An Investigation of the Vertical Bunsen Burner Test for Flammability of Plastics

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16. Abstract

A vertical Bunsen burner test for flammability of plastics (UL-94V) was studied in an attempt to relate the upward burning of plastics to their material fire properties. It was shown that the heat release parameter, the critical heat flux for piloted ignition, and the thermal response parameter account for most of the fire behavior of plastics in the test. The premixed flame of the Bunsen burner during transient ignition and the laminar diffusion flame of the burning material have nominal heat fluxes of about 60 kW/m^2. The heat release rate (HRR) per unit area during burning was a significant factor in correlating UL-94V ratings. The height of the flame, which transfers heat to the burning sample, was proportional to HRR, and critical values of HRR for ignition, sustained burning, and upward flame spread in the test were theoretically estimated to be 80, 250, and 300 kW/m^2, respectively.

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LIST OF SYMBOLS AND ACRONYMS

k_f	Flame spread parameter
h_c	Convective heat transfer coefficient
Δh_c	Heat of combustion
Δh_{ox}	Heat of combustion per unit mass of oxygen
L	Heat of gasification
m''	Mass flux
P_B	Probability of burning
Q	Energy release rate
q''	Heat flux
q''_{flame}	Flame heat flux
t	Time
T	Temperature
$T_{f,\, crit}$	Critical flame temperature
$t_{ig,edge}$	Time for edge ignition
wx_p	Energy release rate per unite pyrolysis area
x_f	Flame height
CHF	Critical heat flux
HRP	heat release parameter
HRR	Heat release rate
NR	No vertical rating
TRP	Thermal response parameter
V	Vertical

EXECUTIVE SUMMARY

The Federal Aviation Administration uses a variety of federal regulatory tests to determine the fire safety of aircraft cabin materials. One of these is a flame resistance test in which a strip of cabin material is suspended vertically from a clamp and briefly ignited from the bottom using the small flame from a Bunsen burner. Once the sample has ignited, the Bunsen burner is removed and the time of burning and the burned length are recorded and compared to federal regulatory pass/fail criteria to determine whether or not the material is safe to use in an aircraft cabin. This study was conducted to determine how the physical and chemical properties of the material influence the outcome of the Bunsen burner test so that they can be optimized to improve the fire safety of cabin components. It was found that the rate at which heat is produced by the sample flame must be above a minimum (critical) value for the sample to ignite and continue burning, and that this critical heat release rate is determined by the thermal stability of the material and the ratio of the heat given off by combustion to the heat absorbed by the solid during the burning process.

INTRODUCTION

Published by Underwriters Laboratories, Inc. (UL), the UL-94 Flammability Test [1] is the most common protocol for assessing the flame resistance of plastic materials. This test determines the tendency of a material to extinguish or to spread flame after a brief exposure to a premixed burner flame. The current study explains the results of this test in terms of the heat transfer mechanism and the material fire response parameters, as part of an overall program at the Federal Aviation Administration Airport and Aircraft Safety Research and Development Group to evaluate fire safe materials.

While attempts at explaining the performance of the test have been made, no correlation with material properties has been attempted [2]. Several investigations, including those by Morgan, et al. [3], Hong, et al. [4], Schartel, et al. [5], and Bundy and Ohlemiller [6] attempted to correlate results with the cone calorimeter (ASTM E 1354). These studies did not yield any clear relationship between the two tests. Lyon, et al. [7], have argued that the probability a sample will fail the UL-94V test can be determined from a 5-mg sample burned in the microscale combustion calorimeter. Lyon [8] has also advocated a correlation of the UL-94V rating with the "intrinsic" heat release rate (HRR) (HRR_0), which is the HRR in a Cone Calorimeter at zero external heat flux. The current approach will draw on physical models for laminar burning [9], correlations for flame heat flux [10], and the use of material fire properties to explain the meaning of "flammability" [11 and 12]. Those further interested in the details of the current study should refer to Downey [13].

ANALYSIS OF THE UL VERTICAL TEST FOR FLAMMABILITY OF PLASTICS.

The UL test for flammability of plastics (UL-94) [1] is actually comprised of six separate tests, but this study will focus only on the Vertical Burning Test, UL-94V. The UL-94V test for vertical specimens continues to be a benchmark of the polymer industry to evaluate flammability (see figure 1). The test yields material ratings of V-0, V-1, V-2, and "fail" (listed from least to more "flammable") [1]. A material that does not meet the criteria of the Vertical Burning Test can be tested in accordance with UL-94HB, a Horizontal Burn Test, and usually receives the HB-rating.

The UL-94V test is conducted on small, vertical, flat, bar-shaped specimens. The bar must be 125 ±5 mm long and 13.0 ±0.5 mm wide.

The thickness is taken as the end-use for the product and cannot be greater than 13 mm. A 20-mm-tall premixed methane flame is applied to the bottom edge of the specimen, and the extent and duration of burning is converted to a rating. The burner is hand-held and can be oriented at 45° to avoid molten plastic dripping into the burner. As small variations in this procedure could produce significant variations in the test outcome, the most severe rating of several tests is recorded.

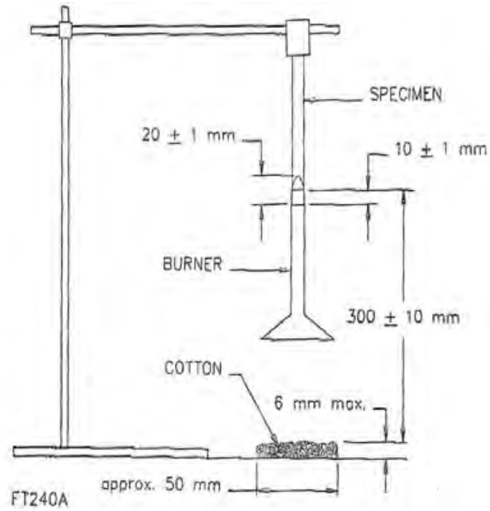

Figure 1. The UL-94V Test Configuration [1]

The burner flame is applied in one or two successive 10-second exposures in an attempt to force the sample to ignite. The duration of flaming combustion after the burner is removed (after-flame) and duration of smoldering combustion (after-glow) are recorded. If the flame tip reaches the holding clamp at the top (125 mm), the sample fails to achieve a vertical (V) rating in the test. Table 1 shows the timing requirements that must be met for each classification. The flame times, t_{flame}, listed in table 1 are the measured after-flame times. Samples that do not ignite, or for which the flame extinguishes within 10 seconds after removal of the burner, receive a V-0 rating. If the sample self-extinguishes within 30 seconds after removal of the burner, and the flame does not propagate up to the holding clamp, and no flaming drips are observed, a V-1 rating is obtained. Samples that have the same extent and duration of burning as V-1, but produce flaming drips that ignite the cotton batting below, receive a V-2 rating. A material that exhibits flame propagation up to the holding clamp or burns for longer than 30 seconds does not pass the UL-94V test.

Table 1. UL-94V Ratings and Associated Fire Phenomena

Duration of Self-Sustained Burning, t_{flame} (seconds)	Rating	Fire Phenomena
≤10	V-0	Material does not burn or barely ignites under the conditions of the test.
10 - 30	V-1	Burning is not sustained.
10 - 30	V-2	Burning is not sustained, but flaming drips ignite cotton below specimen.
>30	NR	Burning is sustained, or material burns 125 mm up to the top clamp. No vertical rating.

NR = No vertical rating

EXPERIMENTAL. To analyze the UL-94V test, its characteristics must be predictable. The heat flux of the burner is responsible for ignition, and therefore, its heat flux must be known. Once ignited, the heat flux from the burning sample must be known, along with the extent of flame over the rest of the test sample. These factors control the subsequent sustainability of burning and the extent of flame spread.

The burner heat flux is peculiar to the application of the premixed methane flame. After the premixed methane flame is removed from the sample, the heat flux to the sample (from its diffusion flame) depends only on the energy release rate, independent of the specific material. Further, it is assumed that the flame height is principally a function of the energy release rate.

A 3.2-mm (1/8-inch)-diameter, water-cooled total heat flux gage was used to measure the incident flame heat flux for both the premixed and diffusion flames. The material flame for the specimen was simulated by two means: (1) a controlled line-burner diffusion flame and (2) wetted dummy specimens burning n-heptane and methanol. The results are described below.

Burner Flame. Figure 2 shows the time-averaged incident heat flux values for orientations of the burner along the centerline at heights of 0.5 and 1 cm and to the bottom edge of the specimen as well.

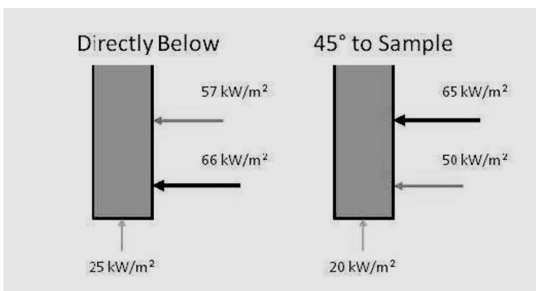

Figure 2. The Time-Averaged Incident Burner Heat Flux

The heat flux to the bottom edge of the specimen was only 20-25 kW/m^2 compared to 50-65 kW/m^2 along the faces of the specimen. The flame was 20-mm tall and the burner port was 10-mm below the specimen, so the top 10 mm of the flame immersed the bottom. Hence, the center of the flame, with lower temperatures than its edge, caused the lower heat flux at the bottom. In these measurements, the methane flow rate, flame height, and position of the burner all complied with the requirements of the UL-94V test. In making predictions for ignition, a nominal representative premixed flame incident heat flux of 60 kW/m^2 was adopted.

An experimental simulation of a burning specimen in UL-94V is described below. To predict the flame spread in the test, a relationship is needed for the flame height and its flame heat flux. To achieve such predictive results, measurements were taken and correlations were established, accordingly.

Flame Height. For these experiments, a specimen of standard length (125 mm) and width (13.0 mm) was cut from an incombustible material, with a thickness of approximately 6 mm. A burning material was simulated in one of two ways: (1) applying a line burner diffusion flame to the bottom edge of the incombustible sample and (2) wetting the incombustible sample with a liquid fuel over a given length to simulate the burning region. Flame height and heat flux measurements above the wetted region were then taken.

First, the burner ventilation ports were closed to produce a methane diffusion flame. A thin-slotted burner tip was fashioned from aluminum foil that fully encompassed the bottom edges of the sample. By varying and recording the methane flow rate, the flame could be simulated for the burning behavior of the UL-94 test. The data were taken when equal flame heights occurred on both faces of the specimen. The HRR was then calculated for the corresponding flow rate.

As the burner simulation could be questioned as not fully representative, additional measurements of flame height were taken for simulated, wetted samples of *n*-heptane or methanol. Using the burning rate of the fuel, the HRR could be calculated. The burning rate was determined by measuring the mass of the incombustible dry specimen, the mass of liquid consumed, and the time of the measurement. The data were examined for both the gas burner and simulated wetted tests in terms of flame height and energy release rate per unit specimen width. The resulting data correlate well, as shown in figure 3. It should be noted that the values for the wetted samples show good agreement with those of the burner flame. Thus, both provide consistent simulations.

As the flame height (x_f) depends primarily on its corresponding energy release rate (Q) per unit width (w), a common form of a correlation for this vertical wall configuration is

$$x_f = C_f (Q/w)^n \tag{1}$$

where C_f = 1/300 kW/m^2 and n = 1 from the best-fit to the data shown in figure 3. In contrast, Ahmad and Faeth [9] find for laminar burning walls that n is 4/3, and 2/3 for turbulent flames. This result can alternatively be expressed as follows, assuming a uniform energy release rate per unit pyrolysis area (wx_p):

$$x_f = \frac{HRR}{300} x_p \tag{2}$$

In equation 2, HRR (kW/m^2) is the energy release rate per unit area, and 300 kW/m^2 can be regarded as the critical energy release rate for upward spread in the UL-94V test, as discussed in the upward flame spread section.

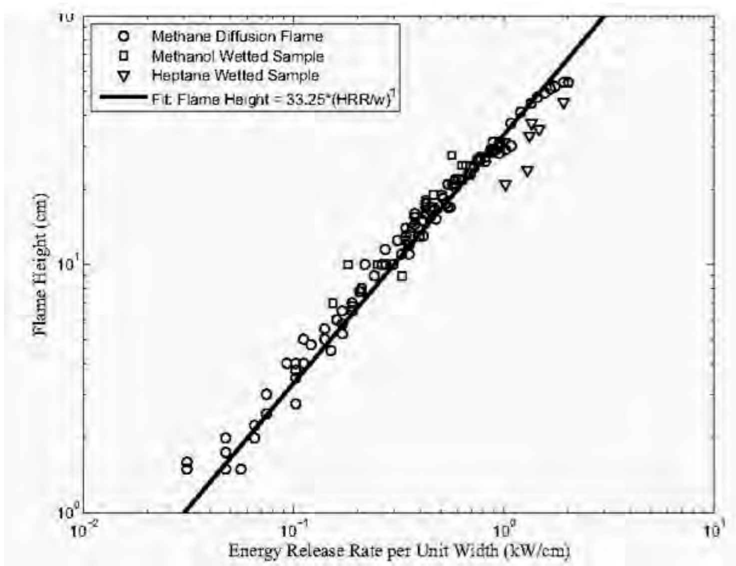

Figure 3. Flame Height for a UL-94V Simulated Specimen

Flame Heat Flux. The incident heat flux from the flame to the specimen was measured using the 3.2-mm (1/8-inch)-diameter, water-cooled heat flux gauge. The face of the gauge was positioned such that it was flush with the front face of the incombustible specimen. Figure 4 shows the time-averaged heat flux plotted against the dimensionless position, x/x_f, and the ratio of the position form the bottom edge to the flame height. Such a variable (x/x_f) has been known to unify heat flux data for wall flames, and does well here [10]. The instantaneous peak heat flux in the flame region is found from these measurements as 65 +5/-15 kW/m^2, and the time average is about 50 +10/-15 kW/m^2, as shown in the figure 4. In subsequent theoretical analyses, the incident flame heat flux over the flame region and over the pyrolysis region was estimated as 60 kW/m^2, based on these measurements, i.e., a constant flame heat flux was assumed.

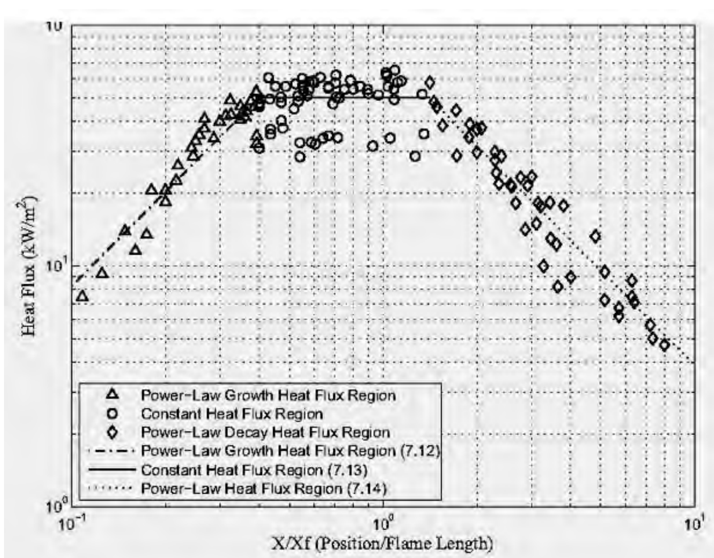

Figure 4. Time-Averaged Heat Flux From Simulated UL-94V Specimens

THEORETICAL. The material properties that control flammability are the critical heat flux (CHF) for piloted ignition, the ratio of the heat of combustion to heat of gasification or heat release parameter (HRP), and the parameter that controls ignition, known as the thermal response parameter (TRP), which includes the ignition temperature, conductivity, density, and specific heat of the material. These property parameters, along with the heat flux of the flame(s), are considered sufficient to account for the HRR in any fire scenario [12]. The UL-94 test is a complex fire scenario that involves up to two ignition attempts of 10 seconds each, unsteady burning, and upward flame spread, as well as melting and dripping.

The thickness of a sample in the UL-94V test can be up to 13 mm, but is commonly 3 to 6 mm for most materials. Unsteady heat transfer analysis [14] suggests that the UL-94V samples can be regarded as thermally thick at the relatively high (60 kW/m^2) heat flux exposure of the burner flame.

Ignition Process. The premixed burner flame envelops the bottom of the sample, simultaneously heating the sides, edges, and corners. For the thermally thick, plastic UL-94V specimen, the time to ignition is [12]

$$t_{ign} = \left(\frac{TRP}{q''} \right)^2 \tag{3}$$

In equation 3, q'' is the net heat flux, which is the difference between the incident heat flux from the flame q''_{flame} and the heat loss by re-radiation flux at the ignition temperature to the ambient temperature environment. This becomes

$$q'' = q''_{flame} - CHF_f \tag{4}$$

Here, CHF_f is the re-radiation component only, while typical values usually found in literature under radiant ignition include the convective loss as well (CHF). Typically, data come from a fire (cone) calorimeter device, in which the convective heat transfer coefficient is 11 ±2 W/m^2-K [15]. A good approximation for CHF_f in terms of CHF in the cone calorimeter is CHF_f = 0.82CHF, as CHF contains both the convective and radiative losses.

In the UL-94V test, the edges and corners of the sample enhance the ignition [16]. Through a standard conduction modeling technique to expand a one-dimensional solution to a three-dimensional case [17], it follows that the time for edge ignition is $t_{ig,edge} = t_{ig,o}/4$, and the time for corner ignition is $t_{ig,cor} = t_{ig,o}/9$. These results have not been experimentally validated.

Alternatively, a criterion for ignition can be expressed in terms of a minimum HRR (kW/m^2) [11 and12], according to a critical flame temperature. It can be shown that

$$HRR_{ign} = 1.28 h_c \quad (\mathrm{W/m^2}) \tag{5}$$

with h_c in W/m^2-K, computed for a laminar flame.

Burning Process. The premixed flame is applied to the bottom of the sample in two 10-second applications in an attempt to ignite the material. Then, after the Bunsen burner is removed from the sample, it may exhibit self-sustained burning or transient ignition, depending on the heat generated by its own flame. Although the process is highly transient and coupled, only a steady-state analysis is considered in the analysis. The HRR under steady burning is given as

$$HRR = (q''_{flame} - CHF_f)\,/\,HRP \tag{6}$$

The critical condition to sustain burning, also based on a critical flame temperature, can be expressed as [12]

$$HRR_b = m''_{crit}\Delta h_c \approx \frac{\left(\dfrac{h_c}{c_p}\right) Y_{ox,\infty}\,\Delta h_{ox}}{\left[1 - \dfrac{c_p(T_{f,crit} - T_\infty)}{Y_{ox,\infty}\Delta h_{ox}}\right]} = 5.24 h_c \text{ (W/m}^2\text{)} \tag{7}$$

where the result has been computed for the critical flame temperature $T_{f,crit}$ = 1300°C, ambient air, and the heat of combustion per unit mass of oxygen of 13 kJ/g.

The convective coefficient for both ignition and burning can be estimated from the standard heat transfer literature [18]. Under natural convection of a vertical flat plate, the average value for a height of 10 mm is 63 W/m^2-K, and for burning over the entire length of the specimen (125 mm), the average value is 33 W/m^2-K. An average value for burning is taken as the mean of the two extreme lengths, 48 W/m^2-K.

This gives the critical values for ignition as 80 and for burning as 250 kW/m^2, on average. However, the critical HRR for burning could range from 175 to 330 kW/m^2 due to the variations in h_c.

Upward Flame Spread. The minimum HRR required for spread comes directly from equation 2 as 300 kW/m^2. This can be shown from the theory for spread [12], ignoring any burnout or melt-drip effects. Then, the time for the flame tip to reach the clamp at 125 mm after an initial ignition over 10 mm can be estimated

$$t_{top} = \left[\frac{\ln(12.5/k_f)}{k_f - 1}\right] t_{ig},\ k_f = HRR(\text{kW/m}^2)/300 \tag{8}$$

A flame spread parameter value (k_f) of 1 indicates no spread (as it would take an infinite time), and therefore, a critical HRR for spread is 300 kW/m^2.

The probability of spread (p_B) to the top might be expressed as $1/(t_{top}/30s + 1)$, as it would be 1 if it spreads in 0 time, and 0.5 if it spreads in exactly 30 seconds (which is the limit for burning to achieve no vertical rating (NR)). Equations 3, 6, and 8 show that proportionally, $t_{top} \sim 1/k_f^{\,2}(k_f - 1)$ for $k_f >> 1$, which suggests that the probability of burning, p_B, is related to k_f

$$p_B \sim k_f^{\,n}/(1 + k_f^{\,n}) \tag{9}$$

RESULTS

To check whether these analyses give a plausible explanation of the UL-94V rating, consistent data are needed. Data from two sources are shown in table 2. The ignition analysis shows that most materials ignite under the burner of UL-94V, especially along the corners and edges. (Due to space limitations, explicit computations are not shown.)

For the most part, the UL-94V rating mostly correlates with the HRR computed as HRR = HRP (q''_{flame} - CHF_f) for a flame heat flux q''_{flame} = 60 kW/m^2 and the data in table 2. These results are shown in figure 5, along with the theoretical limits for ignition burning and spread.

Table 2. UL-94V Ratings and Properties of Plastics

Material	Reference	Rating	HRP	CHF_f kW/m^2	TRP $kW\text{-}s^{1/2}/m^2$
1-PC-NH	6	0	0.8	5.9	349
2-HIPS-BFR	6	0	3.6	2	265
3-HIPS-NFR	6	3	5.6	0.31	358
4-PC-NFR	6	2	2.6	4.8	535
5-PC-BFR	6	0	2.3	3	425
6-PC/ABS-NFR	6	3	0.34	0	455
7-ABS-BFR	6	0	3.2	0	392
8-PC/ABS-PFR	6	2	2.3	0	450
9-HIPS-BFR	6	2	3.7	0	389
10-PC-BFR	6	0	3.3	15.8	296
11-PP-BFR	6	2	7	2.6	387
12-PP-NH	6	0	3	0	343
13-PP-BFR	6	2	12.8	4.3	299
14-PP-BFR	6	2	12.6	0	400
15-PP-NH	6	0	1.7	0	421
17-PVC-NFR	6	0	0.7	0	309
18-HIPS-NH	6	1	2.9	3.4	259
19-ABS-NH	6	1	2.1	0.13	298

Table 2. UL-94V Ratings and Properties of Plastics (Continued)

Material	Reference	Rating	HRP	CHF_f kW/m^2	TRP $kW\text{-}s^{1/2}/m^2$
HIPS	8	3	14	12.3	420
PP	8	3	22	12.3	415
PET	8	3	13	12.3	405
PS	8	3	16	7.4	355
ABS	8	3	13	9.8	365
PBT	8	3	16	16.4	520
UPT	8	3	8	8.2	343
PC/ABS	8	3	11	17.2	344
PA66	8	3	18	14.7	352
PMMA	8	3	14	11.55	274
PA6	8	3	20	13.9	461
HIPS-FR	8	2	5	12.3	351
POM	8	3	6	10.6	269
EP	8	3	13	16.4	425
PE	8	3	18	12.3	454
PBT-FR	8	2	6	13.1	325
ABS-FR	8	2	4	10.6	330
PVC (flex)	8	2	5	17.2	174
SIR	8	0	8	27.8	429
PX	8	0	4	22.9	626
PC	8	2	9	13.9	455
PEN	8	2	5	19.6	545
ETFE	8	0	6	18	478
PVC (rigid)	8	0	3	18	410
UPT-FR	8	0	4	9.8	483
CPVC	8	0	2	32.7	591
PAI	8	0	4	36.8	378
PTFE	8	0	2	40.9	654
PEEK	8	0	6	28.6	623
ECTFE	8	0	3	45.8	410
PPS	8	0	4	29.5	395

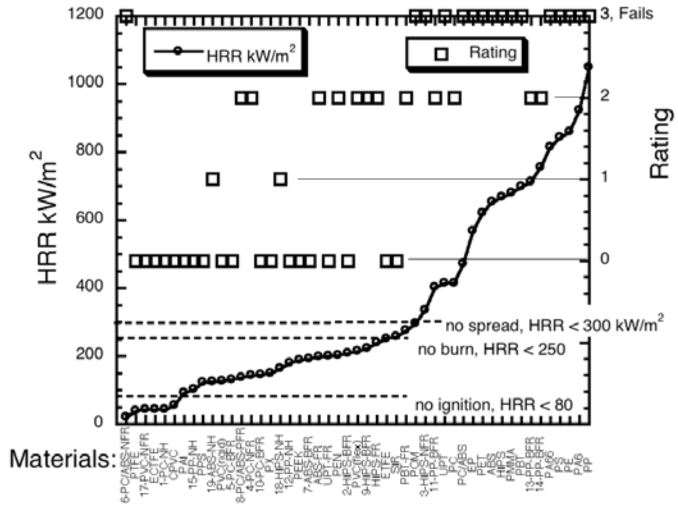

Figure 5. Correlating UL-94 Rating With HRR

Generally, there is a statistical nature for these data that track somewhat with the HRR limits:

- HRR <200 kW/m^2 contain mostly V-0
- 200 <HRR <300 kW/m^2 give a mixture of V-0, V-1, and V-2
- HRR >300 kW/m^2 contain mostly materials that fail

The probability that any rating other than V-0 is obtained in the UL-94V test (i.e., the probability of burning, p_B) was computed from the ranked data by assigning the unit value (1) to a V-0 and a value of zero (0) to any other result, i.e., V-1, V-2, NR, and taking the average binary rating in consecutive eight-sample HRR bins. Material 6-PC/ABS-NFR was eliminated as an outlier because it is reported to have a near-zero HRP, in contrast to literature values for this polymer, HRP = 11 [8]. These p_B are plotted as solid circles versus the average HRR for the bin in figure 6. Taking k_f as HRR/HRR$_b$,with HRR$_b$ = 190 kW/m^2, a critical HRR for burning, equation 9 gives a reasonable fit of the probability data in figure 6 with n = 2.5.

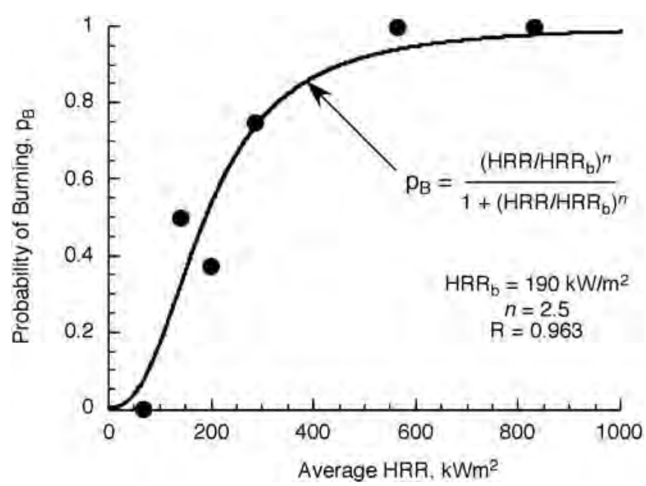

Figure 6. Probability of Failing UL-94V Versus Computed HRR of Sample

CONCLUSIONS

Performance of materials in a small vertical flame test cannot be expected to correlate with performance in other scenarios where conditions can be very different. However, an engineering analysis of the vertical Bunsen burner ignition test using accepted material fire response parameters critical heat flux, heat release parameters, and thermal response parameters, in combination with critical heat release rates for ignition, sustained burning, and upward flame spread, provide a reasonable description of the ratings of plastics in the UL-94V test and a physical basis for this ubiquitous plastics flammability test.

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