FIRE PERFORMANCE OF FLAME RETARDED POLYMERS USED IN CONSUMER ELECTRONICS

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ABSTRACT

An experimental study was performed to compare the bench-scale and full-scale fire performance of commercial polymeric materials used in electronic equipment. The ignition resistance, self-extinguishing behavior, heat release rate (HRR), and combustion product yields of 18 different materials at two thicknesses were characterized using three standard bench-scale fire tests. Five of the 18 materials were molded into 19" computer monitors for full-scale fire testing (using real and simulated internal components). The results of this study were used to assess the predictive value of the bench-scale tests in determining full-scale fire performance and to describe the fire hazard of the full-scale specimens when exposed to three different ignition scenarios. A UL94 HB rated monitor enclosure was easily ignited using a (38 ± 2) W needle flame and resulted in a peak HRR of (200 ± 25) kW. The ignition threat distance (determined using the measured radiant heat flux distribution) for this fire was found to be (58 ± 15) cm for piloted ignition of a stack of paper and (112 ± 28) cm for ignition of insulated cotton fabric. The (23 ± 3) kW fire resulting from ignition of a keyboard was used as a more severe ignition source for the monitor housings. Tests were also performed using a radiant heat panel to simulate an existing burning item. All of the monitor specimens achieved ignition and at least partial burn-up from the larger ignition sources. The full-scale test results were examined to determine the degree of correlation with the bench-scale results. The UL94 vertical burn test showed good agreement with the needle flame ignition results and the bench-scale peak HRR showed some qualitative agreement with the keyboard fire and radiant panel full-scale results. All of the resins exhibited complex physical behavior when burning (i.e. melting and charring) which made comparison with small scale tests more difficult.

INTRODUCTION

Although fires originating from consumer electronics are rare, the hazard presented when exposed to a small external ignition source (such as a candle) is not well known. Even when the equipment is not the first item involved in a fire, its contribution to the total fire load and impact on flashover of a room can be significant. Both of these issues are important due to an increasing number of both candles and electronics in the home. It should also be noted that in recent years the number of television fires has increased in many European countries following a reduction in the use of some flame retardant compounds due to environmental concerns[1]. It is anticipated that this trend could follow in the United States. The objective of this work is to relate the full-scale flammability and fire hazard of consumer electronics assemblies having enclosures made from different resin formulations to bench-scale fire performance of these resins. A research consortium was established between NIST, UL, Dow, PolyOne, Albemarle and Samsung Cheil to conduct this research. Eighteen commercial resins were evaluated using three different standard bench-scale flammability tests. Based on the bench-scale test results, five of these resins were molded into 19" computer monitor housings and examined in full-scale fire tests that measured the heat release rate (HRR) and the radiative ignition threat to surrounding objects. The results are compared and contrasted to bench-scale results to infer useful guidelines.

BACKGROUND

A number of previous studies have examined the fire performance of electronic equipment. A comprehensive study was sponsored by the Society of the Plastic Industry (SPI) in 1981[2] that rated the relative performance of 5 flame retarded plastic materials (UL94 V-0 and V-1) using 10 different bench-scale fire tests and compared the ranked performance to the fire performance of model electronic enclosures exposed to a 3 kW propane sand burner. The results showed reasonable qualitative agreement between the overall bench-scale and full-scale performance. The Flame Retardant Chemical Association (FRCA) sponsored a study by the National Bureau of Standards (NBS) in 1988[3] that showed a significant reduction in the fire hazard of TV cabinets using flame retardant materials. Several reports[4-7] by the Swedish National Testing and Research Institute (SP) and the National Association of State Fire Marshals (NASFM) compared the fire growth of off-the-shelf printers, computer monitors and CPU's to the UL94 ranking of the enclosure material and concluded that enclosures using HB rated plastics are vulnerable to ignition by a small flame and can lead to flashover of a room.

BENCH-SCALE FIRE TESTING

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). A detailed description of the test methods can be found in a previous report[8].

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 the first column of 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). Specimen thicknesses of 1.6 mm and 3.2 mm were chosen to represent typical electronic housings. The resins were injection molded into 10 cm diameter round plaques for the Cone Calorimeter and Glow Wire tests, and standard 125 mm by 13 mm bars for the UL94 tests.

Bench Scale Test Results

The results of the bench scale testing are listed in Table 1. The UL94 vertical burn test mean afterflame times (time to self extinguishment) listed in the fourth column of Table 1 represent the average of ten replicate measurements. The standard uncertainty for the afterflame time measurement ranged from ±1 s to ±10 s. The Cone Calorimeter results listed in Table 1 are the average of 3 replicate measurements with an external heat flux of 50 kW/m^2. HRR_{peak} is the peak heat release rate, HOC_{eff} is the effective heat of combustion, t_{ign} is the time to sustained ignition and $t_{peak,HRR}$ is the time to the peak heat release rate. The relative standard uncertainty for the HRR_{peak} measurement ranged from 2% to 20% with an average value of 8%. The results from the Glow Wire Ignition/Flammability Temperature (GWIT/GWFT) test are shown in the last 2 columns of Table 1. A more detailed description of the uncertainty of the measurements in Table 1 can be found in a previous report[8]. Several noteworthy observations are evident from examination of the results in Table 1. The 3.2 mm thick specimens generally showed an improved performance in the UL94 test compared to the 1.6 mm specimens. However, for 13 of the 18 materials, the opposite effect was observed for the peak heat release rate (thinner specimens had a lower HRR_{peak}). The effect of flame retardant additives showed both increased UL94 performance and a reduction in the HRR_{peak}, although a decrease in the time to ignition was observed for most of the FR specimens. There was no obvious effect of thickness or FR additive on the Glow Wire Ignition Temperature results. Some effort was given to obtaining a qualitative correlation between the results of the different bench scale tests in Table 1 (can we predict UL94 performance from HRR_{peak} or some other measurement from the Cone?).

Although correlations could be found within a particular set of resins (such as HIPS), a more general relationship was not found. This is not unexpected since the upward flame spread and melting/dripping mechanisms inherent to the UL94 test are not captured by the geometry of the cone.

Table 1 Summary of Bench Scale Test Results at 50 kW/m² heat flux.

Specimen ID	thickness (mm)	UL94 class	UL94 Afterflame Time (s)	Cone HRR_{peak} (kW/m²)	Cone HOC_{eff} (kJ/g)	Cone t_{ign} (s)	Cone $t_{peak,HRR}$ (s)	Cone Smoke Yield (g/g)	Cone CO Yield (g/g)	GWIT (°C)	GWFT (°C)
1-PC-NH	1.6	V-2	13.6 ± 5.1	829	23.6	46	70	12.3%	6.4%	800	960
2-HIPS-BFR	1.6	V-0	0.9 ± 1.0	318	12.3	33	90	30.2%	14.6%	650	960
3-HIPS-NFR	1.6	HB	33.2 ± 5.4	723	33.9	30	103	18.1%	6.9%	700	675
4-PC-NFR	1.6	V-2	13.9 ± 6.2	885	24.0	77	96	12.0%	6.0%	900	900
5-PC-BFR	1.6	V-0	1 ± 1.1	378	22.3	51	79	16.3%	7.7%	900	960
6-PC/ABS-NFR	1.6	HB	35 ± 0.0	543	29.7	34	67	15.9%	5.2%	800	775
7-ABS-BFR	1.6	V-0	0.7 ± 1.1	312	13.9	42	80	33.6%	12.7%	700	960
8-PC/ABS-PFR	1.6	V-2	8 ± 4.6	388	20.6	45	88	16.5%	9.0%	725	960
9-HIPS-BFR	1.6	V-2	11.1 ± 6.6	502	16.4	41	97	29.0%	13.1%	700	875
10-PC-BFR	1.6	V-0	3.1 ± 1.9	280	21.2	39	185	12.7%	6.3%	850	960
11-PP-BFR	1.6	V-2	0 ± 0.0	1833	41.0	37	87	11.8%	14.6%	800	960
12-PP-NH	1.6	HB	11.7 ± 7.6	320	41.7	16	85	8.2%	5.1%	700	960
13-PP-BFR	1.6	V-2	3.3 ± 1.7	1663	65.3	33	91	13.7%	9.4%	800	960
14-PP-BFR	1.6	V-2	3.7 ± 4.9	2190	43.1	34	79	9.6%	12.4%	700	960
15-PP-NH	1.6	V-0	1.5 ± 1.6	583	15.3	32	63	16.1%	15.2%	750	960
17-PVC-NFR	1.6	V-0	2.4 ± 1.2	206	13.1	28	36	11.0%	7.0%	875	960
18-HIPS-PFR	1.6	V-1	22.3 ± 7.7	313	22.3	34	83	9.1%	10.1%	--	--
19-ABS-PFR	1.6	HB	22.7 ± 10.2	282	21.0	28	78	10.9%	10.8%	--	--
1-PC-NH	3.2	V-0	1 ± 0.8	586	24.0	63	133	12.6%	5.5%	825	960
2-HIPS-BFR	3.2	V-0	0.3 ± 0.7	428	11.4	33	85	28.0%	13.3%	675	960
3-HIPS-NFR	3.2	HB	34.6 ± 1.3	1307	36.3	40	113	16.2%	8.4%	750	725
4-PC-NFR	3.2	V-2	8.9 ± 4.1	628	22.4	101	145	12.1%	5.3%	850	960
5-PC-BFR	3.2	V-0	0.6 ± 0.8	350	21.9	62	109	14.0%	6.7%	825	960
6-PC/ABS-NFR	3.2	HB	35 ± 0.0	741	27.2	42	81	13.4%	5.2%	725	700
7-ABS-BFR	3.2	V-0	0 ± 0.0	409	11.2	42	115	27.8%	12.9%	750	960
8-PC/ABS-PFR	3.2	V-0	--	524	21.7	52	96	17.1%	8.7%	725	960
9-HIPS-BFR	3.2	V-2	6.3 ± 3.8	985	18.6	46	127	23.4%	14.2%	650	960
10-PC-BFR	3.2	V-0	1.5 ± 0.5	301	22.6	47	368	11.6%	5.8%	875	960
11-PP-BFR	3.2	V-2	0 ± 0.0	2255	38.1	47	147	11.5%	16.0%	725	960
12-PP-NH	3.2	V-0	0.4 ± 1.0	364	40.0	19	261	7.5%	4.9%	750	960
13-PP-BFR	3.2	V-2	8.1 ± 6.9	1916	47.7	38	138	9.9%	8.1%	800	960
14-PP-BFR	3.2	V-2	2.9 ± 2.2	2209	43.6	33	128	10.2%	12.6%	650	960
15-PP-NH	3.2	V-0	0 ± 0.0	422	16.6	43	69	18.7%	15.5%	650	960
17-PVC-NFR	3.2	V-0	0.9 ± 0.9	223	14.0	25	35	11.2%	7.9%	900	960
18-HIPS-PFR	3.2	V-1	19.8 ± 9.1	398	21.5	30	87	9.3%	10.5%	--	--
19-ABS-PFR	3.2	V-1	12 ± 6.6	328	22.2	33	49	10.5%	12.5%	--	--

Cone Calorimeter measurements were also performed at 3 different heat flux levels using the 3.2 mm thick specimens. The heat release rate curves for the non-FR HIPS sample at incident fluxes of 30 kW/m², 50 kW/m², and 90 kW/m² are shown in Figure 1. The results show a greater HRR_{peak} and shorter time to ignition with increasing heat flux and the general shape of the HRR curve was unchanged. This trend was observed for most of the materials examined; however some materials (such as 6-PC/ABS-NFR) showed a decrease in peak HRR as the heat flux was increased.

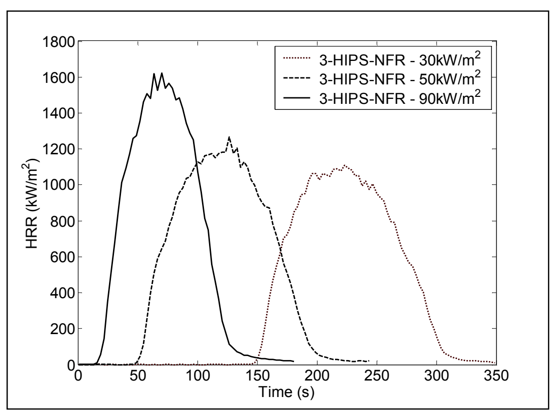

Figure 1. HRR curves for 3-HIP-NFR (UL94 HB) 3.2 mm sample thickness.

It has been shown that a steady state energy balance can be used to predict the functional relationship between the steady HRR and external heat flux[9]. $HRR_{ss}=HRR_o+HRP(q_{ext})$. In this expression the intrinsic heat release rate, HRR_o, represents the heat flux at zero external flux and the heat release parameter, HRP, represents the material sensitivity to external flux and has been used to predict fire propagation. It was observed that for a wide range of polymers the HRR_o value was a good predictor of UL94 performance, where self-extinguishing materials generally had a HRR_o of less than 100 kW/m^2.[10]

A summary of the Cone results at 3 different external heat flux levels is shown in Table 2. Because many of the materials in Table 2 are thermally thin and charring, a steady HRR was never reached. The HRR_o and HRP values were determined using a linear regression of the initial peak HRR value. In general, larger values of HRR_o and HRP relate to increased fire hazard. A comparison of the HRR_o and UL94 rankings is shown in Figure 2. From this limited data set it appears that the criteria for self extinguishing materials (V-0 and V-1) is that the HRR_o is less than 500 kW/m^2. Although these results are qualitatively meaningful, their quantitative values are questionable due to the large uncertainly in choosing an appropriate steady HRR. Because the UL94 ranking can depend on sample thickness (ie. material 12 from Table 1), it cannot be determined solely from an intrinsic property such as HRR_o.

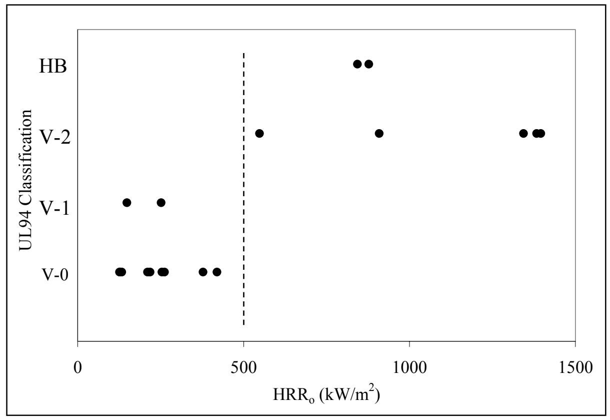

Figure 2. Comparison of UL94 ranking and intrinsic HRR for 3.2 mm specimens.

Table 2. Summary of Cone results at three heat flux levels, specimen thickness = 3.2 mm.

Sample Identification	Peak Heat Release Rate (kW/m^2)			Time To Sustained Ignition (s)			HRR_0 (kW/m^2)	HRP (kJ/kJ)
Irradiation (kW/m^2)	30	50	90	30	50	90		
1-PC-NH	457	482	532	193	67	17	420	1.3
2-HIPS-BFR	304	461	566	87	31	9	211	4.1
3-HIPS-NFR	1108	1265	1623	151	50	16	843	8.6
4-PC-NFR	734	703	984	500	129	40	548	4.6
5-PC-BFR	321	343	437	260	78	24	254	2.0
6-PC/ABS-NFR	850	790	762	137	56	21	877	-1.4
7-ABS-BFR	243	370	515	126	50	17	126	4.4
8-PC/ABS-PFR	428	567	611	154	53	23	378	2.8
9-HIPS-BFR	930	760	827	136	44	17	909	-1.2
10-PC-BFR	191	167	258	461	72	16	133	1.3
11-PP-BFR	1650	2090	2391	221	62	20	1383	11.7
12-PP-NH	265	337	392	50	25	10	218	2.0
13-PP-BFR	1689	2206	2529	124	46	12	1396	13.2
14-PP-BFR	1677	2200	2581	110	35	16	1343	14.3
15-PP-NH	315	487	530	140	48	19	261	3.2
17-PVC-NFR	179	243	305	103	23	11	128	2.0
18-HIPS-PFR	391	445	639	98	30	9	251	4.2
19-ABS-PFR	262	293	454	99	36	11	148	3.3

FULL-SCALE FIRE TESTING

The full scale tests were performed under a 3 m square exhaust hood designed to accommodate sustained fires with a net heat release rate (HRR) of up to 1 MW. The exhaust mass flow rate was set to 2 kg/s (≈3600 SCFM) for these tests to provide optimal resolution for fires less than 400 kW in size. Heat release rate measurements were based on the well-established oxygen consumption principle [11, 12]. A complete description of the hardware and test setup can be found in the final report [13].

The 5 materials used in the full scale tests reported here were selected to represent a wide range of fire performance in the bench scale tests. A list of materials used in these tests and a summary of results from

3 bench-scale tests (3.2 mm thick samples) are given in Table 3. The full scale specimen mass listed in Table 3 is the combined mass of the front and rear pieces of the pre-assembled monitor enclosure.

Table 3. Summary of bench-scale performance for materials used in full-scale tests, and initial mass of combustible material on full scale specimens.

Resin Identification	Cone peak HRR (kW/m^2) @50 kW/m^2	UL94 Classification	GWIT (°C) / GWFT (°C)	Full-Scale Enclosure Mass (g)
3-HIPS-NFR	1307	HB	750 / 725	2335
13-PP-BFR	1916	V-2	800 / 960	1999
18-HIPS-PFR	398	V-1	NT	2453
1-PC-NH	586	V-0	825 / 960	2839
7-ABS-BFR	409	V-0	750 / 960	2683

Full-scale specimens

Two piece 19" CRT computer monitor housings (Figure 3) were molded from the materials listed in Table 3. The average specimen wall thickness was (3.0 ± 0.25) mm. The fire characterization was performed using both real and simulated internal components. The simulated internal frame consisted of 1.6 mm steel sheet metal formed roughly into the shape of the real components. Draped over the frame was a sheet of aluminum foil that served to increase the lateral cross section of the sheet metal frame. The frame also served to partially support the plastic enclosure during the fire test and shield interior surfaces from radiation. The frame was thus intended to achieve the same qualitative effects that real monitor components have on a fire. The real internal components consisted of a cathode ray tube (CRT) and other various electronic components, some of which were combustible. The 22 cm x 29 cm opening at the base of the enclosure was covered with 1.6 mm sheet metal. The specimen was placed on a brick such that the mid-length side lower edge was (8 ± 1) cm from the table surface.

Figure 3. 19" Computer monitor specimen used in full-scale testing.

Ignition Sources

Small local ignition source: A small local ignition source representing a typical candle sized flame was used for these tests. A 0.5 mm I.D. needle flame burner was used to produce an n-butane flame with a height of (20 ± 1) mm. The fuel mass flow rate was measured as (0.84 ± 0.02) mg/s and the net heat release rate of this flame was calculated as (37.5 ± 2) W. The flame was applied mid-length along the side of the specimen, (3 ± 1) cm above the lower edge. This emphasized both the potential for upward flame spread and for the development of an interactive melt pool fire on the table surface. The initial flame application was for a period of 20 s. If the burning specimen extinguished within 60 s, the flame was immediately re-applied for 60 s. The 60 s application was repeated 3 times for a total flame application time of 200 s. In the case that a hole was formed in the specimen, the test flame was moved laterally to remain in contact with the enclosure (chasing the receding material). This ignition method was designed to provide information on the fire performance of the equipment when exposed to a localized short duration ignition source, and also the possibility of a much longer duration ignition source such as an unattended candle.

Large ignition source (radiant heat panel): The response of the specimens to a larger ignition source was simulated using a 48 cm x 33 cm natural gas radiant heat panel. This was intended to represent a situation where the monitor was not the first item involved in a fire. The centerline heat flux was (21 ± 1) kW/m^2 at a location 15 cm from the front surface of the panel. A removable copper plate shutter was used to protect the specimen from the heat flux panel prior to the start of the test. The shutter was water cooled and painted black to minimize the tendency of the gas-fired panel to increase in temperature when shielded. A 1.6 mm I.D. open tube burner was used to produce a 10 cm n-butane pilot flame with a net heat release rate of (178 ± 5) W. This pilot was applied in a location similar to that of the needle flame; the entire side of the monitor was irradiated. In some tests it was held in contact with melted material that had fallen to the table top.

Large ignition source (polystyrene keyboard): A generic, non-FR polystyrene keyboard was used as an ignition source for the monitor specimens in some tests. The total weight of the keyboard was (580 ± 5) g. The keyboard was placed under the front bezel of the monitor and ignited using the 20 mm needle flame described previously. The needle flame was applied for 20 s to the side of the F9 key. Tests were also conducted using only the keyboard to determine its contribution to the heat release rate.

Heat Flux Measurements

An array of four total heat flux gauges (Schmidt-Boelter type, 6 mm diameter sensor face, 13 mm diameter body) was placed in a position to view one side of the burning object (right side of Figure 4). The goal of the array was to obtain data on the distribution of radiative heat flux versus distance along a line perpendicular to the object surface being viewed. This information is used below to infer the maximum distance at which different materials could be ignited as a result of radiative heating from the object fire. The four gauges were arranged as follows. The front and rear gauge were on the same horizontal axis, both facing along this axis, and separated by 25 cm to 30 cm. The remaining two gauges were on a single vertical axis, both facing in the same direction as the first two, i.e., toward the side of the burning object. That vertical axis was displaced 5 cm from the horizontal axis of the first two gauges. The two gauges on this vertical axis were separated vertically by a distance of 15.3 cm, symmetrically above and below the horizontal axis of the first two gauges. This arrangement ultimately supplies three measures of the heat flux versus perpendicular distance away from the viewed surface of the burning object. In addition, since this distribution depends also on the height at which it is measured, the two vertical gauges provide a first order correction for this effect. Since the gauges (and their physical supports) had a finite size and could be within the field of view of those behind them, corrections had to be made to their readings for this shadowing.

Needle Flame Ignition Results

None of the 4 flame retarded materials produced a measurable fire when exposed to the 20 mm needle flame for a total application time of 200 s. The monitor enclosure molded using the non flame retardant material, 3-HIPS-NFR, was easily ignited during the initial 20 s application of the flame and produced a fire that consumed the entire monitor housing. The HRR curves for these specimens are shown in Figure 4. The initial test flame was applied at 4 min into the data file for all tests described here. The fire growth and peak HRR on the monitors with the simulated internal frame (test 1 and 4 in Figure 4) were very reproducible. For each of the specimens the fire grew slowly during the first 3 min then rapidly accelerated to its peak value during the next 3 min. The presence of the CRT (test 26 in Figure 4) decreased the fire growth rate and lowered the peak HRR by approximately 30 %.

The total mass loss measurement in this series of tests was compromised by several factors. The calcium silica sheet below the specimen contained roughly 3 % water weight (150 g) that partially vaporized during the test. In addition, some of the glass from the CRT was ejected from the monitor during the test. For these reasons it was not possible to distinguish the mass loss due to the burning plastic from the overall mass loss. The initial weight of the monitor enclosures for tests 1, 4 and 26 was (2335 ± 5) g. The combined expanded relative uncertainty (95 % confidence level) of the peak heat release rate measurement was ±12 %, based on propagation of measurement uncertainty.

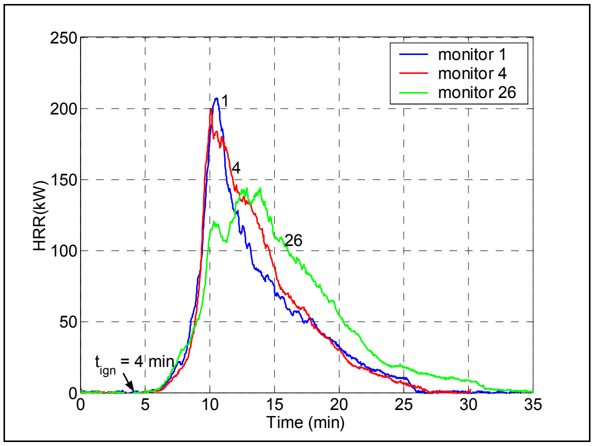

Figure 4. Heat release rate curves for needle flame ignition of 19" monitors. Ignition flame applied to specimen at t = 4 min. Image of monitor test, 3-HIPS-NFR, near peak heat release rate (right). Array of heat flux gauges is shown on right side of image

Keyboard Fire Ignition Results

The keyboard ignition tests were performed following the needle flame ignition method for the four flame retarded specimens that did not ignite and had only local fire damage to the enclosure. Tests conducted to characterize the stand-alone keyboard as an ignition source showed an average peak HRR of 22.7 kW, approximately 10 min after ignition. When the keyboard burned, its resin did not flow outward more than 1 cm to 2 cm. Thus, when used as an ignition source, it was essentially stationary. Portions of the monitor (the front bezel) immediately above it were partially immersed in its flames. More remote portions of the monitor saw only limited radiation from the keyboard fire plume.

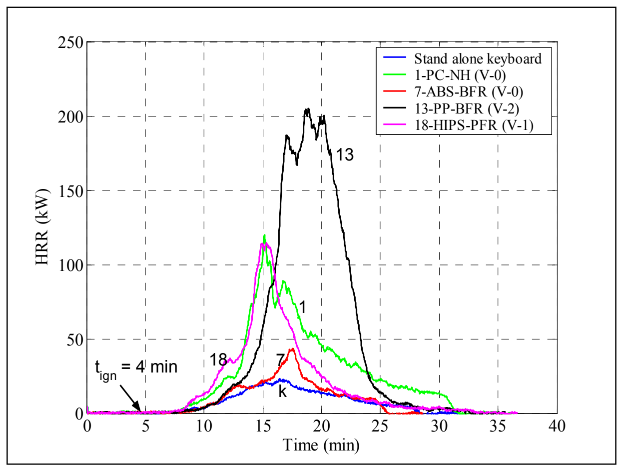

Figure 5. HRR curves for keyboard ignition of 19" computer monitors.

The HRR curves for the keyboard fire ignition of the monitors are shown in Figure 5. The HRR data for the stand alone keyboard fire test is also shown in this figure for reference. With the exception of material 7-ABS-BFR, the monitor specimens were ignited by the burning keyboard and the enclosures were completely consumed by the resulting fire. During the test of monitor 7-ABS-BFR, only the enclosure material directly in contact with the fire from the burning keyboard was ignited. The contribution of the enclosure to the peak HRR was between 10 kW and 20 kW and the rear half of the enclosure was not involved in the fire.

Of the FR specimens, material 13-PP-BFR exhibited the greatest hazard when exposed to the keyboard fire. Once ignited the fire quickly grew into a large pool fire that covered the entire test surface. The edge of the test surface was protected with aluminum foil to contain the melt pool, however a small amount of burning plastic spilled over the edge. It should be noted that polypropylene is not typically used for electronic enclosure housings.

The monitors using materials 1-PC-NH and 18-HIPS-NH had similar performances in the keyboard fire ignition configuration. Although the peak HRR was lower than specimen 13-PP-BFR, the fire spread to the rear part of the enclosure and consumed most of the mass of the enclosure. This result illustrates that the fire hazard is not the same for all V-0 rated materials. As with all of the specimens, the presence of the real CRT delayed the fire growth and lowered the peak HRR. This is likely due to the considerable heat sink of the massive CRT. A summary of the peak HRR results is given in Table 4.

Table 4. Summary of peak heat release rates for all full-scale fire tests.

Specimen ID	UL94 Rating @3.2 mm	CRT	Needle Flame Ignition HRR_{peak} (kW)	Keyboard Ignition HRR_{peak} (kW)	Radiant Panel Ignition HRR_{peak} (kW)
PS-keyboard	HB	----	22.5	----	----
PS-keyboard		----	22.6	----	----
PS-keyboard		----	23	----	----
1-PC-NH	V-0	No	no-ign	46	124
1-PC-NH		No	no-ign	120	117
1-PC-NH		Yes	no-ign	55	----
1-PC-NH		No	no-ign	55	----
3-HIPS-NFR	HB	No	208	----	240
3-HIPS-NFR		No	200	----	190
3-HIPS-NFR		Yes	144	----	----
7-ABS-BFR	V-0	No	no-ign	44	no-ign
7-ABS-BFR		No	no-ign	31	25
7-ABS-BFR		Yes	no-ign	35	----
13-PP-BFR	V-2	No	no-ign	205	193
13-PP-BFR		No	no-ign	199	167
13-PP-BFR		Yes	no-ign	180	----
18-HIPS-PFR	V-1	No	no-ign	115	88
18-HIPS- PFR		No	no-ign	89	94
18-HIPS- PFR		Yes	no-ign	73	----

Radiant Heat Panel Ignition Results

The results of the radiant heat panel ignition of the monitor specimens are summarized in Table 4. All of these tests were performed using the specimens with simulated internal components. The radiant panel was positioned so that a 21 kW/m^2 total heat flux was imposed at the point on the side of the specimen where the local ignition source was applied. As in the previous tests a barrier of foil was applied to the edge of the support surface to prevent material from dripping onto the floor and damaging the load cell and instrument wires. Two 3.2 mm thick steel bars were positioned in front of the heat panel to prevent the enclosure from tipping over and contacting the face of the panel. 4 min after the start of the test the water-cooled radiation shield was removed and the pilot flame was immediately applied to the side of the monitor.

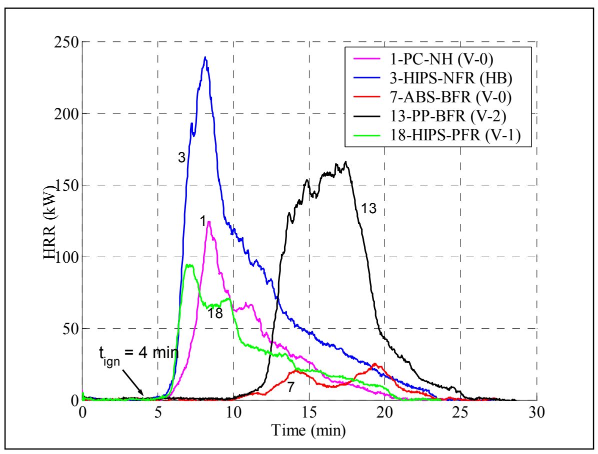

Figure 6. HRR curves for radiant heat panel "forced ignition" of 19" monitors.

Specimen 1-PC-NH was easily ignited with this method and the fire quickly consumed the entire specimen and grew to exceed 100 kW in size. The time from ignition to peak HRR was about 4 min. As expected, the non-FR HIPS specimen, shown in Figure 6, ignited and quickly developed into a large pool fire in less than 5 min. The 7-ABS-BFR specimen did not ignite during the first two attempts. All of the material on the side of the enclosure melted away from the 10 cm pilot flame before it could ignite. During the third attempt, shown in Figure 6, the pilot flame was lowered to remain in contact with the developing melt pool on the surface of the calcium silicate board. The enclosure ignited and slowly spread to the far side of the specimen. The HRR had a peak of 25 kW nearly 15 min after the initial flame application. Similar behavior was observed for the 13-PP-BFR specimens, except that the result was a larger fire. Only after applying the pilot flame to the melt pool for approximately 5 min did the fire begin to propagate to the other sides of the enclosure. Once ignited however the fire grew very quickly and had a similar growth rate and peak HRR to the keyboard fire ignition method of the same material. The heat release rate curve of the 18-HIPS-NH (UL94 V-1) specimen ignited using the radiant panel and pilot flame is also shown in Figure 6. The average peak heat release rate, 91 kW, was substantially lower than the HIPS resin with no flame retardant.

Threat of Ignition of Other Objects

Any fire poses an ignition threat to objects in its surroundings. Such ignition could occur by one of several modes including: direct flame contact with the surface of another object, movement of flaming material, and remote ignition by radiation. For the purpose of comparing relative fire hazard we will consider only radiative ignition here. An important feature of radiative ignition is that below some flux level (corresponding to some distance away from the radiating fire plume), the surface of the heated object will not get hot enough to be ignitable even if a pilot flame is present. The distance beyond which this is true defines the "threat radius" of the fire.

Different target objects have differing ignitability as a result of their specific chemical and physical properties. Since it is not possible to make predictions for all objects which may plausibly be near an electronic equipment fire, surrogate materials are used. Here we consider two materials which are surrogates for common objects of interest in the vicinity of a desktop computer. The first is a stack of paper. Specifically, the surrogate material is a 2.54 cm thick unbound pile of copier paper. This is a surrogate for books, magazines, manuals or printer paper that could be on a desk top. The second is a medium weight cotton fabric which is a surrogate for a drape or for the seatback of an upholstered desk chair. The fabric is 100 % cotton and weighs 0.41 kg/m^2 (12 oz/yd^2). The piloted ignition behavior of these materials was measured in the Cone Calorimeter over a flux range from 70 kW/m^2 down to the minimum flux for ignition. In the monitor fires, the heat flux that would impinge on a target object rises and falls as the monitor fire builds and recedes, therefore the Cone data cannot be used directly. Instead, it forms the basis for inferring the effective ignition properties of the surrogate material. A simple thermal ignition model is used to find effective property values which closely reproduce the measured ignition behavior from the Cone. These properties are the ignition temperature and the apparent thermal inertia (product of density (ρ), heat capacity (c) and thermal conductivity (k)). A comparison of the cone ignition data and the ignition model for the cotton fabric material is shown in Figure 7. Given these effective ignitability properties and the measured heat flux versus time from the monitor fire tests, this information can be used in the model(s) to predict the farthest distance from the fire at which ignition of the surrogate materials can just occur.

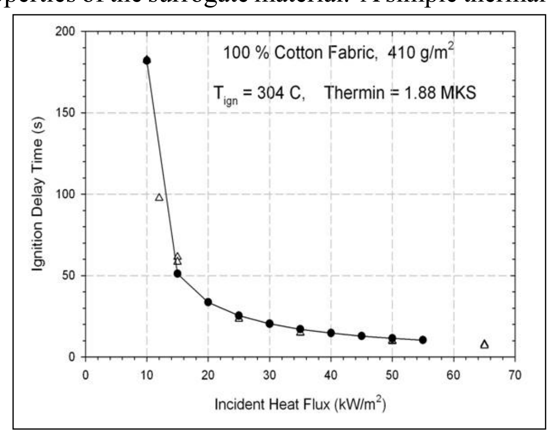

Figure 7. Radiative ignition of cotton fabric in the Cone Calorimeter.

Since the number of heat flux gauges was quite limited, only some portion of the flux versus distance profile was measured in each test and it was necessary to extrapolate/interpolate the measured values. Digital images of the fire, taken from behind the flux gauges, were used to determine an approximate area of the fire which was then used to account for partial shadowing of the rear gauges and to extrapolate the flux distribution based on the radiative view factor. Figure 8 shows this view factor based extrapolation curve and the point measurements for one of the monitor specimens. Because the flux data have substantial variability (due to the turbulent nature of the fire plume), it is simpler to approximate the transient nature of the flux by using a Gaussian time dependence. The Gaussian is specified to match the peak flux and its time width at 50 % of the peak. A detailed description of the flux gauge geometry, ignition model , and extrapolation methods can be found in the full report[13].

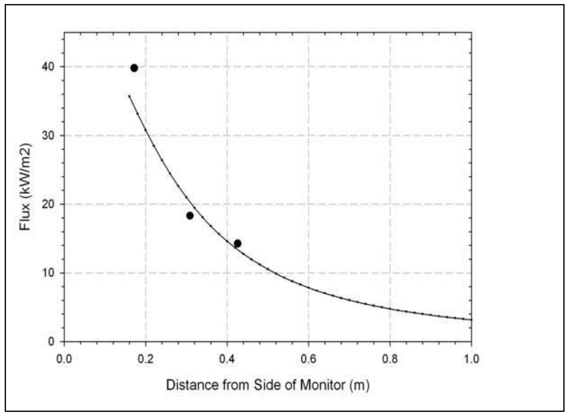

Figure 8. View-factor based extrapolation curve and flux measurements from keyboard ignition of 1-PC-NH monitor.

Table 5 shows the computed maximum piloted ignition reach values for the cotton fabric and the paper. This was done only for a select set of fire tests since it was quite labor intensive. The cases reported here are for the monitor enclosures containing the pseudo-CRT interior; the main goal is a comparison of the differing resins, plus some guidance regarding “acceptable” fire sizes. The results for the cotton fabric were computed for the two extremes; adiabatic back surface or equal back and front surface heat losses (re-radiation plus convection). The ignition behavior of the paper surrogate was computed with a thermally thick model using a 2.5 cm depth. This is thick enough that the back surface condition is irrelevant on the time scale required for ignition. The relative error in the maximum ignition threat distance was estimated to be less than 25%.

Table 5. Results of maximum ignition threat distance analysis.
(a)=needle flame ignition, (b)= keyboard ignition, (c)= radiant heat panel ignition.

Resin (configuration)	**Peak HRR (kW)**	**Max. Ignition Distance (m) Non-insulated Cotton Fabric**	**Max. Ignition Distance (m) Insulated Cotton Fabric**	**Max. Ignition Distance (m) Stack of Paper**
3- HIPS-NFR (a)	200	0.71	1.12	0.58
13-PP-BFR (b)	198	0.65	0.97	0.56
18-HIPS-PFR (b)	89	0.36	0.56	0.29
7-ABS-BFR (b)	31	N. A.	N. A.	N. A.
1-PC-NH (b)	120	0.36	0.58	0.31
1-PC-NH (c)	124	0.36	0.51	0.26
Keyboard (a)	22.5	0.12	0.27	0.08

The best-behaved case was for 7-ABS-BFR for which ignition reach values could not be directly calculated (indicated by N.A. in Table 5). The reason for this was that the fire stopped before it propagated as far along the side as the flux gauge array and the peak flux values recorded even for the front flux gauge, were less than 4 kW/m^2. Even the most ignitable surrogate case (cotton fabric with adiabatic rear surface) required a minimum peak flux of about 8 kW/m^2 to ignite. Extrapolation of the available flux data imply that this would not be reached even at the monitor surface for 7-ABS-BFR, at least in the vertical plane of the flux gauges. The worst fires here threaten to ignite such objects from as much as 1 m away, the more moderate fires from more than half a meter. It is not possible to make a statement about how many secondary fires these situations would induce in the real world. One can only infer that the probability of a secondary fire is roughly proportional to the area encompassed by the ignition reach and thus to the square of the ignition reach value. Even a heat release rate peak of about 23 kW (here seen for the keyboard alone) can potentially ignite the back of an upholstered desk chair or a drape nearly 0.3 m away.

Note that the preceding results show that the peak HRR from an electronic enclosure depends on the size and intensity of the ignition source. Thus it is necessary to put the object in context, decide on plausible ignition sources, and test the object in full-scale to find its peak HRR. Only then can the ignition reach results presented here pertain to a specific monitor. If the only plausible ignition source is match-sized, and the object is not used in proximity with non-FR peripherals, then all FR resins here would be adequate since none led to a significant fire.

Full-Scale/Bench-Scale Comparison

The results from the bench-scale tests and the full-scale monitor tests are shown in Table 6. The bench-scale test results are for 3.2 mm thick samples. The full-scale peak HRR results in Table 6 represent the largest of the replicate measurements. Qualitatively, the UL94 vertical burn test gave the best indication of the full-scale monitor fire performance when exposed to the needle flame ignition source. All of the materials that self-extinguished in the UL94 test resisted sustained ignition in the full-scale monitor tests. The time to ignition in the Cone and the Glow Wire Ignition Temperature were the poorest indicators of full-scale fire performance in these tests. Although the presence of a flame retardant additive can cause a material to ignite faster and at a lower temperature, these factors did not help predict whether or not the flame would propagate once ignited. The peak HRR from the Cone was not a good predictor of the full-scale response to the local ignition source in this study. A notable example of this is the polypropylene specimen (13-PP-BFR) that has a very high peak HRR in the Cone but did not ignite when exposed to the needle flame. The Cone results compared more favorably with the full-scale monitor tests having a larger ignition source. The two specimens with the highest peak HRR in the Cone tests also produced the largest fires when exposed to the keyboard fire and radiant panel ignition sources. More research is needed to develop and interpret bench-scale tests capable of predicting full-scale performance. The most reliable existing measure is full-scale testing, assuming the appropriate ignition scenario can be identified.

Table 6. Comparison of Bench-Scale and Full-Scale test results.

	Bench-Scale Test Results						Full-Scale Test Results		
Material ID	**UL94 rank 3.2mm/1.5mm**	**50 kW/m^2 HRR$_{peak}$ (kW/m^2)**	**HOC$_{eff}$ (kJ/g)**	**HRR$_o$ (kW/m^2)**	**HRP (kJ/kJ)**	**GWIT (^{o}C)**	**Needle Flame Ignition HRR$_{peak}$ (kW)**	**Keyboard Igniton HRR$_{peak}$ (kW)**	**Radiant Panel Ignition HRR$_{peak}$ (kW)**
1-PC-NH	V-0/V-2	586	24	420	1.3	825	0	120	124
3-HIPS-NFR	HB/HB	1307	36.3	843	8.6	750	208	--	240
7-ABS-BFR	V-0/V-0	409	11.2	126	4.4	750	0	44	25
13-PP-BFR	V-2/V-2	1916	47.7	1396	13.2	800	0	205	193
18-HIPS-PFR	V-1/V-1	398	21.5	251	4.2	--	0	115	94

CONCLUSIONS

Progressively larger and more intense ignition sources caused the burning of an increasing number of tested resins. The use of flame retardant materials (including non-halogenated) provided adequate protection against the needle flame that represented a “candle size” ignition source. The fire hazard from needle flame ignition of the enclosure having a non-flame-retarded material (3-HIPS-NFR) was significant and resulted in the threat of fire spread to nearby objects. The keyboard fire ignition source produced a significant fire hazard for all but one (7-ABS-BFR) of the monitor enclosures. The radiant heat panel used to simulate an existing fire produced significant burning for all of the monitor specimens.

Several bench-scale flammability measures were assessed for ability to predict full-scale monitor behavior with limited success. The UL94 vertical burn test was a good indicator of the likelihood of the full-scale specimens to resist sustained ignition by a “candle size” flame. The Cone Calorimeter test was a reasonable indictor of the response of the monitor specimens to ignition by a nearby burning object. The Glow Wire Ignition Test was a poor indicator of the full-scale response to an open flame ignition source.

The radiant ignition of remote objects was analyzed for several of the monitor fires. A 200 kW (peak HRR) fire produced a threat distance of 1.1 m for upholstery fabric. A (20 to 25) kW (peak HRR) fire produced a threat distance of 0.3 m for upholstery fabric. A peak HRR of less than 10 kW would likely produce a minimal radiant ignition threat to its surroundings, comparable to the threat of direct flame contact. Peripheral items (such as the keyboards in this study) are often made from non-FR materials and can serve as an ignition source for other items if ignited.

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