NISTIR 7031

Bench-Scale Flammability Measures for Electronic Equipment

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BENCH-SCALE FLAMMABILITY MEASURES FOR ELECTRONIC EQUIPMENT

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Abstract

An experimental study of the bench-scale fire performance of 18 commercial polymeric materials was conducted by the National Institute of Standards and Technology. The performance of these materials was characterized using three standard flammability tests. The ignition resistance, self-extinguishing behavior, heat release rate, and combustion product yields for these burning materials were evaluated at two material thicknesses and are discussed in terms of fire safety. This report details the first of a two part study in which the relationship between bench-scale and full-scale fire performance will be examined. Several of the materials characterized in this report will be selected for use in the full-scale study.

Introduction

An experimental investigation is in progress at NIST to study the fire hazard of electronic equipment housed in thermoplastic enclosures. This work is part of the project titled "Flammability Measures for Electronic Equipment" which is funded by the NIST "Reduced Risk of Flashover" program. It is one of several related projects aimed at studying fire growth and spread on real materials.

Three standardized bench-scale flammability tests were used to characterize a set of commercially available resins. The bench scale flammability tests included the Cone Calorimeter test (ASTM E 1354), the UL94 vertical burn test, and the Glow Wire Ignitability Temperature test (GWIT) (IEC 695-2-1/3).

The objectives of this report are to describe the bench scale tests performed, and to describe the results of the bench scale tests with statistical uncertainties.

The ultimate goal of this project is to determine the accuracy of bench scale material testing in predicting full-scale end product fire performance. One aspect of fire performance that will be addressed is the extent to which the specimen contributes to the propagation of fire from a candle flame to surrounding objects. Another aspect of fire performance that will be addressed is the response of a specimen to an existing fire.

Experimental Materials

The formulations used in this study were chosen based on industry use and flame retardant (FR) approach. Industry experts were consulted in choosing a set of 18 resins which included a variety of resin types, FR levels and FR approaches. Commercial resins were chosen instead of model formulations so that the effects of processing aids and other additives are included in the fire performance results. The compounded formulations were provided by four different resin manufacturers. The 18 different material identification labels used in this study are listed in Table 1. The format of the label is: number - resin type – FR type. The resin types include Acrylonitrile Butadiene Styrene (ABS), High Impact Polystyrene (HIPS), Polycarbonate (PC), Polypropylene (PP), Polyvinyl Chloride (PVC) and a PC/ABS blend. The flame retardant types include

Bromine/Antimony (BFR), Phosphate (PFR), non-halogenated (NH) and no flame retardant (NFR). Material number 16 was not received from the supplier and was omitted from this study.

Table1. List of materials used in bench-scale tests.

1-PC-NH	7-ABS-BFR	13-PP-BFR
2-HIPS-BFR	8-PC/ABS-PFR	14-PP-BFR
3-HIPS-NFR	9-HIPS-BFR	15-PP-NH
4-PC-NFR	10-PC-BFR	17-PVC-NFR
5-PC-BFR	11-PP-BFR	18-HIPS-NH
6-PC/ABS-NFR	12-PP-NH	19-ABS-NH

Bench-Scale Tests

UL94 Vertical Burn Test

The UL94 horizontal and vertical burn tests are the U.S. industry standard flammability tests for selecting materials to be used as enclosures for electronic equipment. The UL94 vertical burn test was used for this study. This test is a measure of a specimen's resistance to self-sustained ignition in an upward flame spread configuration. The test was designed to simulate a short duration ignition source such as an internal electric fault. The test is not designed to predict full scale fire performance.

The test results reported here were obtained by Underwriters Laboratories at the Melville, NY facility.

The ignition source for this test consisted of a 50 W premixed methane-air flame produced by a standard laboratory Bunsen burner (ASTM D5025 Burner @ 105 ml / min. flow rate). The test flame was calibrated according to standard practice (ASTM 5207-98). The test flame was entirely blue in color and approximately 20 mm in height. Prior to each test the specimen was mounted in a vertical position, 30 cm above a piece of loose cotton on the floor of the test chamber.

All UL94 test specimens were injection molded by the supplier. Each specimen had length of 125 ± 5 mm and width of 13 ± 0.5 mm. The thickness of each specimen was 1.6 ± 0.1 mm or 3.2 ± 0.1 mm.

The flame was applied such that the top of the burner barrel was ~10 mm below the lower edge of the sample, as shown in figure 1. The test operator adjusted the position of the flame during the application such that the separation distance was maintained as the specimen receded and or deformed (some of the specimens used in this study tended to curl when heated by the flame). The burner was tilted at a 45 degree angle when necessary to prevent dripping particles from entering the barrel of the burner. The flame was applied for 10 seconds and removed from the specimen. The amount of time that the specimen continues to burn (visible flames) after the removal of the burner flame was recorded as the after-flame time, t_1. If t_1 was less than 30 seconds, the flame was immediately reapplied to the

Figure 1. Standard 50 W UL94 test flame applied to specimen in vertical burn test.

specimen for 10 seconds and removed. The second after-flame time was recorded as t_2. If the after-flame time (t_1 or t_2) reached 35 seconds, the flaming specimen was manually extinguished. If the specimen continued to smolder after it self-extinguished, the afterglow time was recorded as t_3. The afterglow time was zero for all of the tests reported here. Additional footnotes were used to denote whether or not dripping material was observed, and if dripping material ignited the cotton indicator. The standard UL test data sheet includes a record of specimen thickness, width and color. The specimen weight before and after the test and the measured burn length were also recorded for these tests. The burn length was defined as the difference between the original specimen length and post-burn undamaged specimen length.

To attain a UL94 classification each test was repeated five times, per thickness, per conditioning set. The two different sample conditioning requirement sets are defined as follows. The "normally conditioned" set of specimens was conditioned at 23 ± 2 °C and 50 ± 5 % relative humidity for at least 48 hours. The "thermally conditioned" set of specimens was conditioned at 70 ± 1 °C for 168 hours, and then placed in a desiccator with less than 20 % relative humidity for a minimum of 4 hours. The high temperature conditioning is intended to simulate the effects of material aging over the normal lifetime of the material.

The criteria for V-rated classification are listed below. In addition to the requirements listed below, the specimen should not burn up to the holding clamp for a V-0, V-1 or V-2 classification. If the specimen does not satisfy these criteria, it will be described as V-fail or V-not. Although the horizontal burn test was not performed in this study, it can be assumed that the V-not specimens are classified as HB based on product information from the manufacturers.

V-0 classification:

a) The after-flame time, t_1 or t_2, for each individual specimen is less than 10 seconds.
b) The total after-flame time for any condition set ($t_1 + t_2$ for the 5 specimens) is less than 50 seconds.
c) The cotton indicator is not ignited by flaming particles or drops.

V-1 classification:

a) The after-flame time, t_1 or t_2, for each individual specimen is less than 30 seconds.
b) The total after-flame time for any condition set ($t_1 + t_2$ for the 5 specimens) is less than 250 seconds.
c) The cotton indicator is not ignited by flaming particles or drops

V-2 classification:

a) The after-flame time, t_1 or t_2, for each individual specimen is less than 30 seconds.
b) The total after-flame time for any condition set ($t_1 + t_2$ for the 5 specimens) is less than 250 seconds.
c) The cotton indicator is ignited by flaming particles or drops.

Cone Calorimeter Test

Heat release rate per unit area, mass loss, and smoke yield measurements for each of the 18 materials were performed using the Cone Calorimeter at NIST. The total heat release rate of a fire is important because it defines its size and potential hazard. Heat release rate per unit area, as measured in the Cone Calorimeter, has been used successfully for some situations to predict full scale fire growth and behavior.

Heat release calculations were based on the oxygen consumption principle which states that for complete combustion of a wide range of fuels, 13.1 (± 5 %) kJ of energy is produced for every 1 gram of oxygen consumed by the fire. This calculation required the measurement of oxygen concentration and mass flow rate in the exhaust duct. The oxygen was measured using a paramagnetic analyzer and the exhaust mass flow rate was calculated based on measurements from a thermocouple and the pressure differential across an orifice plate located downstream of the gas sampling ring and exhaust blower. The specimen mass loss rate was calculated at each time scan using a five point numerical differentiation of the load cell output. Additional measurements of carbon dioxide, carbon monoxide and smoke in the exhaust duct were performed. These measurements were used in calculating combustion product yields, but not in the heat release rate calculation.

Figure 2. Cone Calorimeter test at 50 kW/m^2 .

The cone specimens were 10 ± 0.1 cm in diameter and 1.6 ± 0.1 mm or 3.2 ± 0.1 mm in thickness. All of the specimens were conditioned at 50 ± 5 % relative humidity and 23 ± 3 °C for a minimum of 48 hours. The cone heater was positioned 25 mm above the horizontal specimens. The cone heater temperature was adjusted to impose the required heat flux at the surface of the specimen. The heat flux calibration was performed using a water cooled Schmidt-Boelter type flux meter with an accuracy of ± 3 %. The specimens were placed in a round aluminum foil pan with a lip of 5 mm above the top surface of the sample. The samples were then placed on a low density ceramic wool lined sample pan and mounted on the load cell in the test chamber as shown in Figure 2. A cone radiation shutter was used to shield the specimen from heat prior to the start of the test. A standard calibration burner (as specified in ASTM E1354) was used to calibrate the heat release rate measurements on each test day using research grade methane (99.5% purity). The description of the apparatus and procedures are in accordance with ASTM E1354 -02d with the exception of using round instead of square specimens.

Glow Wire Ignition Temperature Test

Glow Wire Ignition Temperature tests (in accordance with UL 746A) were performed at Underwriters Laboratories in Melville, NY for 16 of the 18 materials described previously. The test sample size and shape were the same as described for the Cone Calorimeter tests. The specimens were conditioned at 23 ± 2 °C and 50 ± 5 % relative humidity for at least 40 hours.

The “glow wire” ignition source was a 4 mm diameter chrome-nickel alloy coil imbedded with a type-K thermocouple. The temperature of the wire, as measured by the thermocouple, was controlled by adjusting the voltage applied across the length of the wire. The specimen was mounted to a carriage in the vertical position. A pulley and counterweight were used to bring the specimen into contact with the glow wire, such that

the contact force was 1 ± 0.2 N, for a duration of 30 ± 1 s. For each of the specimens considered here the glow wire tip penetrated through the material surface to a depth of 7 mm (through the back side of the specimen). The temperature was set to the desired value, in increments of 25 °C, and maintained within 2 °C for 60 s prior to contact with the specimen.

The **Glow Wire Ignitability Temperature (GWIT)** - in accordance with IEC 695-2-1/3, is defined as the temperature (in degrees C), which is 25 °C hotter than the maximum temperature of the tip of the glow-wire which does not cause ignition of the material during three subsequent tests. Ignition is defined as the appearance of flames on the surface of the specimen for at least 5 s.

The **Glow Wire Flammability Temperature (GWFT)** - in accordance with IEC 695-2-1/2, is defined as the highest temperature (in degrees C) at which, during three subsequent tests, flaming or glowing of the test specimen extinguish within 30 seconds after removal of the glow-wire without ignition of the indicator by burning drops of material.

The maximum glow wire temperature (GWT) is 960 °C. The initial temperature of the glow wire was set to 750 °C for each set of tests. The following two examples demonstrate the search routine used to determine the test results for a particular material. The after-flame time is defined as the time to self-extinguishment after the 30 s glow wire application. Note that in the second example the material self-extinguished at a GWT of 750 °C, however to establish the GWFT the test was conducted at the maximum temperature of 960 °C. Between 5 and 12 specimens were required for each set of tests.

Example of sequence of glow wire temperatures (GWT) for two typical tests:

GWT (°C)	**ignition**	**After-flame time (s)**	
750	no	--	
800	yes	30+	
775	no	--	
775	no	--	
775	no	--	**→ result: GWIT=800 °C, GWFT=775 °C**
750	yes	4	
700	yes	7	
650	no	--	
675	yes	5	
650	no	--	
650	no	--	
650	no	--	**→ result: GWIT=675 °C**
960	yes	8	
960	yes	2	
960	yes	6	**→ result: GWFT=960°C**

Results and Discussion

UL94 vertical flame test

The UL94 testing was performed by one UL technician over a period of several months. In order to obtain a representation of the measurement reproducibility associated with this test the specimen order was randomized. A summary of the UL94 results is listed in table 2. The results summarized in table 2 represent a total of almost 3 hours of total flame application and after-flame burn time for all of the 350 specimens combined.

The flame classification was based on the test results of 10 specimens (5 specimens per conditioning set). For 15 of the 18 materials tested, the flame classification did not change as the specimen thickness increased from 1.6 mm to 3.2 mm, however the average after-flame time was consistently less for the thicker specimens. For all of the materials considered here, the classification can be determined from the maximum after-flame time, and the footnotes. The footnotes apply to each test specimen; therefore multiple footnotes are listed for some materials where the behavior varied within the set of 10 specimens.

The effect of sample conditioning on the total after-flame time is shown in table 2; see total flame times for the two conditioning sets. Although the flammability of several of these materials was affected by conditioning, these results do not show any significant general trends and no classification was affected by conditioning. This was not unexpected, since the effects of thermal aging and water absorption can have competing effects on flammability which can vary with resin type and FR type.

The mean after-flame times and burn lengths for each material and thickness are listed in table 2 and shown with standard uncertainty bars in figures 2 and 3. The uncertainties listed are based on the standard deviation of the ten total measurements for each specimen. These results indicate that a large range of self-extinguishing behavior was observed for these materials. Note that increased sample thickness usually shortened the mean after-flame time and changed the V-rating of some resins. The UL94 test is thickness sensitive since the 10 s flame exposure time leaves a non-uniform temperature profile in the sample depth. Thicker samples then pose more of a heat sink to the nascent flames, making then less likely to self-sustain.

The materials that were classified V-2 ignited the cotton indicator for at least one of the specimens tested. The behavior of the flaming particles from the specimen varied for different materials. Some V-2 specimens (such as 11-PP-BFR) had low viscosity flaming drips that fell at fairly regular intervals. Some other V-2 specimens (such as 4-PC-NFR) had a highly viscous drip of flaming material break off and immediately extinguish the flame. The later of the two behaviors was less repeatable; however, in both cases the melt/drip event had an apparent impact on the extinguishment of the specimen.

Table 2. Summary of Results from UL94 Testing.

Sample Identification	Color	Thickness(mm)	Flame Classification	Max. after-flame time (s)	Total t_1+t_2 (s) 48h-23C	Total t_1+t_2 (s) 168h-70C	Mean total after-flame time (t_1+t_2) (s)	Mean Burn Length (mm)	Footnotes
1-PC-NH	white	1.6	**V-2**	18	73	63	13.6 ± 5.1	44 ± 10	2,4
2-HIPS-BFR	black	1.6	**V-0**	3	4	5	0.9 ± 1.0	38 ± 13	2
3-HIPS-NFR	white	1.6	**V-not**	35	157	175	33.2 ± 5.4	125 ± 3	4
4-PC-NFR	clear	1.6	**V-2**	14	54	85	13.9 ± 6.2	30 ± 5	4
5-PC-BFR	tan	1.6	**V-0**	3	6	4	1 ± 1.1	35 ± 6	2
6-PC/ABS-NFR	black	1.6	**V-not**	35	175	175	35 ± 0.0	104 ± 16	4
7-ABS-BFR	white	1.6	**V0**	3	6	1	0.7 ± 1.1	44 ± 11	2
8-PC/ABS-PFR	white	1.6	**V-2**	15	50	30	8 ± 4.6	60 ± 8	2,4
9-HIPS-BFR	white	1.6	**V-2**	11	59	52	11.1 ± 6.6	43 ± 13	3,4
10-PC-BFR	black	1.6	**V-0**	5	21	10	3.1 ± 1.9	21 ± 6	2,3
11-PP-BFR	white	1.6	**V-2**	0	0	0	0 ± 0.0	19 ± 7	3,4
12-PP-NH	white	1.6	**V-not****	31	59	58	11.7 ± 7.6	34 ± 21	2,3,4
13-PP-BFR	white	1.6	**V-2**	4	13	20	3.3 ± 1.7	24 ± 8	4
14-PP-BFR	white	1.6	**V-2**	16	5	32	3.7 ± 4.9	23 ± 10	4
15-PP-NH	white	1.6	**V-0**	5	8	7	1.5 ± 1.6	25 ± 13	2,3
17-PVC-NFR	black	1.6	**V-0**	4	12	12	2.4 ± 1.2	26 ± 9	2
18-HIPS-NH	black	1.6	**V-1**	27	106	117	22.3 ± 7.7	59 ± 13	2
19-ABS-NH	black	1.6	**V-not****	35	148	79	22.7 ± 10.2	68 ± 7	2
1-PC-NH	white	3.2	**V-0**	2	6	4	1 ± 0.8	19 ± 4	2
2-HIPS-BFR	black	3.2	**V-0**	2	2	1	0.3 ± 0.7	12 ± 3	2
3-HIPS-NFR	white	3.2	**V-not**	35	175	171	34.6 ± 1.3	52 ± 9	4
4-PC-NFR	clear	3.2	**V-2**	15	30	59	8.9 ± 4.1	14 ± 3	4
5-PC-BFR	tan	3.2	**V-0**	2	2	4	0.6 ± 0.8	14 ± 2	2
6-PC/ABS-NFR	black	3.2	**V-not**	35	175	175	35 ± 0.0	45 ± 13	4
7-ABS-BFR	white	3.2	**V-0**	0	0	0	0 ± 0.0	17 ± 4	2
8-PC/ABS-PFR	white	3.2	**------**						
9-HIPS-BFR	white	3.2	**V-2**	11	26	37	6.3 ± 3.8	21 ± 8	2,4
10-PC-BFR	black	3.2	**V-0**	2	8	7	1.5 ± 0.5	14 ± 6	2
11-PP-BFR	white	3.2	**V-2**	0	0	0	0 ± 0.0	14 ± 8	3,4
12-PP-NH	white	3.2	**V-0**	3	1	3	0.4 ± 1.0	9 ± 5	2
13-PP-BFR	white	3.2	**V-2**	22	52	29	8.1 ± 6.9	19 ± 4	3,4
14-PP-BFR	white	3.2	**V-2**	7	18	11	2.9 ± 2.2	19 ± 4	4
15-PP-NH	white	3.2	**V-0**	0	0	0	0 ± 0.0	9 ± 3	2
17-PVC-NFR	black	3.2	**V-0**	2	6	3	0.9 ± 0.9	17 ± 4	2
18-HIPS-NH	black	3.2	**V-1**	27	100	98	19.8 ± 9.1	23 ± 7	2
19-ABS-NH	black	3.2	**V-1**	20	57	63	12 ± 6.6	32 ± 5	2

** Only 1 of the ten specimens failed V-classification

footnotes:

(2) Specimen did not drip

(3) Specimen dripped particles which did not ignite cotton

(4) Specimen dripped particles which ignited cotton

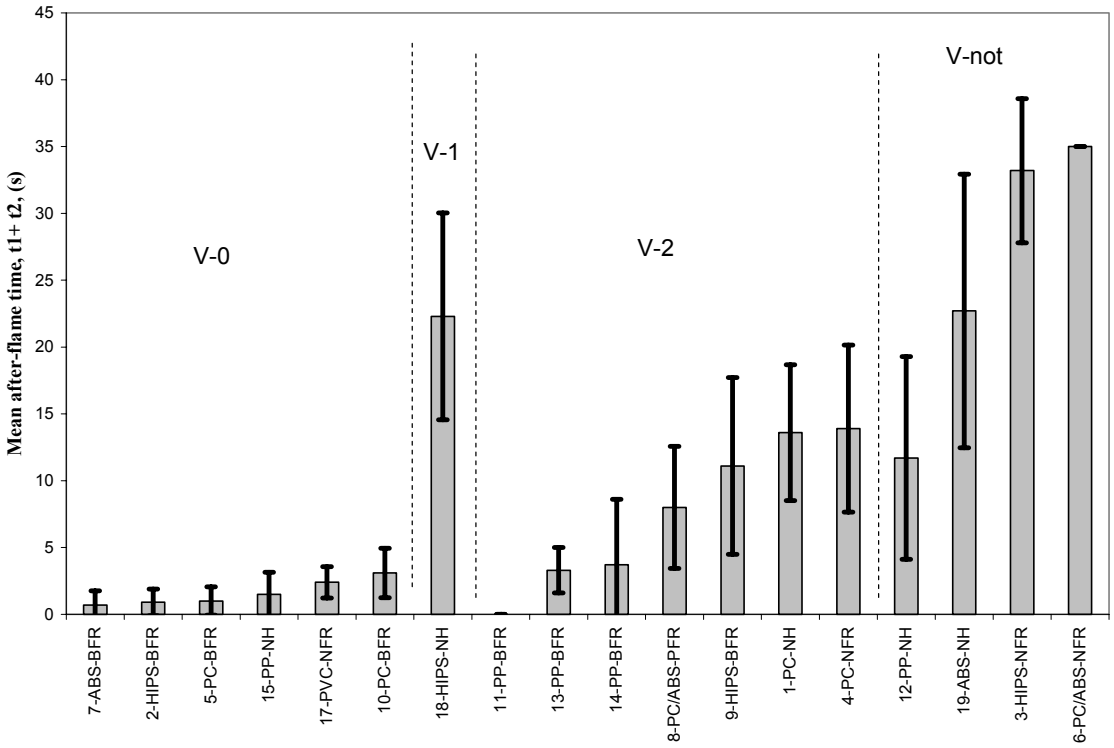

Figure 3. UL94 mean after-flame times for 1.6 mm specimens.

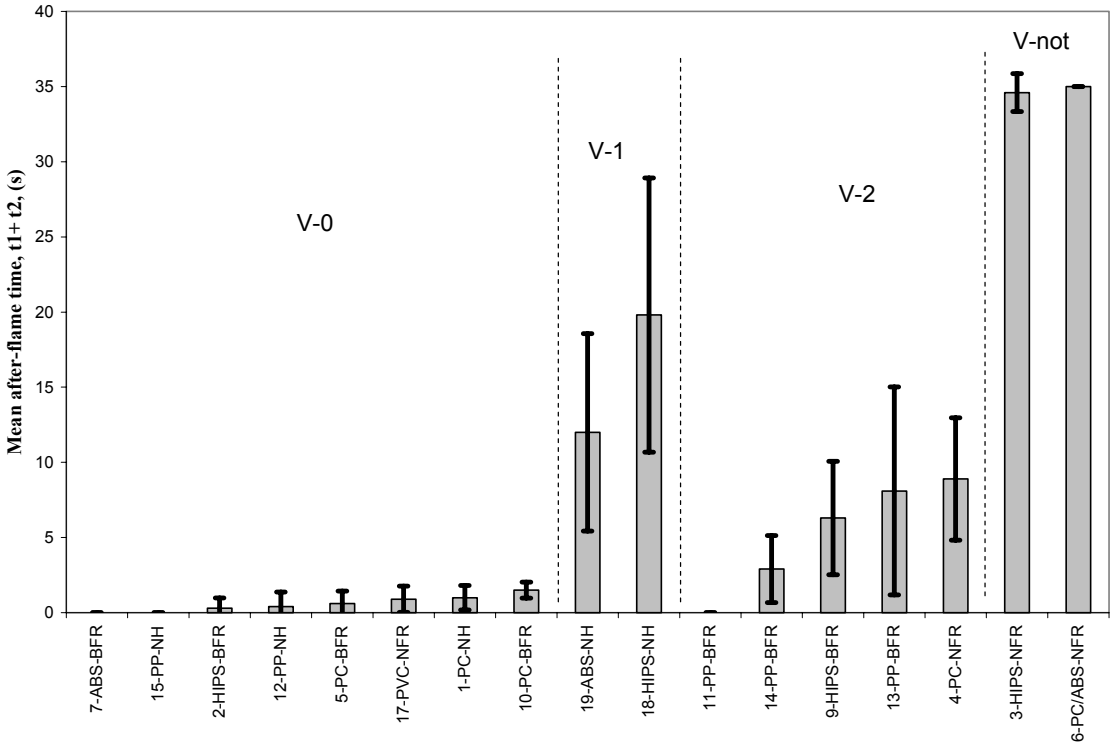

Figure 4. UL94 mean after-flame times for 3.2 mm specimens.

Cone Calorimeter

The results from Cone Calorimeter measurements for material 3-HIPS-NFR at a cone heat flux level of 50 kW/m^2 are shown in figures 5 and 6. These data were acquired at 3 second intervals, with time zero equal to the opening of the cone shutter. The heat release rate and mass loss rate profiles shown in figure 5 are represented per unit surface area of the specimen, A_s=0.00785 m^2. The smoke extinction coefficient, k (1/m), was calculated by measuring the transmission of visible light in the exhaust duct, $k = \ln(I / I_o) /L$. The CO and CO_2 yields shown in figure 6 represent the mass of combustion product species per unit mass of fuel consumed.

A summary of the Cone results at an external heat flux of 50 kW/m^2 is listed in table 3a. Each of the values in Table 3a represents an average of three replicate measurements. The type A standard uncertainty listed for each of the values represents the statistical measurement repeatability. In addition, the type B uncertainties are given for the peak heat release rates. These values were calculated using the results of a ASTM/ISO study that described the lab to lab reproducibility of the peak heat release rate as, $R = 60.4 + 0.141\, \dot{q}''_{\max}$, using a linear regression model and results from a set of inter-laboratory trials. For three of the materials considered here the peak heat release rate was greater than 1500 kW/m^2 (or ~12 kW). The flame height above this heat release rate level can exceed the height of the exhaust hood and the accuracy of these measurements is not well characterized. For these 3 materials the total time above this threshold was less than 20% of the total test time. It should be noted that these results represent a forced flaming scenario and are not representative of heat release for a material in a free-burning scenario. The UL94 test is more akin to a single item free burning scenario.

The values in table 3b represent the products of combustion per mass of specimen consumed. The mean effective heat of combustion is defined as the total heat release divided by the total specimen mass. To compare the amount of smoke generated by different burning materials it is useful to define an average specific extinction area, $\sigma_f = k\, V / m_f$, where k is the average extinction coefficient, V is the total exhaust volume and m_f is the total mass loss of the specimen. A specific extinction area can also be defined in terms of the mass of the smoke particulate, σ_s. It has been observed (Mulholland and Croarkin, 2000) that for a wide range of materials, within a 95% confidence level, $\sigma_s = 8.7 \pm 1.1$ m^2/g. Therefore, the smoke yield can be determined by, $Y_s = \sigma_f / \sigma_s$.

A comparison of peak heat release rate, at 50 kW/m^2 irradiance, and UL94 mean after-flame time is shown graphically for all 18 materials in figure 7. It is evident from this plot that a strong correlation between these two measurements does not exist. Several V2 rated materials exhibited a very large heat release rate ($HRR_{peak,50} > 1500$ kW/m^2) and a short after-flame time in the UL94 test ($t_1+t_{2,max} < 10$ s). This suggests that mass loss in the UL94 vertical flame test due to melting can be an important mechanism for flame extinguishment (and it has no counterpart in a horizontal Cone test). Conversely several materials with relatively low heat release rate ($HRR_{peak,50} < 500$ kW/m^2) performed poorly in the UL94 test ($t_1+t_{2,max} > 30$ s).

Additional Cone measurements were performed at heat flux levels of 30, 50 and 90 kW/m^2 using the 3.2 mm thick specimens. The results of these tests for all 18 materials are summarized in table 4. Each of these values represents a single measurement. Note that, because the heat release rate dependence on heat flux differs

among the resins, the relative rankings of the resins by heat release rate can change with flux level.

A steady state energy balance at the surface of the fuel can be used to predict the functional relationship between external heat flux, $\dot{q}''_{ext}$, and heat release rate, HRR, of the material. In the following equation $\dot{q}''_{flame}$ is the surface heat flux from the flame, $\dot{q}''_{rad}$ is the net radiative heat flux at the surface, $\dot{m}''_f$ is the fuel mass loss rate, L_g is the heat of gasification and $\Delta h_{c.eff}$ is the effective heat of combustion.

$$\dot{q}''_{net} = \dot{q}''_{ext} + \dot{q}''_{flame} - \dot{q}''_{rad} = \dot{m}''_f \cdot L_g \quad , \quad HRR = \dot{m}''_f \cdot \Delta h_{c.eff}$$

$$HRR = \frac{\Delta h_{c.eff} \cdot \dot{q}''_{net}}{L_g} = \frac{\Delta h_{c.eff}}{L_g} \cdot \dot{q}''_{ext} + HRR_0 \qquad (1)$$

Although several simplifying assumptions were made in this analysis, the result can be used as a first order predictor of heat release rate as the external heat flux goes to zero. The unforced peak heat release rate, HRR_0, for each material is plotted in figure 8, and grouped by UL94 classification.

Note that many of these resins may not burn at all as the external heat flux is reduced to small values. HRR_0 is the intercept of a plot made in accord with eqn. (1). HRR_0 contains the difference between the flame heat flux and the surface re-radiation and, as such, can be viewed as a measure of the net driving force that the flame provides. Figure 8 suggests that HRR_0 may correlate somewhat better with UL94 rating than does peak HRR at one specific flux (i.e. 50 kW/m^2).

The error bars in figure 8 represent the standard error associated with the three point linear regression analysis of the data. There are several possible reasons why a linear relationship between $\dot{q}''_{ext}$ and HRR may not be observed, including measurement uncertainty and unsteady burning. In addition, the assumption of a constant $\dot{q}''_{flame}$ and $\Delta h_{c,eff}$ may not be valid.

An unsteady heat transfer analysis of thermally thick fuels heated by a constant surface heat flux yields the following well-known relationship between ignition delay time, t_{ign}, and incident heat flux, $\dot{q}''_{ext}$. T_{ign} is the surface ignition temperature, Ta is the ambient temperature (and initial fuel temperature), and kρc is a term which contains material properties of the solid fuel and is sometimes called the "thermal inertia" or "thermal response parameter". The minimum heat flux for ignition is $\dot{q}''_{critical}$.

$$t_{ign} = \frac{4}{\pi} \frac{k\rho c}{\left[\dot{q}''_{ext} - \dot{q}''_{critical} \right]^2} \qquad (2)$$

The main assumption in this expression is that the material is thermally thick. By definition, thermally thick means the heat transfer to the solid is independent of sample thickness and thermally thin means that the temperature is uniform within the solid. Most of the specimens considered here are somewhere in between these two limiting cases. Equation (2) can be rewritten to show a linear relationship between $\sqrt{1/t_{ign}}$ and $\dot{q}''_{ext}$. A three point linear regression analysis was used to predict the external heat flux for sustained ignition at an arbitrary fixed time of 300 s. The results of this analysis are

given in table 4 and plotted in figure 9 with uncertainty bars representing the combined standard uncertainty based on a propagation of error analysis. Of all the materials considered here the 4 polycarbonate resins had the highest ignition resistance as defined in this manner. Specimen 12-PP-NH exhibited the shortest ignition delay time at 30 kW/m^2. The calculated heat flux of 1.2 kW/m^2 for ignition at 300 s is not physically realistic for this material, possibly because the assumption of infinite thickness may break down at very low external heat flux levels.

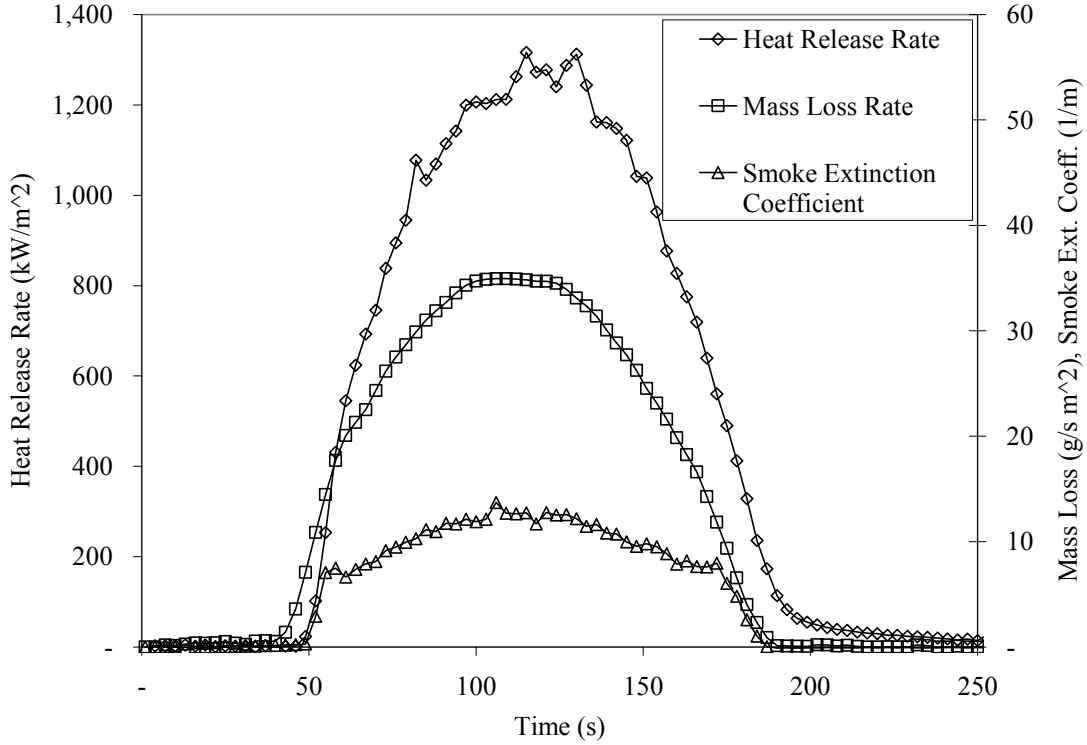

Figure 5. Cone Calorimeter measurements for material 3-HIPS-NFR, 3.2 mm thickness. Cone heater flux = 50 kW/m^2.

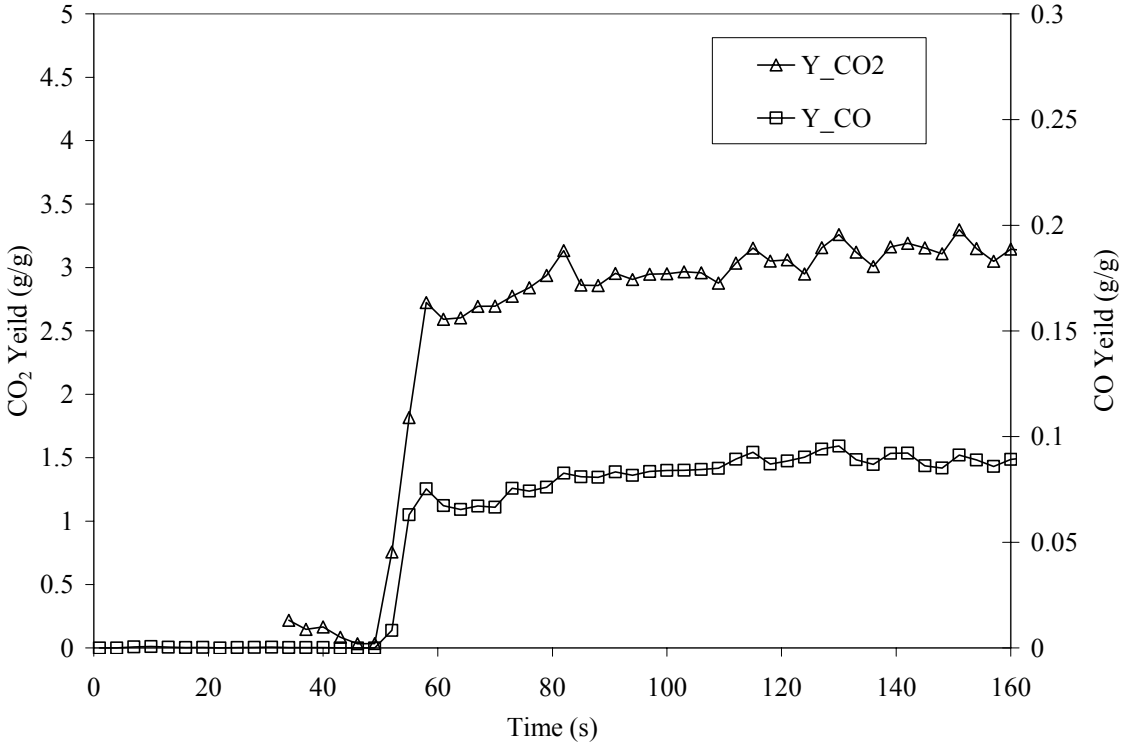

Figure 6. Cone Calorimeter measurements for material 3-HIPS-NFR, 3.2 mm thickness. Cone heater flux = 50 kW/m^2.

Table 3a. Summary of results from Cone Calorimeter tests at 50kW/m^2 flux level.

Sample Identification	color	Thickness (mm)	Peak Heat Release Rate (kW/m^2)	Std. Uncertainty (type A)	Std. Uncertainty (type B)	Total Heat Release (MJ/m^2)	Std. Uncertainty (type A)	Time to Ignition(s)	Std. Uncertainty (type A)	Time to Peak HRR (s)	Std. Uncertainty (type A)
1-PC-NH	white	1.6	**829**	17	177	**38.8**	1.0	**46**	2.5	**70**	0
2-HIPS-BFR	black	1.6	**318**	41	105	**23.8**	0.4	**33**	8.8	**90**	10
3-HIPS-NFR	white	1.6	**723**	15	162	**59.5**	0.7	**30**	8.2	**103**	10
4-PC-NFR	clear	1.6	**885**	33	185	**37.5**	0.9	**77**	4.8	**96**	2
5-PC-BFR	tan	1.6	**378**	21	114	**35.2**	1.6	**51**	11.5	**79**	13
6-PC/ABS-NFR	black	1.6	**543**	34	137	**44.4**	1.7	**34**	3.0	**67**	5
7-ABS-BFR	white	1.6	**312**	6	104	**21.0**	1.2	**42**	7.4	**80**	11
8-PC/ABS-PFR	white	1.6	**388**	47	115	**35.0**	2.3	**45**	1.0	**88**	5
9-HIPS-BFR	white	1.6	**502**	94	131	**33.8**	1.0	**41**	10.3	**97**	3
10-PC-BFR	black	1.6	**280**	20	100	**45.9**	1.5	**39**	2.8	**185**	21
11-PP-BFR^{++}	white	1.6	**1833**	142	319	**60.3**	3.5	**37**	1.3	**87**	3
12-PP-NH	white	1.6	**320**	25	105	**67.0**	11.4	**16**	1.9	**85**	3
13-PP-BFR^{++}	white	1.6	**1663**	219	295	**73.5**	5.6	**33**	1.8	**91**	10
14-PP-BFR^{++}	white	1.6	**2190**	430	369	**69.8**	3.6	**34**	2.8	**79**	3
15-PP-NH	white	1.6	**583**	40	143	**28.9**	1.2	**32**	0.9	**63**	6
17-PVC-NFR	black	1.6	**206**	19	89	**31.2**	1.0	**28**	0.1	**36**	3
18-HIPS-NH	black	1.6	**313**	24	105	**42.2**	0.3	**34**	4.0	**83**	9
19-ABS-NH	black	1.6	**282**	11	100	**37.6**	0.8	**28**	1.0	**78**	7
1-PC-NH	white	3.2	**586**	43	143	**82.3**	2.7	**63**	7.9	**133**	52
2-HIPS-BFR	black	3.2	**428**	58	121	**42.2**	2.1	**33**	0.9	**85**	3
3-HIPS-NFR	white	3.2	**1307**	17	245	**122.3**	1.5	**40**	6.8	**113**	3
4-PC-NFR	clear	3.2	**628**	53	149	**72.8**	2.7	**101**	7.2	**145**	3
5-PC-BFR	tan	3.2	**350**	41	110	**73.4**	3.2	**62**	1.5	**109**	8
6-PC/ABS-NFR	black	3.2	**741**	38	165	**87.5**	3.3	**42**	2.7	**81**	3
7-ABS-BFR	white	3.2	**409**	22	118	**40.4**	0.9	**42**	4.5	**115**	29
8-PC/ABS-PFR	white	3.2	**524**	86	134	**69.4**	2.4	**52**	2.1	**96**	2
9-HIPS-BFR	white	3.2	**985**	124	199	**62.0**	2.2	**46**	5.1	**127**	14
10-PC-BFR	black	3.2	**301**	17	103	**77.5**	4.8	**47**	4.7	**368**	15
11-PP-BFR^{++}	white	3.2	**2255**	252	378	**121.6**	0.3	**47**	6.5	**147**	12
12-PP-NH	white	3.2	**364**	17	112	**125.1**	2.2	**19**	2.1	**261**	15
13-PP-BFR^{++}	white	3.2	**1916**	178	331	**129.9**	3.6	**38**	3.7	**138**	11
14-PP-BFR^{++}	white	3.2	**2209**	403	372	**130.4**	15.8	**33**	1.5	**128**	12
15-PP-NH	white	3.2	**422**	12	120	**60.0**	1.2	**43**	0.5	**69**	3
17-PVC-NFR	black	3.2	**223**	12	92	**48.8**	2.3	**25**	1.9	**35**	6
18-HIPS-NH	black	3.2	**398**	13	117	**67.5**	1.1	**30**	0.6	**87**	10
19-ABS-NH	black	3.2	**328**	18	107	**67.7**	1.4	**33**	3.2	**49**	4

$^{++}$ HRR_{peak} > 12 kW (1540 kW/m^2), above calibrated range of calorimeter.

Table 3b. Summary of results from Cone Calorimeter tests at 50kW/m^2 flux level

Sample Identification	color	Thickness (mm)	Mean Effective Heat of Combustion (kJ/g)	Std. Uncertainty (type A)	Mean Specific Extinction Area (m^2/kg)	Std. Uncertainty (type A)	Mean CO_2 Yield (g/g)	Std. Uncertainty (type A)	Mean CO yield (g/g)	Std. Uncertainty (type A)
1-PC-NH	white	1.6	**23.6**	0.6	**1072.0**	64.6	**2.19**	0.08	**0.06**	0.003
2-HIPS-BFR	black	1.6	**12.3**	0.2	**2624.0**	210.5	**0.59**	0.03	**0.15**	0.008
3-HIPS-NFR	white	1.6	**33.9**	0.6	**1578.2**	123.4	**2.63**	0.08	**0.07**	0.001
4-PC-NFR	clear	1.6	**24.0**	0.7	**1043.0**	86.2	**2.28**	0.08	**0.06**	0.003
5-PC-BFR	tan	1.6	**22.3**	2.2	**1416.0**	146.8	**1.88**	0.12	**0.08**	0.001
6-PC/ABS-NFR	black	1.6	**29.7**	4.9	**1385.8**	247.6	**2.24**	0.08	**0.05**	0.005
7-ABS-BFR	white	1.6	**13.9**	4.2	**2924.5**	850.2	**0.50**	0.10	**0.13**	0.008
8-PC/ABS-PFR	white	1.6	**20.6**	1.4	**1433.2**	108.7	**1.75**	0.07	**0.09**	0.003
9-HIPS-BFR	white	1.6	**16.4**	1.8	**2518.7**	342.5	**0.93**	0.09	**0.13**	0.015
10-PC-BFR	black	1.6	**21.2**	1.0	**1103.4**	128.8	**1.88**	0.10	**0.06**	0.004
11-PP-BFR	white	1.6	**41.0**	3.0	**1027.4**	148.5	**2.30**	0.06	**0.15**	0.012
12-PP-NH	white	1.6	**41.7**	7.2	**716.0**	30.8	**2.63**	0.10	**0.05**	0.011
13-PP-BFR	white	1.6	**65.3**	11.4	**1195.2**	233.9	**2.98**	0.12	**0.09**	0.006
14-PP-BFR	white	1.6	**43.1**	1.2	**833.8**	5.3	**2.80**	0.16	**0.12**	0.008
15-PP-NH	white	1.6	**15.3**	0.1	**1396.9**	47.4	**0.62**	0.02	**0.15**	0.005
17-PVC-NFR	black	1.6	**13.1**	0.3	**960.3**	13.0	**0.84**	0.07	**0.07**	0.002
18-HIPS-NH	black	1.6	**22.3**	0.3	**1715.6**	205.3	**1.55**	0.03	**0.10**	0.002
19-ABS-NH	black	1.6	**21.0**	0.4	**1931.1**	75.5	**1.37**	0.05	**0.13**	0.000
1-PC-NH	white	3.2	**24.0**	0.9	**1100.4**	146.2	**2.21**	0.07	**0.06**	0.002
2-HIPS-BFR	black	3.2	**11.4**	0.6	**2434.1**	139.5	**0.56**	0.02	**0.13**	0.007
3-HIPS-NFR	white	3.2	**36.3**	1.0	**1408.7**	70.3	**2.94**	0.07	**0.08**	0.001
4-PC-NFR	clear	3.2	**22.4**	0.9	**1049.5**	94.5	**2.08**	0.08	**0.05**	0.003
5-PC-BFR	tan	3.2	**21.9**	1.0	**1217.0**	66.0	**2.00**	0.10	**0.07**	0.005
6-PC/ABS-NFR	black	3.2	**27.2**	0.7	**1163.5**	94.8	**2.22**	0.13	**0.05**	0.004
7-ABS-BFR	white	3.2	**11.2**	0.3	**2415.5**	141.7	**0.53**	0.03	**0.13**	0.005
8-PC/ABS-PFR	white	3.2	**21.7**	0.6	**1484.6**	127.8	**1.87**	0.05	**0.09**	0.003
9-HIPS-BFR	white	3.2	**18.6**	1.1	**2036.9**	202.0	**1.03**	0.02	**0.14**	0.006
10-PC-BFR	black	3.2	**22.6**	1.3	**1005.9**	132.8	**2.05**	0.10	**0.06**	0.003
11-PP-BFR	white	3.2	**38.1**	1.2	**998.9**	31.4	**2.20**	0.10	**0.16**	0.011
12-PP-NH	white	3.2	**40.0**	0.9	**653.9**	40.8	**2.82**	0.08	**0.05**	0.008
13-PP-BFR	white	3.2	**47.7**	6.4	**857.8**	85.5	**2.99**	0.19	**0.08**	0.004
14-PP-BFR	white	3.2	**43.6**	4.4	**886.3**	93.7	**2.67**	0.07	**0.13**	0.009
15-PP-NH	white	3.2	**16.6**	0.3	**1625.1**	84.0	**0.66**	0.02	**0.15**	0.002
17-PVC-NFR	black	3.2	**14.0**	0.6	**974.3**	49.8	**0.92**	0.03	**0.08**	0.010
18-HIPS-NH	black	3.2	**21.5**	0.5	**1821.3**	86.7	**1.47**	0.04	**0.10**	0.001
19-ABS-NH	black	3.2	**22.2**	0.3	**1965.4**	45.3	**1.46**	0.03	**0.13**	0.003

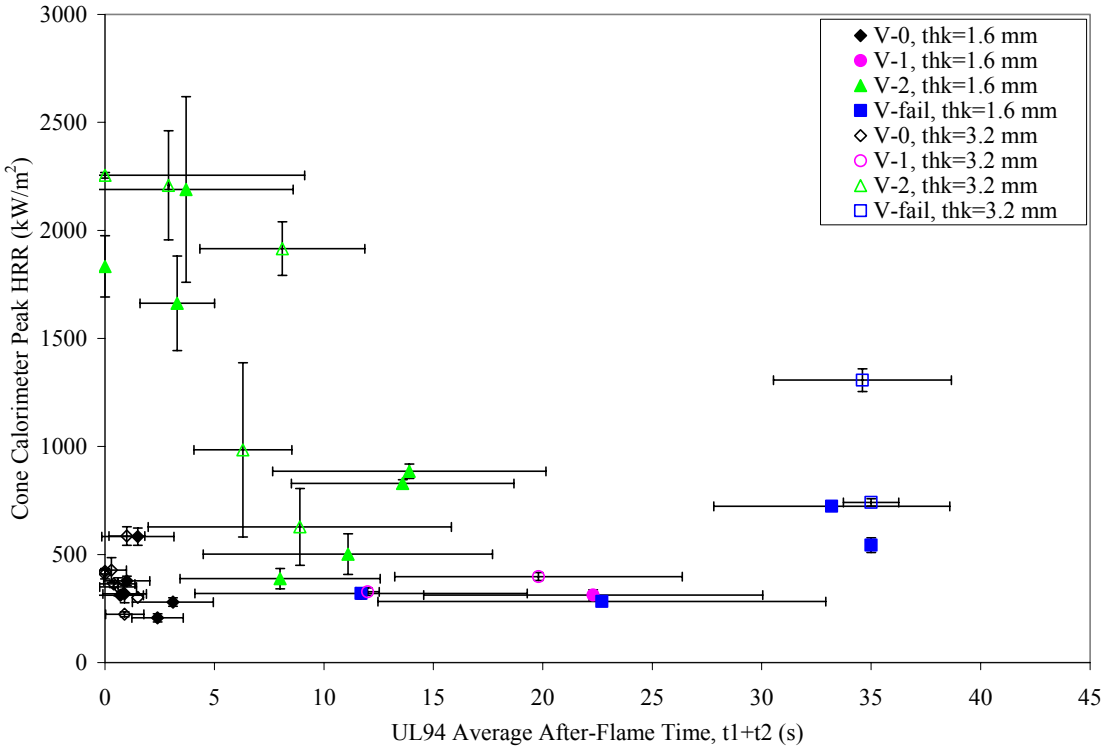

Figure 7. Comparison of peak heat release rate at 50 kW/m^2 irradiance and UL94 after-flame time.

Table 4. Summary of results from Cone Calorimeter, 3.2 mm thick specimens.

Sample Identification	Peak Heat Release Rate (kW/m^2)			60 s Average Heat Release Rate (kW/m^2)			Time To Sustained Ignition (s)			Heat Flux for 300 s Sustained Ignition (kW/m^2)
Irradiation (kW/m^2)	30	50	90	30	50	90	30	50	90	
1-PC-NH	576	531	532	333	385	388	193	67	17	26.0
2-HIPS-BFR	304	461	566	162	283	388	87	31	9	17.2
3-HIPS-NFR	1108	1265	1623	739	734	1051	151	50	16	21.0
4-PC-NFR	734	703	984	494	523	644	500	129	40	35.7
5-PC-BFR	321	343	437	168	240	311	260	78	24	27.5
6-PC/ABS-NFR	850	790	762	506	530	530	137	56	21	16.6
7-ABS-BFR	459	395	515	221	268	411	126	50	17	17.4
8-PC/ABS-PFR	428	567	611	212	322	361	154	53	23	16.1
9-HIPS-BFR	930	760	827	349	376	562	136	44	17	17.0
10-PC-BFR	225	214	258	10	124	219	461	72	16	32.9
11-PP-BFR	1650	2090	2391	747	662	1136	221	62	20	25.0
12-PP-NH	265	337	392	30	101	214	50	25	10	1.2
13-PP-BFR	1689	2206	2529	382	727	1169	124	46	12	21.5
14-PP-BFR	1677	2200	2581	348	219	1025	110	35	16	11.2
15-PP-NH	380	487	530	256	361	371	140	48	19	16.6
17-PVC-NFR	179	243	305	127	176	231	103	23	11	11.8
18-HIPS-NH	391	445	639	284	378	463	98	30	9	18.3
19-ABS-NH	290	293	454	188	243	319	99	36	11	17.4

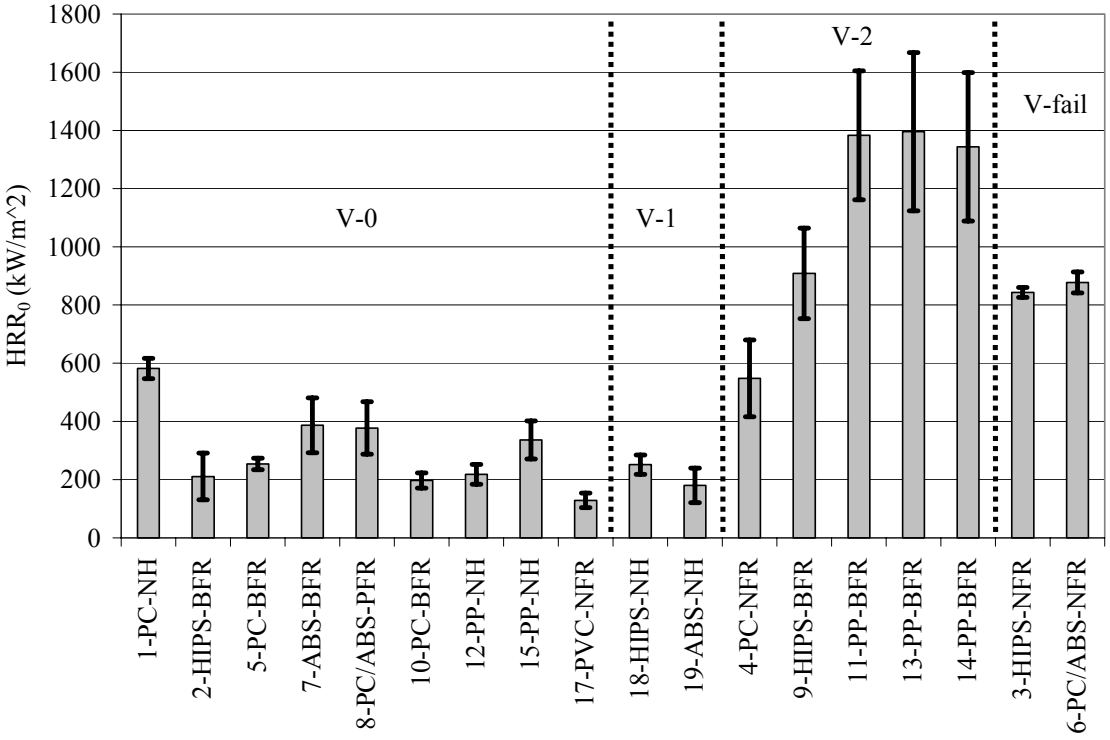

Figure 8. Cone calorimeter unforced, zero flux, peak heat release rate from the intercept of the plot of peak HRR vs. incident flux (see equation 1).

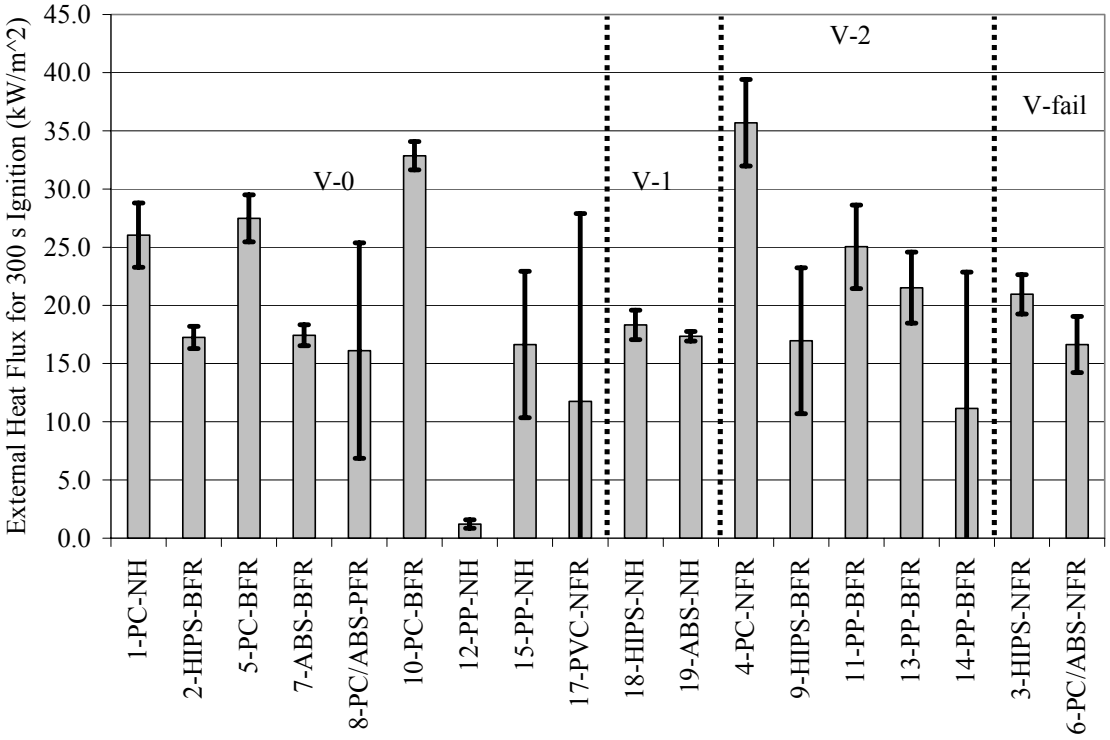

Figure 9. Cone calorimeter critical external heat flux for sustained ignition at 300 seconds.

Glow Wire Ignition Temperature Test

Ignition resistance to a hot wire was characterized for 16 of the 18 materials in this study. The results of the glow wire ignition temperature (GWIT) tests and the glow wire flammability temperature (GWFT) tests are summarized in Table 5. There does not appear to be a consistent effect of thickness on the GWIT; values go both up and down with increased thickness depending on the resin.

A GWFT of less than 960 ^{o}C indicates the specimen did not self extinguish within 30 seconds. Two of the 1.6 mm thick specimens, 4-PC-NFR and 9-HIPS-BFR, were classified as V-2 in the UL94 vertical flame test, and did not self-extinguish in this test. The self extinguishing nature of all the V-0 specimens was confirmed by the GWFT results.

Figure 10 shows a comparison of GWIT and external heat flux for 300 s ignition for the 3.2 mm specimens. With the exception of two materials, (12-PP-NH and 17-PVC-NFR), there is a reasonably good correlation between the ignition resistance measured using the cone and using the glow wire apparatus.

Table 5. Summary of results from Glow Wire Ignition Temperature Testing.

Sample Identification	Color	Glow Wire Ignition Temperature (°C) 1.6 mm	Glow Wire Ignition Temperature (°C) 3.2 mm	Glow Wire Flammability Temperature (°C) 1.6 mm	Glow Wire Flammability Temperature (°C) 3.2 mm
1-PC-NH	white	800	825	960	960
2-HIPS-BFR	black	650	675	960	960
3-HIPS-NFR	white	700	750	675	725
4-PC-NFR	clear	900	850	900	960
5-PC-BFR	tan	900	825	960	960
6-PC/ABS-NFR	black	800	725	775	700
7-ABS-BFR	white	700	750	960	960
8-PC/ABS-PFR	white	725	725	960	960
9-HIPS-BFR	white	700	650	875	960
10-PC-BFR	black	850	875	960	960
11-PP-BFR	white	800	725	960	960
12-PP-NH	white	700	750	960	960
13-PP-BFR	white	800	800	960	960
14-PP-BFR	white	700	650	960	960
15-PP-NH	white	750	650	960	960
17-PVC-NFR	black	875	900	960	960

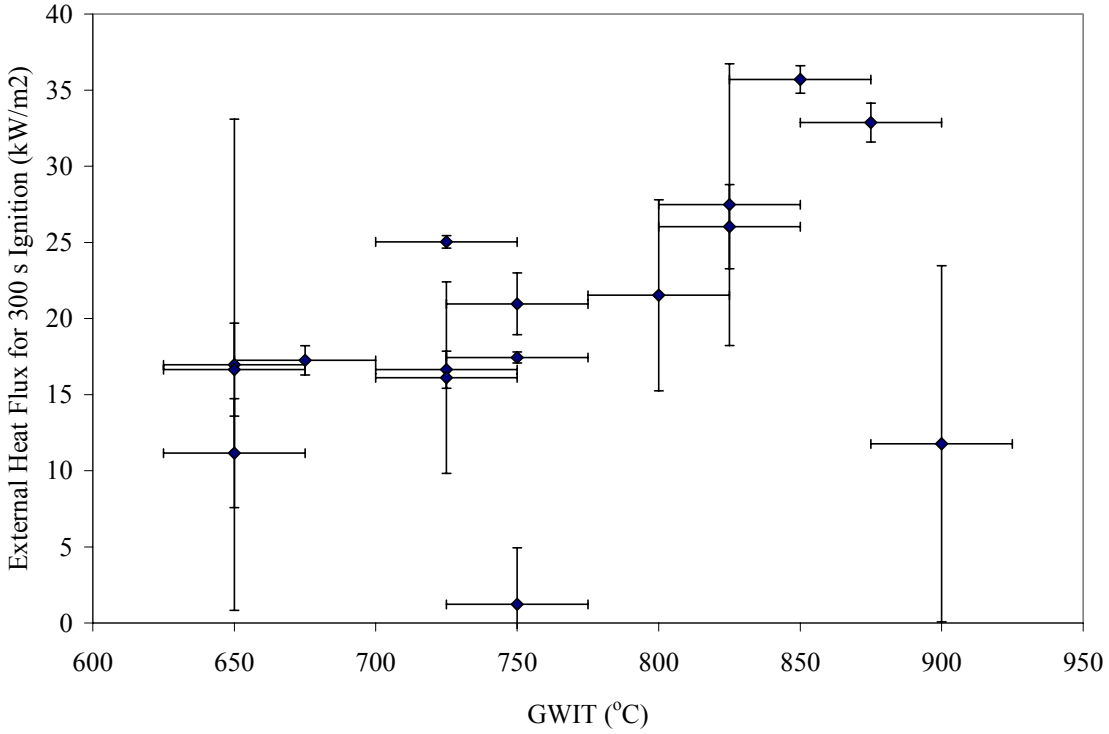

Figure 10. Comparison of glow wire ignition temperature and Cone ignition heat flux for 16 of the materials at a thickness of 3.2mm.

Conclusions

The materials considered in this study exhibited a wide range of performance in three standard bench-scale flammability tests. The ignitability, upward flame spread resistance, heat release characteristics and product yields were characterized for these materials in several well-defined configurations. Although a detailed study of full-scale performance of these materials is not available at this time, it is likely that both UL94 performance and the rate of heat release measurements are necessary to predict how these materials can be expected to react in a real fire hazard scenario. Each of these standard tests are fundamentally very different and therefore strong correlations between them were not expected; however some generalizations were observed. The unforced peak heat release rate, HRR_0, was lower for V-0 and V-1 materials than that for HB and V-2 materials (see figure 8). On average, materials that exhibited a longer ignition delay time (or higher critical heat flux for ignition) in the Cone Calorimeter had a higher glow wire ignition temperature (see figure 10). The effects of melting and material thickness on flammability performance in these tests were not consistent and these effects should be reconsidered when determining fire hazard.