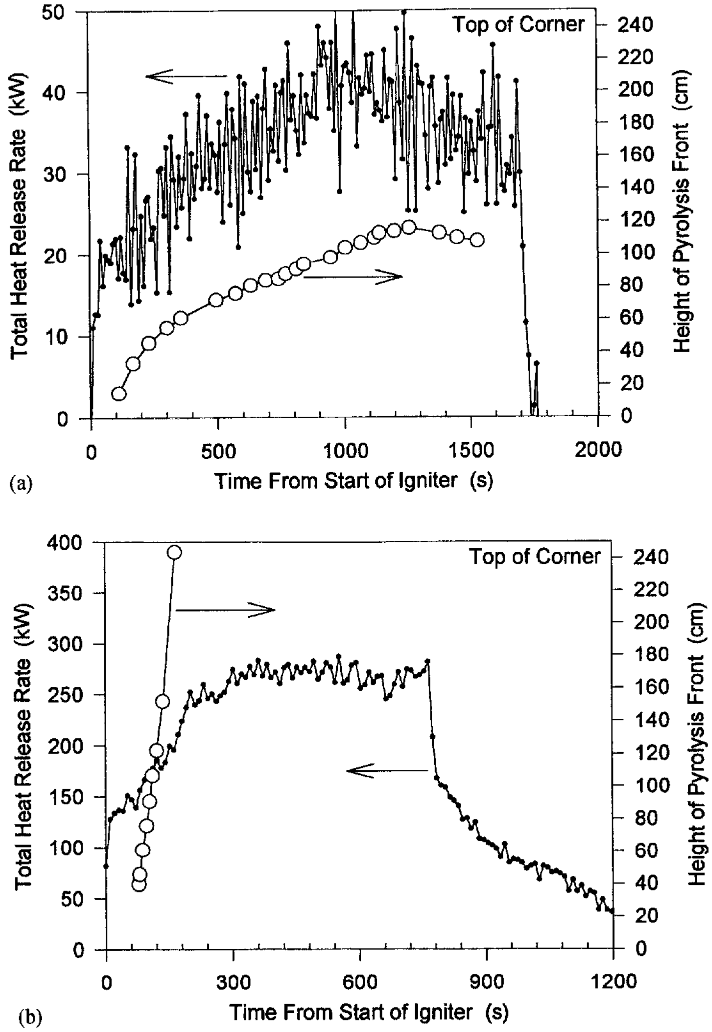

Fig. 3. Transient fire growth and heat release rate behavior observed for vinyl ester/glass composite exposed to: (a) 38 cm burner operated at 30 kW; (b) 38 cm burner operated at 150 kW.

net fire output power on burner power. There is a shifting balance between rate of spread and the complex, time-varying heat release rate per unit area subsequent to ignition. However, the data reveal a simple, linear relation as follows:

$$\text{Peak Net RHR (kW)} = 0.49 + 0.83P \tag{3}$$

This fits the available data with a squared correlation of 0.95. Note that it also essentially passes through the origin, as one would expect. This is approximately the same as Eq. (1) with a value of W equal to 38 cm substituted; the slight differences are due to the noise in the data points and the new points at a higher power level. This simple dependence suggests that data for other burner sizes might be extrapolated in a linear manner to higher propane flow rates, provided one does not move into a new regime dominated by fire spread on the ceiling (if made of vinyl ester composite).

Figures 3a and b show the transient upward fire spread and resultant total heat release rate for the smallest and largest fires with the retarded vinyl ester composite. Note the differing scales in these two plots. These fire data correspond to the incident burner heat flux data in Fig. 2. As Figs 2a and 3a show, at 30 kW the 38 cm burner heats only the lower portion of the sample panels. There is an ignition delay and then a rapid upward spread of flame in this region where the igniter flames provide a strong augmentation to the sample's own flame heat feedback flux. As the flame front moves above this domain, its upward progress is slowed drastically and it finally stops altogether, less then halfway up the corner, after an extended period of nearly linear progress upward. A close look at the rate of heat release behaviour suggests the reason for this halt—the local burning process on the ignited portions of the composite is slowing. This causes the overall flame height to begin to decay. The net heat transfer rate to surface elements above the flame front falls to a level insufficient to yield ignition. The local burning process on the ignited portions slows, not because the resin is completely burned out of the 13 mm depth but because the glass plies comprise an insulation layer of increasing thickness as resin degrades at increasing depths in the composite.

It is worth noting that the flame-retarded composite, in this configuration, requires the continuing heat input from the external ignition source (the propane burner) to sustain its burning. Thus when the burner is shut off the rate of heat release drops drastically and the fire essentially fizzles out. Unfortunately, this result cannot be generalized. For a larger ignition source or more adiabatic fire configuration, this might not be the case.

Figures 2b and 3b show that the nominal 150 kW fire in the 38 cm burner provides a strong heat input over a large fraction of the corner height. Figure 3b shows that the result is very rapid upward flame spread following a roughly 1 min ignition delay interval. In contrast to the deceleration of the flame front above the 30 kW igniter, this case shows a slight hint of acceleration above the igniter flame. Accelerating spread is a worst-case behaviour which, in the more thoroughly analyzed flat wall flame spread situation, signals likely flashover of the compartment. Here the subsequent behavior of any flame spread on the ceiling is less clear but the rapid fire growth in the corner seems clearly to be avoided since it implies little time for fire suppression or even escape. The other ominous feature implied by accelerating spread is the possibility that the fire is growing past the point of needing the ignition source to sustain its spread. Note that the fire dies out much more slowly when the igniter is terminated at 760 s in Fig. 3b, implying that it is closer to a self-sustaining condition. A full assessment of the level of threat implied in the behavior seen here for this composite requires either more extensive (and expensive) full-scale testing of more elaborate (and physically larger) configurations or a verified fire growth model capable of predicting the present results and generalizing them.

3.2.3. *Effect of an intumescent coating*

The last two rows of Table 1 compare the behavior of coated and uncoated non-flame retarded vinyl ester/glass composites in the corner burn configuration. The intended function of the intumescent coating is to char and swell in response to the heat input from the igniter, thus forming an insulation layer that protects the composite beneath it. Here, in a 30 min exposure to a nominal 150 kW fire, the coating appears to have functioned very well. There was essentially no flame spread process on the sample surfaces. The only areas where flames appeared to anchor were at joints (which provided discontinuities in the coating). The heat output of these flames was within the uncertainty of the measurement system; it probably was of the order of 5–10 kW. The coating swelled to as much as 2–3 cm in thickness in some areas and stayed attached to the panels. On the day after the test, the least heated portions of the coating showed clear signs of poor attachment and buckling; it appeared as if this had occurred during the cool-down process. Since no effort had been made to remove a possible mold release agent before the panels were painted, this could have contributed to the less than tight bonding of the paint.

Once again, it should be noted that the intumescent paint coating was used at a thickness substantially greater than normal. It is to be expected that it would be less protective if thinner[2]. This can be assessed to some degree in Cone Calorimeter tests. Validated flame spread models should provide explicit guidance on the required degree of ignitability and heat release rate suppression for successful coating containment of fire growth. In addition, it remains to be seen whether mechanical loading and any resultant flexure of the panels might cause loss of the coating during a fire.

The reference case provided by the corner fire on the composite panels with no coating and no flame retardant provides a benchmark for poor behaviour. Flame spread to the full height of the corner in about 1 min, after a seemingly slow start that lasted an initial minute. A sound previously associated with extensive delamination in flat wall tests emanated from the sample immediately preceding the spread process but no other direct evidence for a possible role of delamination was seen. The spread process was clearly acceleratory. The net heat release rate peak exceeded the flame retarded case with the same igniter conditions by a factor of 3.6. This is a clear indication that the flame retarded resin provides a substantial improvement in fire behavior. Overall it appears promising that a combination of flame retardant and a protective surface coating might yield a viable approach for fire growth suppression with vinyl ester composites.

4. Conclusions

The severity of a full-scale corner test of a composite (or any other material) can be varied over a wide range by changing the burner size and power output. The results

[2] In a subsequent study (Ref. [11]) the effect of thinner layers of this coating and the effect of other coatings were examined in a full-scale corner configuration at a higher burner power level.

reported here provide a basis for estimating the external fire size tolerance of a vinyl ester glass composite for naval or infrastructural usage assuming, at this point, that load stresses do not worsen the fire growth behavior. The results indicate that this material is susceptible to fire growth beyond the area of origin for sufficiently large ignition sources. The 150 kW (38 cm width) fire for which this growth was indicated here is fairly modest; bedding or upholstery fires can provide a substantially larger ignition source, both in terms of power level and width of area heated. It should also be noted that the results here are not conservative with regard to possible growth in a compartment environment; feedback from heat accumulation in such circumstances could lead to faster or more extensive fire growth than seen here. The data and the equations which generalize them provide a basis for a planned test of the ability of a modified flat wall upward flame spread model to predict fire growth in this more serious corner configuration. Also, the results here do demonstrate a potentially substantial benefit from intumescent surface coatings in suppressing fire growth on composites.

Acknowledgements

The unretarded vinyl ester panels were provided by Structural Composites Inc., Melbourne, Florida through the assistance of Eric Greene.

References

[1] Ohlemiller T, Cleary T, Brown J, Shields J. Assessing the flammability of composites materials. J Fire Science 1993;11:308
[2] Ohlemiller T, Cleary T. Upward flame spread on composite materials. Fire Safety J, submitted.
[3] Cleary T, Quintiere J, A framework for utilizing fire property tests. In: Cox G, Langford B, editors. Fire Safety Science, Proc 3rd Int Symp. New York: Elsevier, 1991:647–656.
[4] Karlsson B, Mathematical models for calculating heat release rate in the room corner test. In: Fowell A, editor, Fire and flammability of furnishings and contents of buildings, Vol. ASTM STP 1233. Philadelphia, PA: ASTM, 1993;216–235.
[5] Wickstrom U, Goransson U, Full-scale/bench-scale correlations of wall and ceiling linings. Fire and Materials. 1992;16:15.
[6] Qian C, Ishida H, Saito K, Upward flame spread along PMMA vertical corner walls Part II: mechanism of "M" shape pyrolysis front formation. Combust Flame 1994;99:331.
[7] Qian C, Ishida H, Siato K. Upward flame spread along the vertical corner walls. National Institute of Standards and Technology Report NIST-GCR-94-648, June 1994.
[8] Qian C. Turbulent flame spread on vertical corner walls. National Institute of Standards and Technology Report NSIT-GCR-95-669, April 1995.
[9] Kokkala M. Characteristics of a flame in an open corner of walls. Interflam '93, London, UK: Interscience Communications Limited, 1993:14–24.
[10] Box G, Hunter W, Hunter J. Statistics for Experimenters. New York: J Wiley, 1978:306.
[11] Ohlemiller T, Shields J, The effect of surface coatings on fire growth over composite materials. National Institute of Standards and Technology Report NISTIR 5940, Gaitherburg, MD, December 1996.