SAND2011-3761C

Carbon fiber composite characterization in adverse thermal environments

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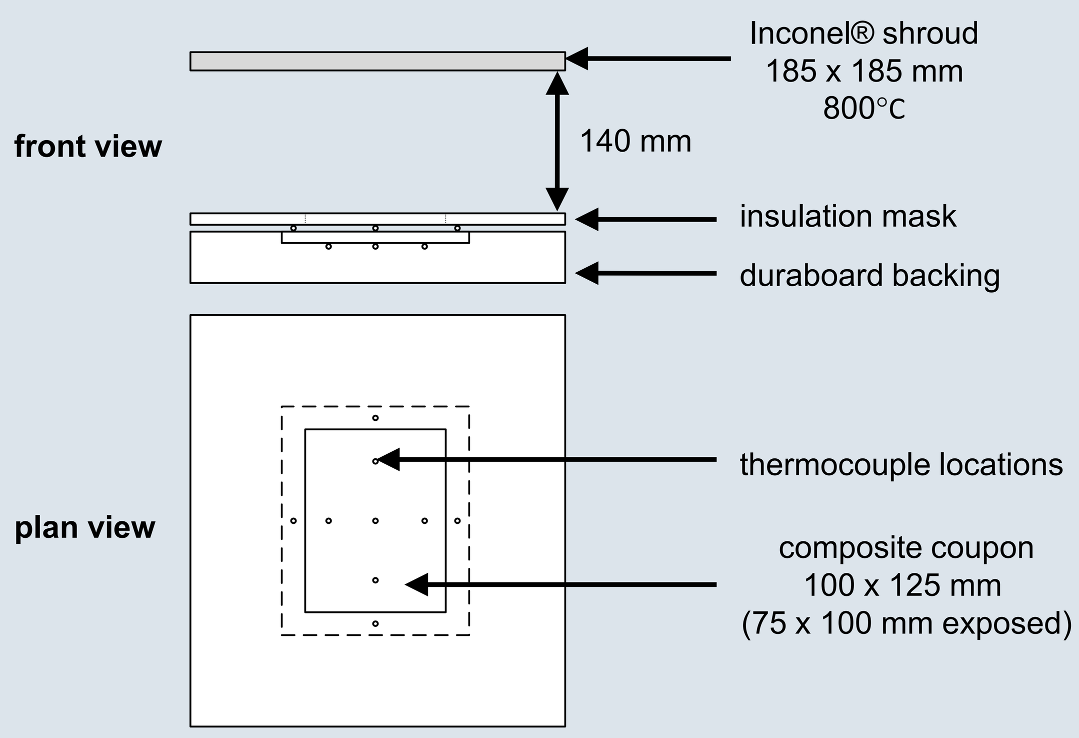
BACKGROUND

Carbon fiber composite materials are increasingly found in transportation vehicles. Greater than 50% of the structural mass is now composite for some new commercial aircraft designs. Composite materials behave differently from conventional fuel sources and have the potential to smolder and burn for extended time periods. As a result, the response of composite materials in adverse thermal environments is of interest. Volatile gases are emitted when composite surfaces are elevated above the resin's decomposition temperature. Gases subsequently ignite and begin a series of complex anisotropic heat and mass flows, char formation, cracking and delamination, and chemical decomposition processes within the solid. The purpose of this work was to begin to understand the behavior of carbon fiber composite materials in fire as well as to provide experimental data for model development and validation.

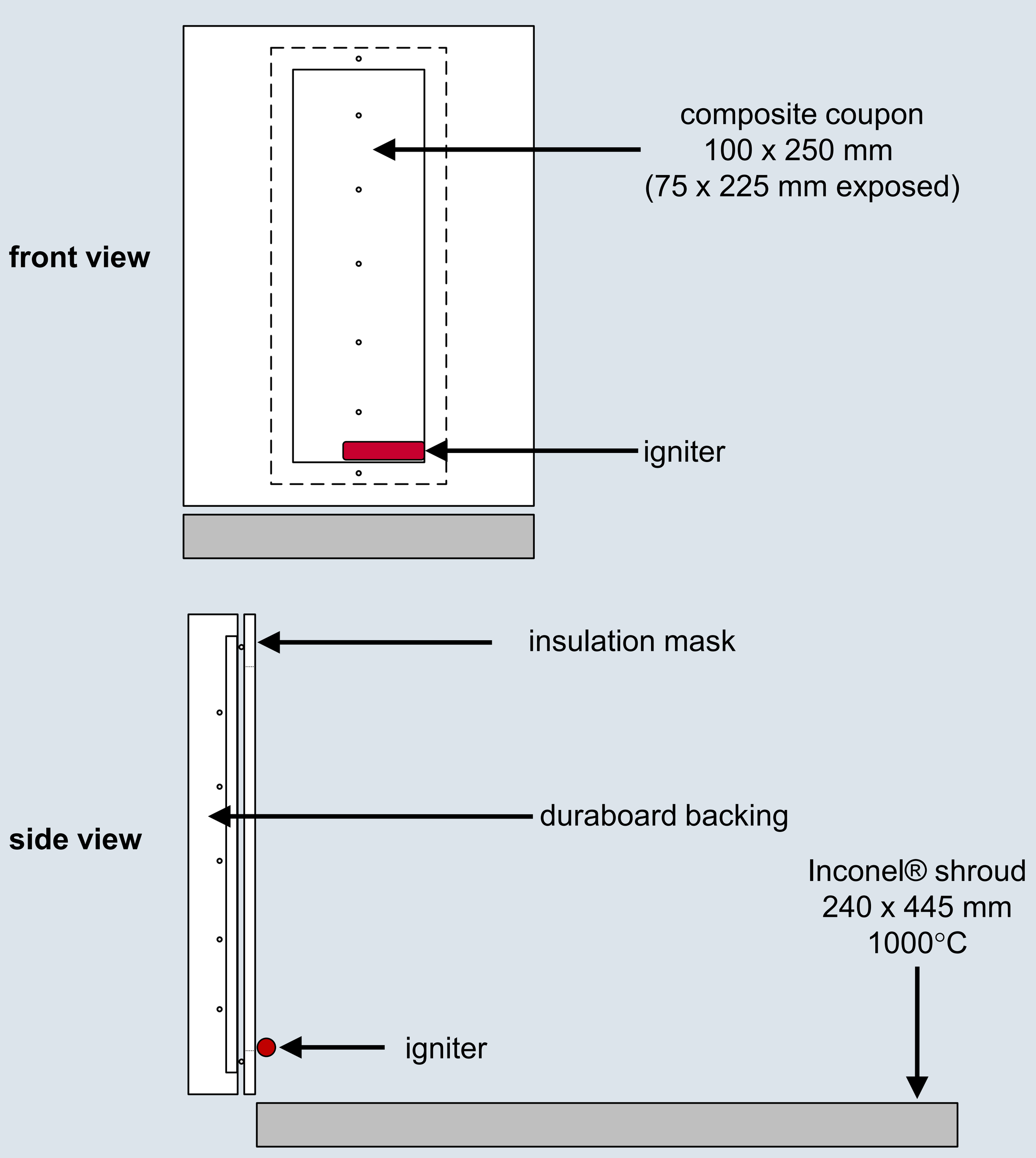
EXPERIMENT

The effects of carbon fiber composite properties (e.g., resin composition and fiber orientation) were examined in two test configurations. Test materials consisted of Epoxy and Bismaleimide coupons composed of uni-directional and woven carbon fibers.

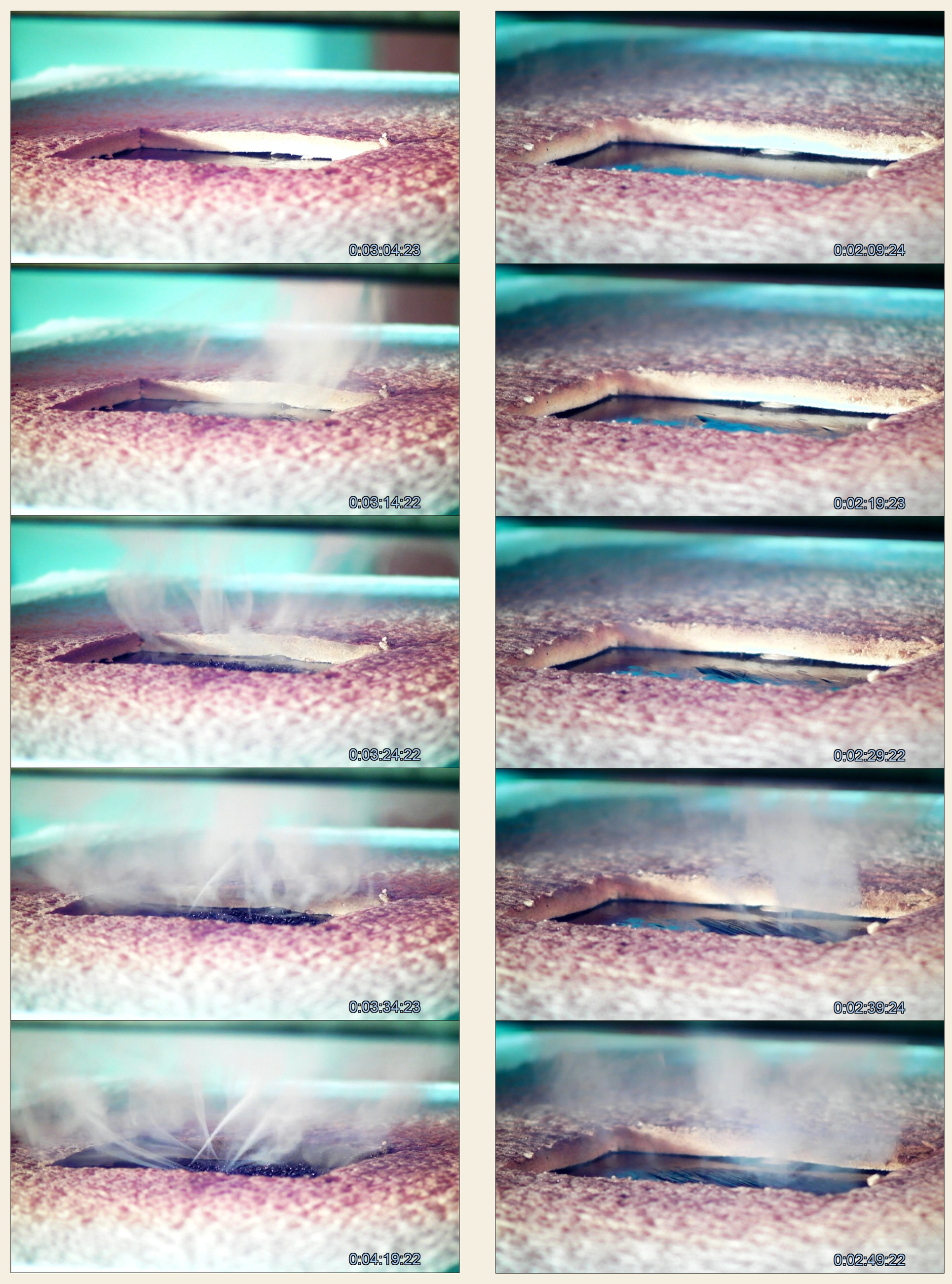
- In the first test configuration (**RADIANT HEAT**), 100 by 125 millimeter laminate coupons were irradiated by a parallel Inconel® shroud. The shroud was heated to 800°C giving an approximate irradiance of 22.5 kW/m^2. The back face of the coupon was insulated.



- In the second configuration (**PILOTED FLAME SPREAD**), 100 by 250 millimeter test coupons were irradiated by a 1000°C shroud giving a spatially averaged irradiance of 30.7 kW/m^2. Here, the coupon was vertical, insulated on the back face, and perpendicular to the shroud. In this set of tests, volatile gases were piloted to characterize flame spread in the upward direction.

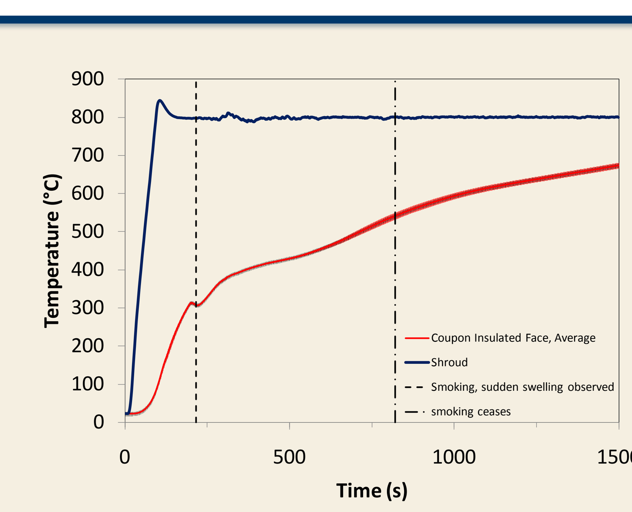


RADIANT HEAT TEST

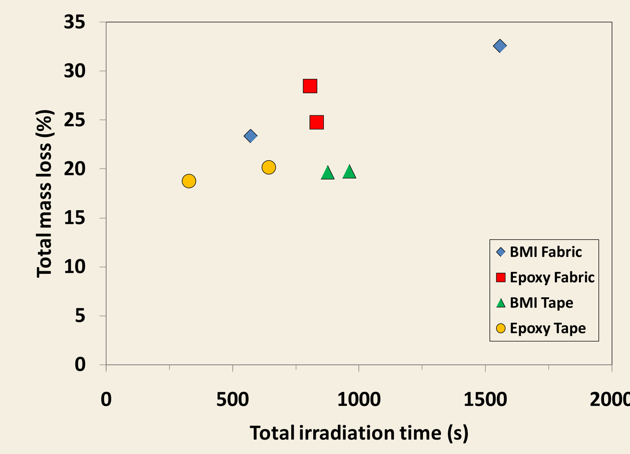


Woven (fabric) carbon-fiber epoxy — **Uni-directional (tape) carbon-fiber epoxy**

- The average temperature profile for the insulated face of a woven carbon fiber epoxy coupon is shown (right) and is representative of most data. Smoking and **sudden swelling** were observed at 200 seconds when the coupon reached 300°C. This is where resin decomposition was expected.

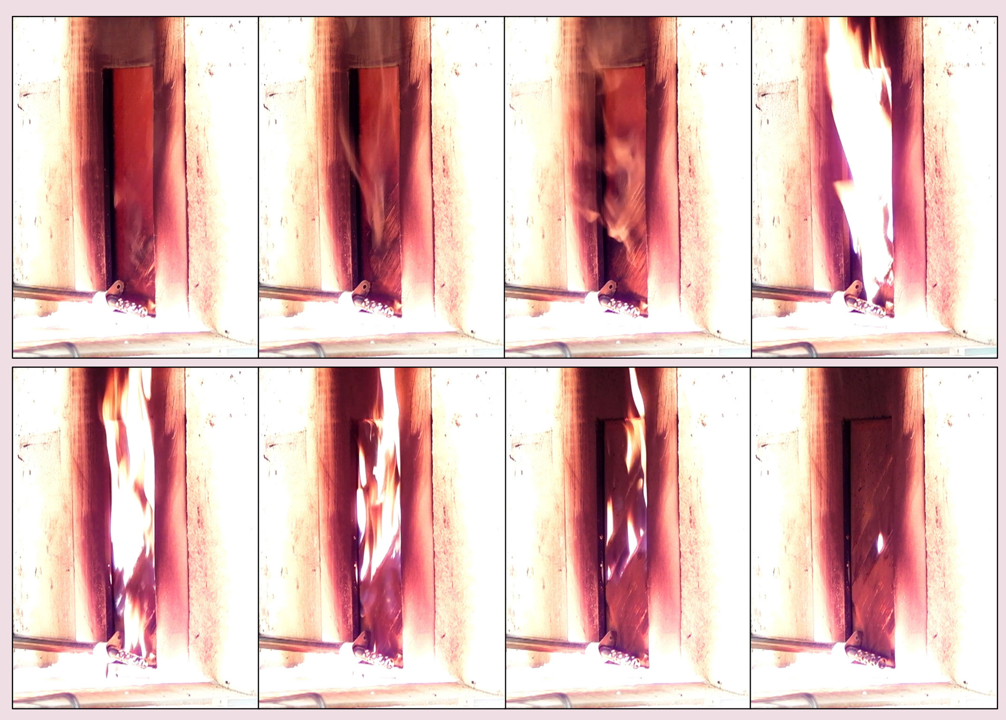


- Time lapse images show frequently observed behavior. For woven carbon fiber epoxy coupons (left), smoking is observed along with sudden swelling at the approximate resin decomposition temperature. Residues formed on the surface and **localized smoke jets** appeared. Uni-directional carbon fiber epoxy coupons (right) also displayed swelling although **cracks formed parallel to the fibers**. Smoke subsequently emanated from these cracks.
- In general, **BMI coupons produced less dense smoke than epoxy coupons** over a longer duration. This was not quantified but is consistent with the work of others [1].
- **Spontaneous ignition** was observed for the following: one BMI fabric coupon, and one epoxy tape coupon.
- Coupon mass loss and volumetric expansion were 24±5% and 146±59%, respectively. Statistically significant differences between materials were problematic due to small sample sizes (two per material). Mass loss was not measured as a function of irradiation time, thus, it was concluded resin depletion was complete at the end of each test.

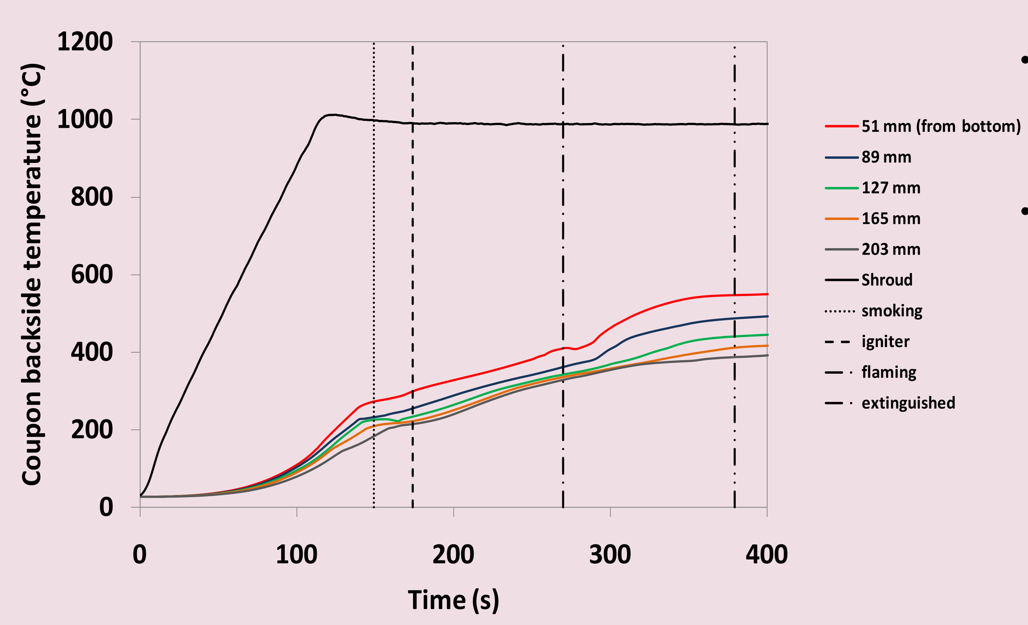


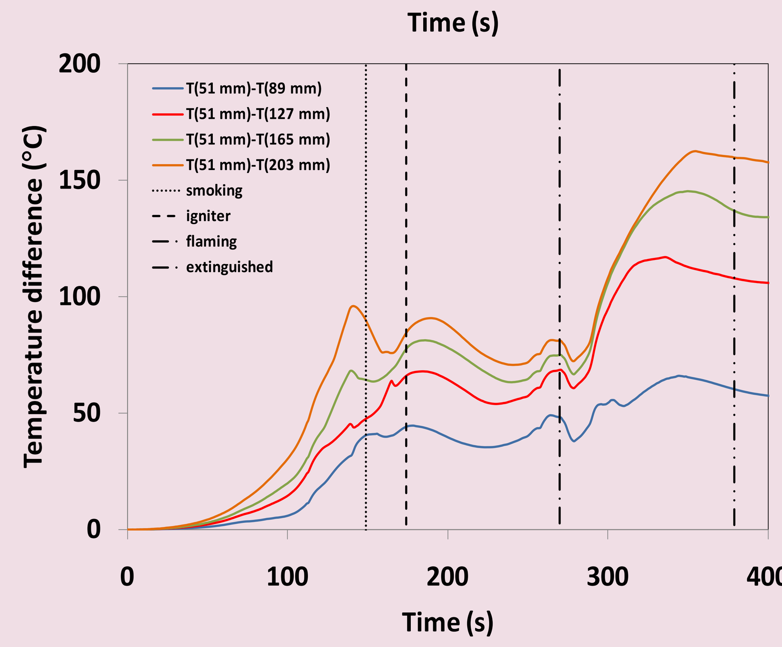
PILOTED FLAME SPREAD TEST

- A glow plug igniter was activated once the coupon temperature reached 300°C and inactivated at the onset of flaming combustion. Below, a time sequence of images is shown with a spacing of 40 seconds to illustrate the primary phase of flaming combustion. This set of images is for a BMI tape coupon.

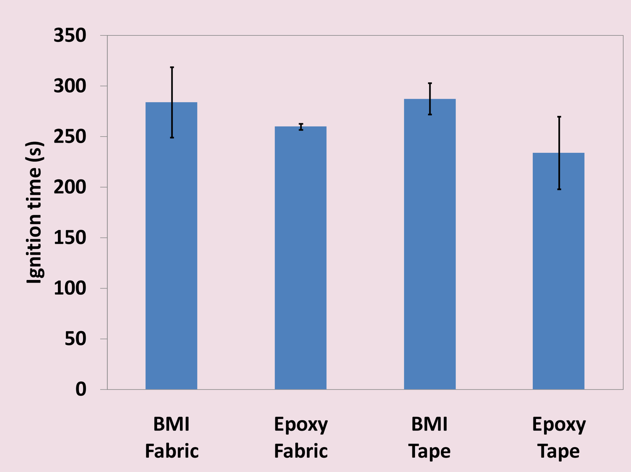


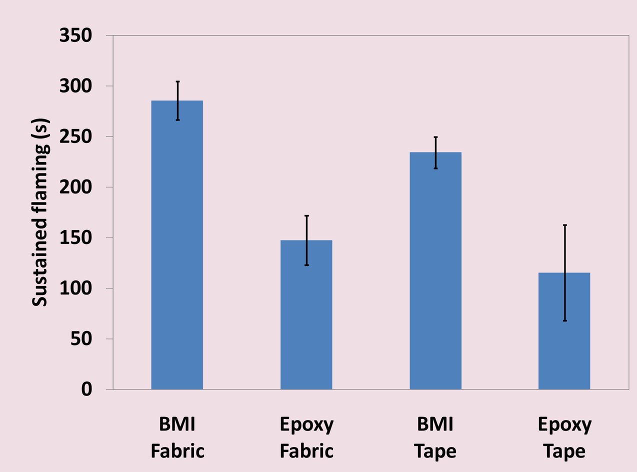
- **Temperature profiles** are given below for an epoxy tape coupon. Only the insulated face thermocouples are shown. Flames and shroud radiation effects likely affected thermocouple measurements on the irradiated face of the coupon. Surface temperatures were measured vertically along the centerline, every 38 mm, starting 51 mm from the bottom of the coupon. Temperature differences are also shown relative to the thermocouple at 51 mm. Changes in decomposition and combustion are observed near the onset of smoking and flaming.





- **Piloted ignition times** show reasonable agreement with values in the literature [1]. Bismaleimide is a high temperature thermoset resin with high thermal stability, low off-gassing, and high char yield. These characteristics result in prolonged ignition times.
- Data collected by Gibson et al. show piloted ignition for epoxy-glass fiber and phenolic-glass fiber occur at 120 seconds and 500 seconds, respectively, for an incident heat flux of 30 kW/m^2 [1]. Average ignition times measured here were 286 seconds and 247 seconds for Bismaleimide and epoxy composites, respectively. The relative difference (40 seconds) does not appear to be statistically significant given the sample size, nor does there appear to be a significant difference between tape and fabric for a particular resin material.





- Bismaleimide composites **sustained flaming** combustion longer than epoxy composites. Due to high char yield, one would expect these materials to self-extinguish more rapidly than epoxy. Flame intensity may explain some of this difference. Flames that persisted for long periods in BMI tests were less vigorous than those observed for epoxy materials. The material appeared to release volatile gases at a slower rate over a longer period. Little evidence of this is clearly identified in the literature.
- Char acts as a thermal insulator thereby slowing decomposition, and also provides additional resistance to the flow of volatile gases to the flame front. Epoxy resin produced noticeably more smoke than Bismaleimide although it was not quantified. This is consistent with findings of other researchers and differences between epoxy and BMI. Gibson et al. show the average **smoke density** for epoxy to be an order of magnitude greater than for phenolic [1].
- **Flame spreading rates** for epoxy coupons were approximated from HD videos. Estimated flame spread rates were 380-760 mm/min and were on the same order of magnitude as measurements made by Ohlemiller and Cleary [2].
- **Spontaneous reignition** was observed for one fabric BMI coupon (below) where each image is separated by 1/30th of a second. Intermittent flamelets lasted approximately 0.1 seconds and occurred at a period of approximately 5 seconds. This lasted for one minute although it was not observed for any other test coupons.

Spontaneous reignition (BMI Fabric)

- Coupon mass loss was 20±3%. Statistically significant differences in mass loss were not apparent and could have been obscured by small sample sizes. However, there was a clear trend in the change in thickness. Measured at the edge, tape coupons had an average change of 105±7% while fabric coupons had an average change of 167±22%.

REFERENCES

1. Gibson, A.G., and J. Hume. 1995. Fire performance of composite panels for large marine structures. Plastics, Rubber, and Composites Processing and Applications 23: 175-183.
2. Ohlemiller, T.J., and T.G. Cleary. 1999. Upward Flame Spread on Composite Materials. Fire Safety Journal 32: 159-172.

ACKNOWLEDGEMENTS

The materials tested here were obtained as samples from Cytec Engineered Materials (Greenville, Texas). We are grateful for their contributions. The authors also acknowledge Sylvia Gomez-Vasquez and Ciro Ramirez for their work conducting the tests at Sandia National Laboratories Thermal Test Complex.

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