

Effect of Resin Type and Glass Content on the Fire Engineering Properties of Typical FRP Composites

by

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Abstract

This study is designed to provide the composites industry as well as the fire engineering industry baseline data and engineering “properties” of common fiber reinforced polymer (FRP) systems. Four resin systems and three glass contents will be considered. This matrix of FRP systems has been carefully fabricated and documented so as to provide “transparency” as to the system compositions. An important and interesting aspect of these FRP systems is that all the resins used are listed by the manufacturers as Class 1 or Class A per ASTM E 84. The FRP systems are being evaluated in bench scale modern fire test apparatuses (FPA, ASTM E 2058, and the Cone Calorimeter, ASTM E 1354). These apparatuses provide a range of measurements such as heat release rate that can be used to calculate engineering “properties” of these FRP systems. The “properties”, such as minimum heat flux for proper ignition and the b flame spread parameter, can then be used to compare the fire performance of these FRP systems according to resin type and glass content. The fire performance criterion to be used is flashover (full room involvement). Modern building codes in general require the fire engineer to design to prevent flashover from occurring.

Introduction

Traditionally, the UL Steiner Tunnel Test has been used to evaluate the fire hazard of interior wall finishes, such as composite materials. The sample in the Tunnel Test is placed horizontally on a ceiling of a tunnel-like test apparatus. Although it has been used for over 50 years, the Tunnel Test has a number of important shortcomings. First, the results of the test only provide a classification scheme for ranking materials; the results do not include useful engineering data. The result of the test is a flame spread index (FSI), which is an arbitrary scale in which fiber-cement board represents zero and red oak represents 100.¹ The FSI is used in modern building codes to determine where to allow installation of certain materials in a building. A rating of Class 1 or A, such as

the resins that were tested in this study, means that the FSI is less than 25 and the material can be installed anywhere in the building. Second, some materials do not behave in the Tunnel Test as they would in a real fire scenario. In a real world scenario, fire will spread most quickly in the upward direction due to the effect of the buoyancy-induced flows aiding flame spread. Since the sample in the Tunnel Test is a horizontal sample, upward flame propagation is not modelled.^{2, 3}

A more appropriate test would be one in which both concurrent flow (up a wall and under a ceiling) and opposed flow (lateral and down a wall) flame spread were possible, such as in the room/corner test (ISO 9705, NFPA 265 and NFPA 286). In this test method, a large (4m²) sample is placed on the walls as well as on the ceiling of a corner in a standard test room. The corner is then exposed to an incident heat flux from a large flame. This more closely represents a realistic fire scenario however, the main disadvantage of the room/corner test is that it is expensive and time-consuming. Therefore, many different researchers have worked toward developing a model to use bench-scale data (such as the Fire Propagation Apparatus (FPA), ASTM E 2058⁴, or the Cone Calorimeter, ASTM E 1354⁵) to predict room/corner test results.^{2, 3}

In this study, properties such as the heat release rate, minimum heat flux for proper ignition and the Quintiere⁶ flame spread parameter, b, will be used to differentiate the composite systems based on resin type and glass content. The b parameter will also be used to estimate whether flashover might occur in the room/corner test from bench scale experiments done in the FPA and the Cone Calorimeter on the fiber reinforced polymer (FRP) composite systems.

The FPA and the Cone Calorimeter

The FPA is a bench-scale fire test apparatus in which the sample is heated by four radiant lamps. Each IR lamp consists of 6 bulbs with a tungsten wire in argon gas, which provides a uniform heat flux over the specimen surface of up to 60kW/m². The lamps emit with spectral energy peaks of 1.15 and 0.89 microns.⁷ A long quartz tube can be used to create an atmosphere for the test that is different than the ambient (i.e. enhanced oxygen up to 40% and pure nitrogen). A flowrate of air at 200lpm is run through the bottom of the air chamber so that the sample is in a flow field during the test. The ignition source is a 10mm long blue pilot flame located 10mm above the center of the sample. The combustion products are collected into a duct where smoke obscuration, oxygen consumption, CO/CO₂ generation, total hydrocarbons and temperature are recorded. The mass loss history of the sample is also recorded. This raw data can be used to calculate useful engineering data such as heat release rate, mass loss rate, smoke yield and smoke ex-

inction coefficient. The standard specifies a carbon dioxide generation based heat release rate, which will be used for the FPA in this study.⁴

The Cone Calorimeter is similar to the FPA but it also has some important differences. The heater in the Cone is an electrically heated rod in the shape of a cone, instead of the IR lamps in the FPA. The Cone is designed to compute heat release rate based on oxygen consumption instead of carbon dioxide generation as in the FPA, so oxygen consumption calorimetry will be used for the Cone in this study. The sample in the Cone is exposed to the ambient environment and is not in a flow field so the apparatus can only perform tests under ambient conditions.

The difference in the radiant source between the Cone and the FPA is noteworthy because the FPA radiation apparently tends to absorb at depth into the composites evaluated in this study while the Cone does not. This difference causes a discrepancy in the time to ignition and burn duration between results obtained from the Cone and the FPA. An attempt was made to resolve this issue by applying carbon black powder to the surface of the specimen in the FPA to prevent in-depth absorption. The carbon black decreased the time to ignition in the FPA to match that of the Cone but did not affect the overall burning duration as compared to tests in the FPA without carbon black. In some cases, this is thought to be due to near surface effects preventing the carbon black from covering the whole surface after initial radiant exposure and subsequent reactions (e.g. jetting at the specimen surface causing disruptions in the carbon black layer). The carbon black did not affect the heat release rate or the *b* parameter from results without carbon black in the FPA but it did increase the range of the minimum heat flux for proper ignition compared to tests without carbon black in the FPA for the System 1 composites. The results from the tests with carbon black on the specimen surface in the FPA are not reported in this study due to inconsistencies in the results; future work is needed.

Sample Holder

Instead of the non-insulated aluminium dish that is specified in ASTM E 2058, an insulated sample dish described by de Ris and Khan⁸ is used. The sample is surrounded by Cotronics® paper insulation on the back and sides as shown in Figure 1 to provide a barrier to heat loss. The assumptions that can be made based on the presence of the insulation (e.g. no heat loss from the back face or sides of the sample) are very useful in modelling the sample's reaction to the applied heat flux. The sample holder is also beneficial for installing thermocouples on the surface, center and back of the sample as well as embedding a heat flux gage to lie flush with the sam-

ple surface, which is the next step to be completed in the current work.

Apparatus Calibration

Before any testing of the composite samples was started, tests were done with well-known materials in an attempt to determine the uncertainty in the time to ignition, burn duration and heat release rate in the FPA, since it is a new apparatus at WPI. The analysis for the uncertainty in the time to ignition and the burn duration for the FPA is based on three PMMA tests. A sample set of three is believed to be sufficient in this case because the FPA standard calls for three identical tests to be performed to correctly determine other properties. From these tests, the uncertainty in the time to ignition and the burn duration were found to be 9s and 101s, respectively. These uncertainties are full scale (as opposed to \pm half scale).

FPA tests were done with methane, propylene and acetone, as well as PMMA, and the heat release rate was calculated using three different methods. The ASTM E 2058 and the Beaulieu⁹ methods are based on carbon dioxide generation while the Parker¹⁰ method is based on oxygen consumption. All three methods can be formulated as either fuel specific or generic (i.e. published average values). The effective heat of combustion was found by dividing the cumulative heat release rate by the total mass lost. This effective heat of combustion was compared to the chemical heat of combustion (equal to the published total heat of combustion corrected for the published smoke yield); this method is specified as a heat release rate calibration procedure in ASTM E 2058, using acetone as a model material. The standard states that the effective heat of combustion, calculated using the fuel specific heat release rate equation, must be within $\pm 5\%$ of the published value for acetone.⁴ As can be seen from Table 1, the accuracy (defined as a deviation of the average value from all of the tests as compared to the published value; all of the reported uncertainties are full scale as opposed to \pm half scale) in the acetone heat of combustion, calculated from the fuel specific equation, was found to be 7.9%. Therefore, the heat release rate for the FPA was found to be calibrated according to ASTM E 2058. Effective heat of combustion accuracies determined using the other methods of calculating heat release rate are also shown in Table 1 to demonstrate that there is not a significant difference between the results from the different methods.

In Table 1, the number listed as the accuracy in kW is the maximum value that the heat release rate trace derived from the ASTM E 2058, Parker and Beaulieu equations deviates from the reference heat release rate trace (the mass loss rate multiplied by the published chemical heat of combustion). There is an asterisk in the last column for both propylene and methane because

both of these gases were coming from the FPA's gas burner. The mass flowrate of the gas was stepped up and down during the experiment, which increased the heat release rate of the fire. In the case of both propylene and methane, it was found that the absolute difference between the calculated and the reference heat release rate curves got larger as the mass flowrate was increased. The value listed in Table 1 is the maximum value of the deviation.

The absolute accuracy in Table 1 is listed in kW even though units of kW/m² are generally used. Since the propylene and the methane are in the gaseous state and are coming through the FPA's gas burner, there is no specimen surface to divide by to achieve units of kW/m². Since the average specimen surface of the composites is 0.007m², the uncertainty in kW/m² is then approximately 70kW/m², full scale, based on data from Table 1.

The uncertainty in the time to ignition and the burn duration for the Cone are expected to be within the same range as the FPA. Therefore, the uncertainty values for these variables from the FPA will be used for the Cone as well. The heat release rate uncertainty in the Cone is governed by the C factor, which is determined by calculating the heat release rate of a methane fire at different mass flow rate steps and inserting the subsequent values into an equation for the C factor that is provided in ASTM E 1354. The required uncertainty from the standard is 5% and it is known that the Cone meets this requirement. Therefore, no additional calibration testing was required on the Cone for the purposes of this study.

Description of Composite Systems

In the following discussions, the term "system" will be used to differentiate between resin types (e.g. System 1 is a polyester). The term "sample" will be used to differentiate between glass contents (e.g. sample 1A has a lower glass content than 1B). Lastly, the term "specimen" will be used to represent one individual composite from the sample that will be tested.

Eleven different fiber reinforced polymer (FRP) samples are being tested for the current work. There is a total of 4 different resin systems, each with three different glass contents (except for System 3, which has only two glass contents). Table 2 shows the base resin and the glass content for all of the FRP composites that were tested in the current study. Antimony trioxide was added to the polyester (System 1) as a smoke inhibitor. The neat resole phenolic (System 3) is comprised of formaldehyde and phenol and was modified with the addition of a char forming, fire retardant plasticizer that lowers the viscosity of the resin and further enhances its physical and resistance properties. An inorganic fire retardant for System 4 is used to create a high charring effect while an

organic fire retardant for System 5 creates an intumescent effect. All of the resins used in this study are listed as Class 1 or A with regards to ASTM E 84.

The fiberglass in each of the composites is Vectorply's 0/90 biaxial glass with a chopped strand mat stitched to it. In an attempt to keep all of the FRP composites approximately the same thickness (see Table 2 for a range of thickness for each sample), one pair of glass layers (chopped strand mat plus the 0/90 biaxial) was removed as the glass content was decreased. For example, sample 1A has one less pair of glass layers than 1B and two less than 1C.

Proper and Improper Ignition

The concept of proper ignition that was used in this study is an extension of the concept of "sustained flaming" that was developed in ASTM E 2058. The standard defines sustained flaming as the "existence of flame on or over most of the specimen surface for at least a 4s duration". Since one of the goals of this study is to produce useful data for the development of a pyrolysis model, a fully developed flame cone is necessary to make the simplifying assumption of one-dimensional burning. Another benefit to this definition is that it does not count edge burning as significant burning because the end use of this product (i.e. a wall, ceiling, floor) would be so large that edge effects would be very minor. A flame is considered to be effectively one-dimensional if it is even over the entire sample surface and is unified into a single flame cone (not necessarily axisymmetric). A distinction was made between cellular burning (flamelets over most or all of the surface) and edge burning. If a sample started to burn with cellular flaming and then progressed into a flame cone, it was still called proper ignition for the purposes of this study. Visual observations were made as to the time of the beginning and end of the flame cone so that data could be properly truncated for modelling purposes. This definition of proper ignition was also used in the calculation of the b parameter (where the time to ignition is defined as the start of the flame cone and the burn out is defined as the loss of the flame cone) and in determining the minimum heat flux for proper ignition.

FPA and Cone Testing

After tests were done to calibrate the FPA, testing on the composites was started. In order to get a good initial set of data, each sample was tested twice in the FPA at an incident heat flux of 50kW/m² with the quartz tube in place. This is a practical choice for a heat flux because it represents an average between the heat fluxes typically observed in room/corner tests. In these tests, the lateral flames have a heat flux of approximately 25kW/m² while upward flame spread generates about 100kW/m².¹¹

After this initial set of tests was performed at 50kW/m^2 , additional tests were done to determine the minimum heat flux for proper ignition. System 3, 4 and 5 (the phenolic samples) did not properly ignite at 50kW/m^2 so some tests were also performed at 60kW/m^2 . None of the Systems 3, 4 and 5 composites would ignite in the FPA at 60kW/m^2 , which is the highest heat flux that the FPA can achieve. Therefore, the minimum heat flux for proper ignition for these systems had to be determined in the Cone, which can achieve up to 100kW/m^2 . The minimum heat flux for proper ignition for the System 1 (polyester) composites was determined with the FPA.

FPA Results

The only system that properly ignited at 50kW/m^2 in the FPA was the polyester (System 1), which had significant amounts of black smoke with large stringy particulates of styrene in the smoke. The neat phenolic with the low glass content (3A) delaminated violently and the test had to be stopped in one case. The rest of the samples had only edge burning (i.e. flames emerging from between the sample and the layers of Co-tronics®) after hundreds of seconds of exposure.

Figure 2 is a graph of the heat release rate traces from FPA tests done at 50kW/m^2 for the System 1 composites. The end of the trace is truncated based on visual observations of the loss of the fully developed flame cone. Recalling that the heat release rate uncertainty for the FPA is a maximum of 70kW/m^2 , it can be seen that the top layer has a significantly higher heat release rate than the rest of the layers for 1A and 1B but 1C does not have a significant initial peak. Considering the difference in the initial peak with changing glass content, it can be seen that the magnitude of the initial peak is significantly different between 1A and 1B as well as between 1A and 1C but there is not a significant difference between the initial peaks of 1B and 1C. However, the graph shows a trend that as the glass content is increased, the magnitude of the initial peak decreases. These differences are believed to be related to the surface texture. The surface texture of 1A and 1B is smooth and 1A is highly glossy, which seems to indicate that there is a resin film on the surface. However, 1C has a very bumpy surface due to the weave from the glass layers, which may indicate that there is much less resin near the surface than for 1A or 1B and thus a less significant initial peak in the heat release rate trace.

Given the accuracy with which the heat release rate can be determined in the FPA, the difference in the plateau region of the curve is insignificant (see Figure 2) across all of the System 1 samples. Once the top layer of resin is burnt off, the glass layers block the heat transfer into and the mass transfer out of the specimen, slowing

the decomposition of the resin. This effect appears to be present irregardless of the glass content for the range of glass contents studied.

From the test data, the time to ignition for samples 1A, 1B and 1C are 124s, 145s and 159s, respectively. Given that the uncertainty in the time to ignition is 9s, there is a significant increase in the time to ignition with glass content for all of the polyester composites. Recalling from previous discussion that the burn duration uncertainty is 101s, it can be seen from Figure 2 that the burn duration significantly shortens as the glass content increases. The burn duration would be expected to be shorter for the higher glass content specimen since there is less resin to burn off in the sample than for those with a lower glass content (higher resin content).

Another interesting view on the results was observed by looking at the sample's response to a range of applied heat flux. Figure 3 and Figure 4 show that neither the average nor the peak heat release rate for System 1 significantly changed over an applied heat flux range of $20\text{-}50\text{kW/m}^2$. This demonstrates that the System 1 composites have a similar burning rate over the range of applied heat fluxes considered, given the heat release rate uncertainty. Figure 5 and Figure 6 show how the time to the start of the flame cone, which is essentially the time to ignition for the System 1 composites, and the burnout time vary with applied heat flux. Considering the uncertainty in the time to ignition and burnout previously stated, the time to the start of the flame cone significantly decreases and the burn duration significantly increases as the applied heat flux is increased. The higher heat flux will heat the sample up to ignition faster and will provide sufficient energy to decompose more of the resin and expel it through the glass layers.

Minimum Heat Flux for Proper Ignition

The only composite system that properly ignited in the FPA was System 1 so the rest of the samples had to be tested in the Cone at higher heat fluxes. The last column in Table 2 gives the minimum heat flux for proper ignition as a range. A change in the range of the minimum heat flux for proper ignition is considered to be significant if it is greater than or equal to the step that is being taken (i.e. 5kW/m^2 or 10kW/m^2).

There is a significant change over all of the systems with resin type. The polyester resin (System 1) has a lower minimum heat flux for proper ignition range than any of the phenolic resins. Among the phenolics, the neat phenolic (System 3) has the lowest minimum heat flux for proper ignition, which shows that the additives (Systems 4 and 5) are having a significant effect on the fire performance. The intumescent additive, System 5, tends to have a significantly higher minimum heat flux for proper ignition than the charring additive, System 4.

There also appeared to be a trend for most of the systems with changing glass content, except for System 1. The data in Table 2 seem to indicate that the minimum heat flux for proper ignition increases as the glass content increases. That is, as the glass content of the sample increased, more energy was needed to overcome the blocking effect of the glass and release enough vapors at the sample surface to create a steady flame cone over the entire surface.

System 1 seems to have an effect that is unexpected (i.e. the lowest glass content has the lowest minimum heat flux for proper ignition) however, more tests should be done to fully confirm this effect. Only one test was done with each sample at each heat flux.

System 3 appears to show a significant change with glass content. It should be noted that 3A was tested in the FPA at 50kW/m^2 and did not properly ignite due to significant delamination and violent popping early in the test. While 3A did pop and delaminate in the Cone, it properly ignited before severe popping and delamination occurred. The difference in reaction of the 3A sample between the two different apparatuses is thought to be due to in-depth absorption of the FPA lamp's wavelength into the specimen, as discussed before. Therefore, the 3A sample was tested in the Cone even though the minimum heat flux for proper ignition range would indicate that it could be tested in the FPA.

System 4 showed an increase in minimum heat flux for proper ignition at each change in glass content (i.e. 4A, 4B and 4C all have different minimum heat flux for proper ignition ranges) while System 5 only demonstrated a change for the highest glass content. Sample 5C has a minimum heat flux for proper ignition that is higher than the maximum applied heat flux that the Cone can achieve.

Analysis

A bench scale test, such as those outlined in this study are useful for preliminary observations regarding the fire characteristics of a particular material. They are also relatively inexpensive and not as time consuming as large scale tests. However, the end use of the composites that were studied in these experiments is not to use them as small circles. Rather, the end use would be to use them as building materials to make walls, ceilings and floors, which is a completely different situation that involves different types of physics (e.g. concurrent versus opposed flow flame spread as is described in the next section). Experiments that would test these composites in a situation that would be more similar to their end use would be a room/corner test, such as ISO 9705 in Europe and NFPA 265 and 286 in the United States. In these tests, a corner of a standard size fire room is lined with

the material and a propane burner is used as the ignition source. The ISO 9705 is the most severe due to the higher applied heat fluxes that it requires as compared to the NFPA standards.

Although room/corner tests are more close to the end use of the product, the test has its own drawbacks, including the significant time and money that each test consumes. Therefore, it would be beneficial if the bench scale tests could predict results from the room/corner test. In the next few sections, the idea of a flame spread parameter will be introduced. The b parameter can be used to estimate flashover potential in the room/corner test from results obtained in a bench scale test, such as the FPA.

Flame Spread Theory

Although flame spread is not important in a bench scale apparatus, such as the FPA and the Cone, due to the small size of the specimen, it is extremely important in a real world environment. The flame spread velocity determines how the heat release rate increases with time and thus will be a large factor in the outcome of the fire (e.g. how many items will ignite, if the room will flashover, etc.) The general theory of flame spread is that there is a pyrolysis front in which the material is currently burning and the flame that it is produced is causing the material right next to it to preheat. This preheating may eventually cause enough vapors to be released from the surface to create a mixture that is in the flammable range. The flame will then be the ignition source that will ignite the flammable mixture and the flame will spread slightly and the process will continue. Therefore, flame spread can be thought of as a series of ignitions along the sample surface. If the flame spread is very slow (i.e. the burn time is fast compared to the time to preheat the sample to release vapors in the flammable region), then the fire will decelerate with time. However, if the flame spread is very fast, then the fire will accelerate.¹²

There are other factors that will affect flame spread including ambient conditions (e.g. presence of wind) and the orientation of the burning surface. Concurrent flow spread, either by natural convection or ambient flows, will be faster than identical conditions with no wind because the flame will be leaning in the direction of the flame spread and will create a higher incident heat flux for the target elements. Flame spread up a wall is aided by natural buoyancy induced flows and thus is much faster than opposed flow flame spread.

This theory demonstrates how the Steiner Tunnel Test cannot accurately predict real world scenarios because it only models flame spread along a ceiling in a forced flow field. It is unclear how forced concurrent flow spread, such as in the Steiner Tunnel Test, relates to

buoyancy-induced concurrent flow spread, such as that found when a vertical wall is burning. There are also many other issues with the Tunnel Test that are detailed in the literature, including in the standard itself. Quintiere developed a flame spread b parameter to help correlate bench scale data to room/corner tests to determine flashover, which will be discussed in the next section.

Quintiere b Parameter

Quintiere's flame spread parameter is given as:

$$b = k_f \cdot Q'' - 1 - \frac{t_{ig}}{t_b}$$

Where b is the flame spread parameter
 Q'' is the average or the peak HRRpuA [kW/m²]
 k_f is a constant equal to 0.01m²/kW
 t_{ig} is the time to ignition [s]
 t_b is the total burning time [s]

This approach was chosen over the others in the literature because it is the classical approach and has values that are easy to determine in the FPA. Some of the methods in the literature use peak heat release rate and some use an average heat release rate in the equation for the b parameter. In this study, both the average and the peak heat release rate were used because the values were significantly different in some cases due to a strong initial peak (see Figure 2). Since the same burn duration was used for both the peak and the average heat release rate in the b parameter equation, the b parameter calculated using the peak heat release rate assumes that the heat release rate is at its peak value for the entire burn duration. Therefore, the b parameter calculated using the peak heat release rate and the overall burn duration represents a worst case scenario.

Since all of the information about the sample is not known (e.g. the chemical formula), the generic heat release rate formulas were used. As stated before, the heat release rate for the FPA is calculated using carbon dioxide generation calorimetry and that for the Cone⁵ is calculated using oxygen consumption calorimetry.

Related to the idea of proper ignition discussed in a previous section, the time to ignition was defined as the time to the start of the flame cone. In most cases, this was the same as the time to ignition. However, it was slightly longer in some cases. Along the same line, the total burning time was defined as the time from the beginning to the end of the fully developed flame cone on the specimen surface, which was determined from visual observations. The observations of the end of the flame cone generally correlated with a change in the heat release rate trace. For System 1, which properly ignited at much lower heat fluxes than any other system, the disappearance of the flame cone usually correlated with the

beginning of the decay tail or, in some cases, with the beginning of the second rounded peak in the heat release rate trace. For every other system, the flame cone generally ended after the initial peak.

From the FPA calibration tests, it was determined that the uncertainty in the heat release rate trace is a maximum of 70kW/m². The uncertainty in the time to ignition and the burn duration were found to be 9s and 101s, respectively. Given these uncertainties, the equation for the propagation of uncertainty¹³ was used to determine that the uncertainty in the b parameter is approximately 0.7 full scale (± 0.35).

Referring to the literature,^{2,6} the flame spread is considered to be accelerating if the b parameter is greater than zero and decelerating otherwise. Beyler et. al. extend this idea to correlate a b parameter based on a test performed at an applied heat flux of 50kW/m² to the probability of flashover. They concluded, based on their data, that a material with a b parameter less than 0.3 is not expected to flashover in a room/corner test. However, materials with a b parameter larger than 0.3 are much more likely to flashover (although there were some outliers in their data set). Beyler et. al. did not publish any uncertainties related to the b parameter in their report.

The b parameter for both the FPA and the Cone Calorimeter tests are given in Table 3 and Table 4. The tests performed at 50kW/m² are highlighted because the correlation from Beyler et. al. is based on tests done at this applied heat flux. Considering those tests done at 50kW/m² in both Table 3 and Table 4, 1A and 1B based on a peak heat release rate in the FPA and 1B based on a peak heat release rate in the Cone are the only composite samples that would be expected to flashover in a room/corner test. The b parameter based on the peak heat release rate is significantly higher than that based on the average heat release rate due to the strong initial peak in the heat release rate for the 1A and 1B samples (see Figure 2).

However, the uncertainty in the b parameter is 0.7 so, in order to truly determine if the b parameter has a chance of obtaining the threshold value of 0.3 for flashover, this uncertainty needs to be added to the value that was obtained from the data. Table 5 represents the maximum possible values of the b parameter based on the data in Table 3 and Table 4. The maximum possible value of the b parameter for each FRP sample was determined by taking the value of the b parameter from Table 3 and Table 4 (the largest value was taken if there were duplicate tests) and adding 0.7.

From the data in Table 5, it can be seen that all of the polyester (System 1) samples have a b parameter larger than 0.3 and thus have the potential to flashover in

the room/corner test based on the Beyler et. al. correlation. 3A displays very negative b parameters, which indicate that the phenolic is not expected to flashover in the room/corner test. Comparing the tests done at 50kW/m², it is apparent that the phenolic has better fire performance than the polyester resin.

For the tests that are not completed at 50kW/m², the Beyler et. al. correlation cannot be reliably used. Therefore, the discussion will be based on other references^{2,6} that correlate a negative b parameter with decelerating flame spread and a positive b parameter with accelerating flame spread. If the maximum possible value of the b parameter is again considered (i.e. the b parameter plus the uncertainty of 0.7), the only samples that are expected to exhibit accelerating flame spread are 1A at 40kW/m² in the FPA, 1B at 30kW/m² in the FPA, 3A at both 70kW/m² and 80kW/m² in the Cone, and 5A and 5B at 100kW/m² in the Cone. This again demonstrates that the phenolics are superior to the polyester resin and that the additives (System 4 with the charring additive and System 5 with the intumescent additive) make the phenolic perform better.

An important observation regarding the b parameter is the significant increase in the b parameter with applied heat flux for the System 1 composites (see Figure 7). Since the uncertainty in the b parameter is 0.7, it can be seen that there is a very significant difference between low and medium heat fluxes but it seems to level off as the applied heat flux increases up to 50kW/m². From Table 3 and Table 4, it can also be seen that the b parameter makes a significant jump (see, for example, the b parameter for 1A in the FPA with applied heat flux) to become more negative just before the minimum heat flux for ignition (30kW/m² for 1A).

Conclusions and Future Work

The work being done in this study is important to the composites industry because it is a beginning to research into how the resin type and the glass content affect the overall fire performance of the composites. The resin type was found to greatly affect the resultant fire performance, however the effect of glass content is a little more subtle. For example, there is a difference in the peak heat release rate with glass content for the System 1 composites (see Figure 2) but there is no significant difference in the average heat release rate in the plateau region of the trace. There is an increase in the time to ignition and a decrease in the burning time with glass content for the System 1 composites (see Figure 2). The minimum heat flux for proper ignition greatly changed with resin type with the polyester resin (System 1) having a significantly lower minimum heat flux for proper ignition range than the phenolic resins and the phenolics with additives (Systems 4 and 5) improving over the performance of the neat phenolic (System 3). Except for

System 1, the minimum heat flux for proper ignition range increased with glass content (see Table 2).

This work is also very important to the fire industry because the industry is leaning toward performance based design in modern building codes. This requires fire engineers to determine whether a room will flashover or not. From the results of the b parameter, it is expected that the FRPs with the polyester resin (System 1) would be expected to flashover in a room/corner test while the phenolics (Systems 3, 4 and 5) are not expected to flashover based on tests done at 50kW/m². Based on the large uncertainty in the b parameter and to verify the results of this study, it would be very interesting to perform large scale room/corner tests with the specimens. It will also be very important to relate the results obtained from the FPA with the results obtained with the Cone since much work has been done with the Cone. A correlation between the two apparatuses will be needed to compare the FPA to past work done with other materials.

In the near future, there are plans to instrument the sample with embedded and surface thermocouples as well as an embedded heat flux gage and an IR thermometer in order to determine additional information such as temperatures at depth and the flame heat flux. This is especially useful information for modelling purposes.

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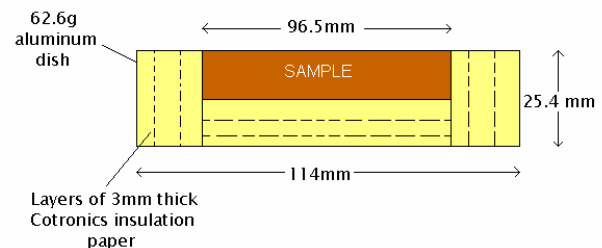


Figure 1: Insulated Sample Holder Designed by de Ris and Khan

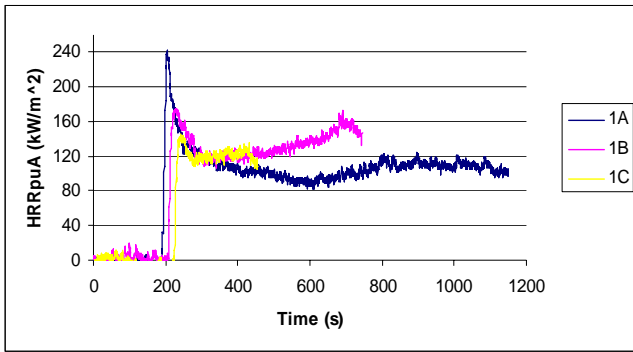


Figure 2: Comparison of the Generic CO₂ Based Heat Release Rate per Unit Area (HRRpuA) for System 1 at an Applied Heat Flux of 50kW/m² in the FPA, Truncated at Loss of Flame Cone

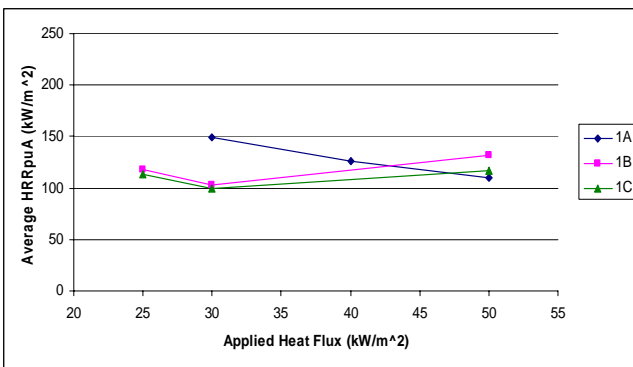


Figure 3: Comparison of Average CO₂ Based Heat Release Rate per Unit Area (HRRpuA) for System 1 over a Range of Applied Heat Flux in the FPA

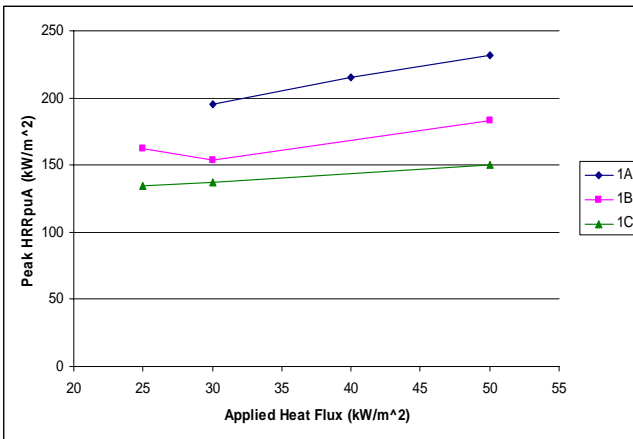


Figure 4: Comparison of Peak CO₂ Based Heat Release Rate per Unit Area (HRRpuA) for System 1 over a Range of Applied Heat Flux in the FPA

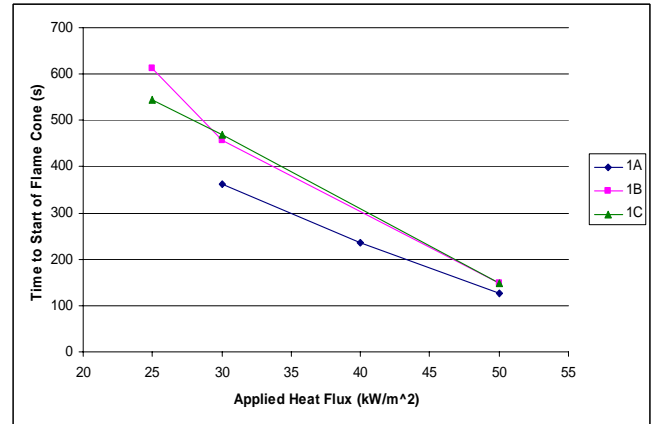


Figure 5: Comparison of Time to Start of Flame Cone for System 1 Composites at a Range of Applied Heat Flux in the FPA

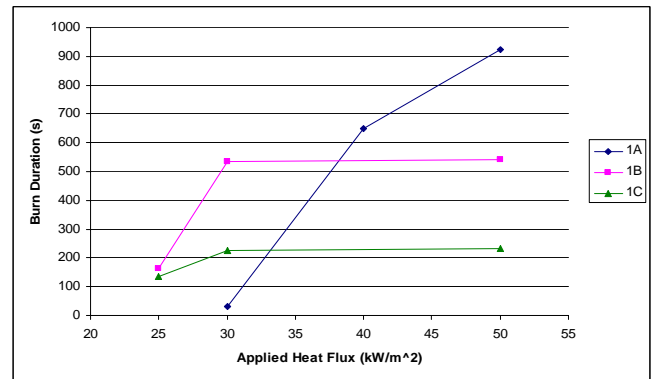


Figure 6: Comparison of Burnout Time for System 1 Composites at a Range of Applied Heat Flux in the FPA

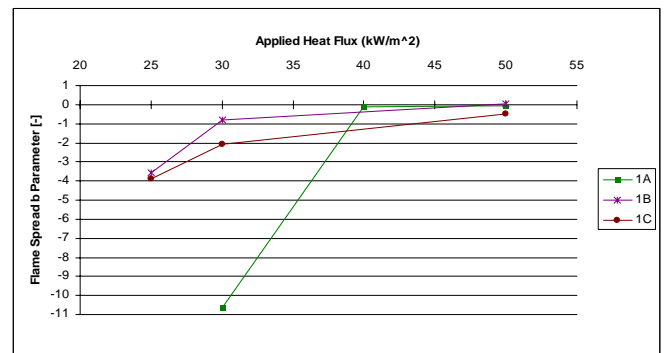


Figure 7: b Parameters Based on Average Values of CO₂ Based Heat Release Rate for System 1 Tests in the FPA⁴

Table 1: Results from FPA Calibration Tests. The accuracy in percent is defined as a deviation of the average value from all of the tests as compared to the published value. The accuracy in kW is the maximum value that the heat release rate trace derived from the ASTM E 2058, Parker and Beaulieu equations deviates from the reference heat release rate trace (the mass loss rate multiplied by the published chemical heat of combustion). All of the reported uncertainties are full scale as opposed to \pm half scale. EHC stands for Effective Heat of Combustion (the cumulative heat release rate divided by the total mass lost). The Phase column represents the phase the material was when it was burnt (G=Gas, L=Liquid, S=Solid).

EHC -- 2058 ⁴ Fuel Specific (CO2 Generation)				
Material	Phase	# Tests	Accuracy (%)	Accuracy (kW)
Propylene	G	6	-1.2	<0.5 *
Methane	G	6	8.6	<0.5 *
Acetone	L	4	7.9	<0.5
PMMA	S	3	-2.9	<0.5
EHC -- Parker ¹⁰ Fuel Specific (O2 Consumption)				
Material	Phase	# Tests	Accuracy (%)	Accuracy (kW)
Propylene	G	6	5	<0.5*
Methane	G	6	11	<1 *
Acetone	L	4	9	<0.5
PMMA	S	3	-1.4	<0.5
EHC -- Beaulieu ⁹ Fuel Specific (CO2 Generation)				
Material	Phase	# Tests	Accuracy (%)	Accuracy (kW)
Propylene	G	6	4.3	<0.5*
Methane	G	6	14.2	<1 *
Acetone	L	4	12.2	<0.5
PMMA	S	3	3.9	<0.5

Table 2: Description of the FRP Composites and the Minimum Heat Flux for Proper Ignition Range for each Composite Sample. The Thickness of the Sample and the Minimum Heat Flux for Proper Ignition are listed as ranges. The Minimum Heat Flux for Proper Ignition was determined in the Cone except for System 1, which was determined in the FPA. %RFG = % Refined Glass Content.

FRP Sample	Resin System	Glass (%RFG)	Thickness (mm)	Min HF (kW/m ²)
1A	Brominated Polyester	33	8.5-10	25-30
1B	Brominated Polyester	46.5	8.0-9.0	20-25
1C	Brominated Polyester	73.3	6	20-25
3A	Neat Resole Phenolic	38	6-9.5	40-50
3C	Neat Resole Phenolic	79.1	7-8	60-65
4A	Resole Phenolic w/ Charring Additive	30	7-8	50-60
4B	Resole Phenolic w/ Charring Additive	38	7.5-8	70-80
4C	Resole Phenolic w/ Charring Additive	48	8.5-10.5	90-100
5A	Resole Phenolic w/ Intumescent Additive	30	6	90-100
5B	Resole Phenolic w/ Intumescent Additive	45	8-9	90-100
5C	Resole Phenolic w/ Intumescent Additive	59	8-9	>100

Table 3: Table of FPA Tests for System 1 and the Corresponding b Parameters Using both the Average and the Peak Heat Release Rate Determined from the Generic CO₂ Based Formula Presented in ASTM E 2058

FRP Sample	Heat Flux (kW/m ²)	Average -- Generic 2058	Peak -- Generic 2058
1A	50	0.0	1.1
1A	50	0.0	1.3
1A	40	-0.1	0.8
1A	30	-10.6	-10.2
1B	50	0.0	0.6
1B	50	0.1	0.5
1B	30	-0.8	-0.3
1B	25	-3.6	-3.1
1C	50	-0.4	0.0
1C	50	-0.5	-0.2
1C	30	-2.1	-1.7
1C	25	-3.9	-3.7

Table 4: Table of Cone Calorimeter Tests and the Corresponding b Parameter Using both the Average and the Peak Heat Release Rate Determined from the Generic O₂ Based Formula Presented in ASTM E 1354

FRP Sample	Heat Flux (kW/m ²)	Average -- Generic 1354	Peak -- Generic 1354
1A	50	-0.7	-0.4
1A	50	-0.3	-0.1
1B	50	0.0	0.4
1C	50	-0.4	-0.2
3A	50	-6.3	-6.2
3A	60	-2.3	-2.1
3A	65	-3.8	-3.6
3A	70	-0.3	0.1
3A	80	-0.3	0.2
3C	65	-2.2	-2.1
3C	70	-1.7	-1.6
3C	80	-1.5	-1.4
4A	60	-4.0	-3.9
4A	65	-2.9	-2.7
4A	70	-2.9	-2.7
4A	80	-0.9	-0.7
4B	80	-1.4	-1.1
4C	100	-4.4	-4.3
5A	100	-0.1	0.1
5B	100	-0.3	0.1

Table 5: Table of Maximum Possible Values of the b Parameter for Tests Performed at 50kW/m² in both the FPA and the Cone. The Maximum Possible Value is Obtained by Taking the Value from Table 3 and Table 4 (the Maximum Value was taken if there were Two Identical Tests) and adding the Maximum Uncertainty in the b Parameter, equal to 0.7. There is no Data for 3A at 50kW/m² in the FPA because this FRP Sample Popped and Delaminated Violently in this apparatus (see discussion in text).

FRP Sample	Avg. -- Generic 2058	Peak -- Generic 2058	Avg. -- Generic 1354	Peak -- Generic 1354
1A	0.7	2.0	0.4	0.6
1B	0.8	1.3	0.7	1.1
1C	0.3	0.7	0.3	0.5
3A	[-]	[-]	-5.6	-5.5

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