Fire Performance as a Function of Incident Heat Flux

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ABSTRACT

Numerous fire test standards exist to qualify materials for use in transportation applications. A large number of these tests deliver a pass/fail result without yielding quantitative information applicable to engineering calculations and fire risk assessments. A methodology is described involving fire tests employing external heating, quantifying performance in terms of incident heat flux, resulting in Flammability Diagrams. These Flammability Diagrams provide a comprehensive picture of a material's fire performance that can be used in engineering applications.

INTRODUCTION

In the process of selecting new or alternative materials for transportation vehicles, a necessary consideration is the fire performance of the material. In other words in the event that the material becomes exposed to an ignition source or a fire environment, what will be the extent of the material's involvement and effect on the outcome of the fire. Will the material easily ignite and spread the fire, or will its involvement be non consequential? The critical role of material flammability, in the development and survivability of fires has long been recognised, and for this reason it is required that the materials selected for use must successfully pass certain "Flammability tests". Strangely it seems that each industry or organisation requires a different set of tests to evaluate materials, so there is a multitude of "Flammability test methods". Reviewing the requirements of the different agencies in the US DOT it is found that there are approximately 23 different tests used all to assess material flammability. These are generally small scale (with a few large scale) screening tests. Although the characteristics that would define the flammability of a material should be universal, the multitude of different test methods would indicate otherwise.

The general nature of most flammability tests is to benchmark or screen a material's performance. The performance criteria are typically determined by adopting the test results of a material chosen to give the measure of acceptable performance. The results of these tests either classify a material's performance as belonging to a certain group of materials that behave similarly or they provide some sort of index based result. In very few cases do these tests provide results in terms of properties that could be used in engineering calculations. For example the Bunsen burner type tests are simply tests in which a sample material is suspended from a holder inside a draft proof chamber and temporarily exposed to the burner's flame. There are different variants of these tests in which the orientation of the sample or the duration of flame exposure is changed. In all of the variations there is no external heating being applied to the sample. The results given by these tests are in the form of a classification. Each classification is related to factors such as the length the flame spread on the sample, the time for the flame to extinguish after removal of the burner flame, and/or if flaming droplets formed. The results or classification from this test do not provide a complete description the materials performance under typical fire conditions nor are they useful in an engineering analysis. Conversely the ASTM E-648 test for flooring materials uses a radiant panel in an inclined configuration to expose a horizontal test sample to a heat flux gradient. The sample is ignited at the high heat flux end and the flame front travels towards the low heat flux end. The point at which the flame spread ceases corresponds to a minimum or critical heat flux for flame spread. This result can be applied to engineering calculations and is not a relic of the test itself.

In spite of the vast number of tests that are available none gives a complete picture of the fire performance of a material. Because in the initial stages of a fire the most influential parameter is the incident heat flux[1], it seems logical that the most relevant description of a material's fire performance should be given in terms of incident heat flux. With information like time to ignition, flame spread rate, and energy release rate as functions of incident heat flux, and along with properties such as and critical heat flux for ignition, flammability diagrams can be drawn to give a more complete picture of a material's fire behaviour. Additionally this approach would provide information suitable for use in an engineering analysis. Knowing the properties and behaviour of a material as a function of incident heat flux is an essential part in understanding what will be the performance of the material in a fire situation. This paper presents a method for flammability testing which establishes the material's fire performance as a function of incident heat flux. The same methodology could be applied using other equipment and test setups than are described here, providing the idea of testing as a function of incident heat flux is maintained.

EXPERIMENTAL METHODS AND PROCEDURES

The materials used in the test series were thermoplastics. Availability was the driving force for this selection and the fact that at an increasing rate traditional materials are being replaced by modern plastic components. The challenging thermo physical behaviour exhibited by some of the plastics made obvious the potential pitfalls of some testing approaches. The materials used for the study were obtained in sheet form and were cut to the desired sample sizes. Twelve different plastics (Table 1) were used for the study but in the end only four of them have been tested in both the Cone Calorimeter and flame spread apparatus. The results for these four materials will be discussed in this paper (Table 2).

Table 1 (Materials tested in the Cone)

Sandwich panel	High-Impact Polystyrene [HIPS]	Polycarbonate [PC]
Polyphenylene sulfide [PPS]	High-Density Polyethylene [HDPE]	Poly(methyl methacrylate) [PMMA]
Polyvinyl chloride [PVC]	Polyvinylidene fluoride [PVDF]	Acrylonitrile butadiene styrene [ABS]
Polyamide 6,6 [PA66]	Polyoxymethylene [POM]	Polyetherimide [PEI]

Table 2 (Materials tested in the Cone & flame spread apparatus)

Materials	Heat of Combustion (kJ/g)	Critical Heat Flux (kW/m2)
High Impact Polystyrene [HIPS]	28.8	16
Polyoxymethylene [POM]	13.5	8
Poly(methyl methacrylate) [PMMA]	23.3	8
Acrylonitrile butadiene styrene [ABS]	28.2	12

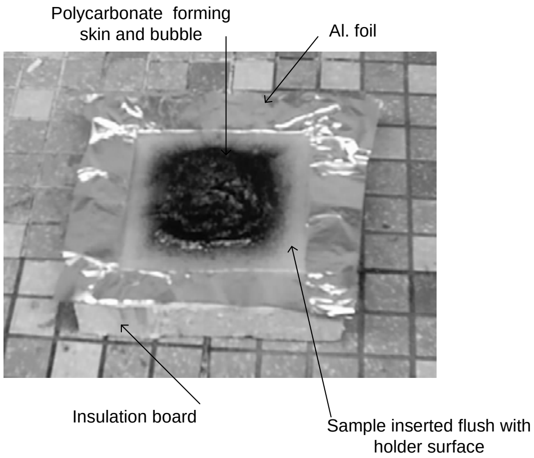
The experimental methods to determine the material's fire performance in terms of incident heat flux consisted of tests using the well established Cone Calorimeter to obtain ignition, energy release, and mass loss data, and a custom built radiant panel apparatus for measuring flame spread as shown in Picture 2.

Cone Calorimeter experiments

The tests using the Cone Calorimeter were carried out on a modified Atlas Cone Calorimeter. The major modification being that all the original controls and circuits had been replaced by a LabView program providing the user interface and data acquisition system. Also, Instead of using the standard metal sample holder a sample holder was made from insulation board by hollowing out a square area on the board, the same size as the sample so that when the sample was placed in the holder it would sit flush with the top surface and conceal the edges. Pressed between the sample and the holder would be a sheet of aluminium foil so that after the test the holder could be reused. An example of this can be seen in Picture

1. The test specimens were cut into squares of 76mm on side with a nominal thickness of 6.5 mm. The general objective was to measure the time to piloted ignition (t_{ig}), energy release rate per unit area $(\dot{Q}'')$, and the mass flux $(\dot{m}'')$ as functions of applied heat flux. Initial testing consisted of a broad sweep of incident heat flux levels using all the materials and testing at 20, 30, 40, 50 and 60 kW/m^2.

Picture 1 (Sample holder used in Cone tests)



With this initial test set as a reference point individual materials were further tested in order to narrow down their critical heat flux for piloted ignition. The cut off point to declare a non ignition was 25 minutes of exposure with no ignition and no indication of imminent change. Ignition needs to also be defined since during the tests, phenomena, such as flashing, temporary ignition or the need for constant presence of the spark igniter to sustain the fire were sometimes observed. This became problematic especially in the case of materials with fire retardant chemicals (PVDF, PVC) where there were multiple temporary ignitions which could be a few seconds to a minute long. So the ignition time was defined to be the time when ignition was sustained until burn out. The times that temporary ignitions occurred were also recorded but the sustained ignition time is what was considered time to ignition

Additional complications occur when a material has a tendency to form a “skin” over the surface (Nylon). This skin traps the gasses being generated from pyrolysis resulting in the formation of a bubble. The bubble continues to grow until it ruptures at which point a jet of hot fuel erupts from inside as the bubble collapses. Occasionally this jet self ignites (seen at 60 kW with PEI) alternatively it can usually be ignited with the spark igniter or a manually held lighter. In some instances the ignition from the erupting gas will persist like a small pilot light and gradually will wear away at the skin and the fire will spread across the sample’s surface. In other instances the fire extinguishes and the skin reseals resulting in the beginning of a new bubble. Some times it is not possible to use the Cone’s built in spark igniter since it would come into physical contact with the rising bubble (see Picture 1).

Flame Spread Experiments

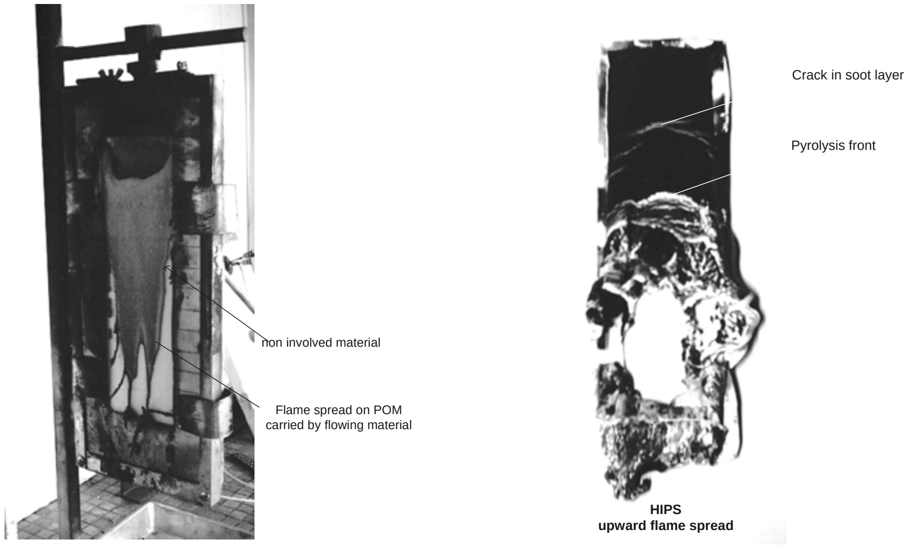
For the tests involving flame spread as a function of incident heat flux a custom apparatus was constructed. The apparatus consisted of two propane fuelled, infrared radiant heaters mounted on a frame as shown in Picture 2. The heaters were oriented so that the irradiance on the sample is uniform from top to bottom. This was verified by inserting a board with two Gardon type heat flux gauges, one at the top and one at the bottom into position where the sample holder would go (this is also shown in Picture 2). This gave a measure of the magnitude and uniformity of the incident heat flux. To adjust the incident heat flux either the fuel flow to the heaters was adjusted or the sample holder was translated along a fixed track keeping it alignment with the heaters. The sample holder consisted of a refractory board held by an aluminium frame with a hinged front cover. The front cover was a thin piece of sheet metal with a cut out in it. It was held in place in front of the sample, to both secure the sample in place and cover its edges. The cut out in the cover had an area of 76mm by 280mm. An example can be seen in Picture 2. Along the edge of the sample holder there were marks every 2 cm to aid in recording the flame spread rate. It was attempted to get discrete data for the spread rate but in most instances, especially during rapid upward spread, it was only practical to measure the time to reach the half way mark and the end point.

Picture 2 (Flame Spread Apparatus and Sample Holder)

The procedure was to set a certain heat flux level and then to place the sample holder and sample into position in front of the heaters. It was intended that the sample be left in place to preheat so the surface would reach a steady state temperature and then it would be subsequently ignited either from the top or bottom depending on the test. The igniter was constructed to be like a small ribbon burner so that the whole edge of the sample would be ignited at once. Both upward and downward flame spread rate was measured for a few of the materials. Not all of the materials were tested in this apparatus due to an unforeseen difficulty. The subset of the original 12 materials that were tested with the flame spread apparatus includes HIPS, ABS, PMMA and POM. The problem was that before the preheating period would end, the sample would reach its melt or flow temperature and begin to slump and fall out of place. The preheating time needed to be reduced while maintaining the idea of reaching a steady state. To do this a methodology akin to what is used in ASTM LIFT test was used to compensate for a preheating time less than the time required to reach steady conditions[3]. This method successfully correlated the ignition results.

Just as in the calorimeter tests various unforeseen phenomena occurred during the experiments. Two distinct issues that had a significant impact on the test results were the effect of melting/flowing of the material and soot deposition. The melting and flowing phenomena played a role in both upward and downward flame spread whereas the “sooting” phenomenon only played a role in upward flame spread. The molten material increased the downward flame spread velocity and decreased the upward velocity. This was because in the downward tests the flowing material carried heat to the sections below, and at times carried the flame itself down the sample surface (Picture 3). In the upward direction the downward flow of material carried heat away from the direction of travel and thus slowed down the progression. The sooting phenomenon exhibited by some materials during upward spread had the effect of insulating the sample surface. At times the soot layer could be 1mm thick. It appeared that this effect was more influential in the tests with lower heat flux levels. This was seen by examining the remains of the tested samples and noting a decreasing amount of soot deposition as the incident heat flux was increased. Also it was noticed that the flame front progressed by causing the material ahead, under the soot, to melt and flow downwards. This would cause the soot layer to crack and allow the flames to ignite the surface. This would slowly be repeated up the sample surface as can be seen in Picture 3. Downward flame spread rate was fairly easy to observe and measure even when flowing occurred. On the other hand upward flame spread was more challenging since the flames obscured the sample surface and the extent of the sample's involvement was hard to see.

Picture 3 (melting/flowing and "sooting" phenomena)



ANALYSIS

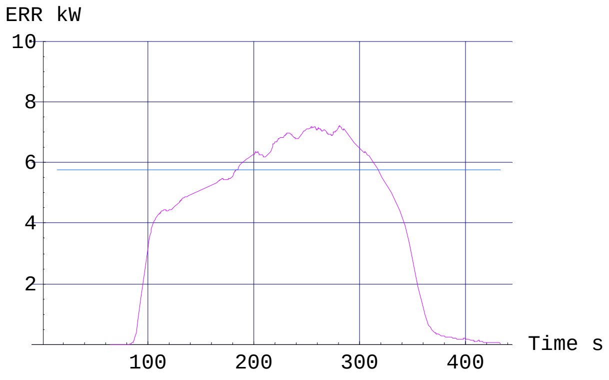
The following is the description of the data reduction procedure for both the calorimeter and flame spread data. It was necessary to first analyse the ignition data from the calorimeter and establish the critical heat flux for ignition which could then be used in finding the time response function F (t) used in the reduction of the flame spread data.

Cone data

The data measured with the cone calorimeter include time to ignition, energy release rate, mass loss rate, heat of combustion and mass flux at ignition. For the calculation of the energy release rate the standard[4] relationship given in ASTM E-1354 was used.

Since the test samples were not very thick (~6.5mm) the fires in the Cone seldom reached a sustained peak burning rate and generally displayed narrow peaks in the energy release rate. To obtain a more consistent and meaningful energy release rate an 80% peak average energy release rate was computed. This was done in the following manner. Once the actual peak was found the points on the energy release rate curve corresponding to 80% peak were found. This was done by plotting the energy release rate along with a straight line corresponding to 80% of the peak value. The energy release rate was then integrated between the intersecting points and divided by the time interval. This is graphically shown in Figure 1. The same exact technique was used in calculating the 80% peak average mass loss rate.

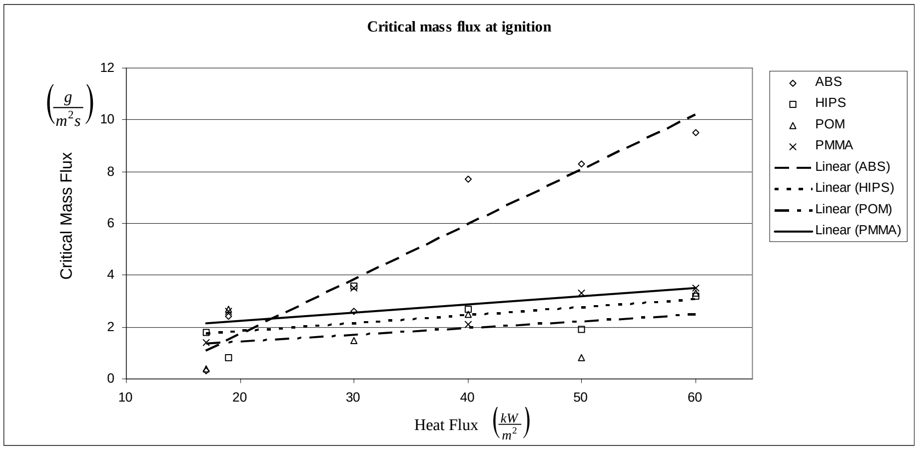
Figure 1 (Energy release rate, HIPS @ 40kW/m2)



The heat of combustion was calculated by dividing 80% peak energy release rate by the 80% peak mass loss rate. The calculated values for heat of combustion are generally within $2kJ/g$ of the values reported by Tewarson[2] for the same types of plastics.

A measure of the mass flux at ignition could be found by evaluating the mass loss rate at the instant of ignition. Although ignition does not always occur at the instant when the mass flux has reached a critical value. The ignition occurs when the a flammable mixture forms near the spark igniter, so when ignition occurs it does not necessarily coincide with the exact time the mass flux has reached its critical value. It is possible that this delay may have a larger effect at high levels of heat flux where the change in mass loss rate is high and so a delay would make a significant difference in the measured mass flux. At low levels of heat flux this delay would not result in such a large change in the mass flux. For these tests the critical mass flux was evaluated at a point 5 seconds prior to sustained ignition. The results are shown in Figure 2. For all except ABS, the measured mass flux at ignition remained fairly constant over the range of tests. These values are slightly lower than those reported by Tewarson[2] for comparable materials.

Figure 2 (critical mass flux at ignition for four selected materials)



Flame Spread Data

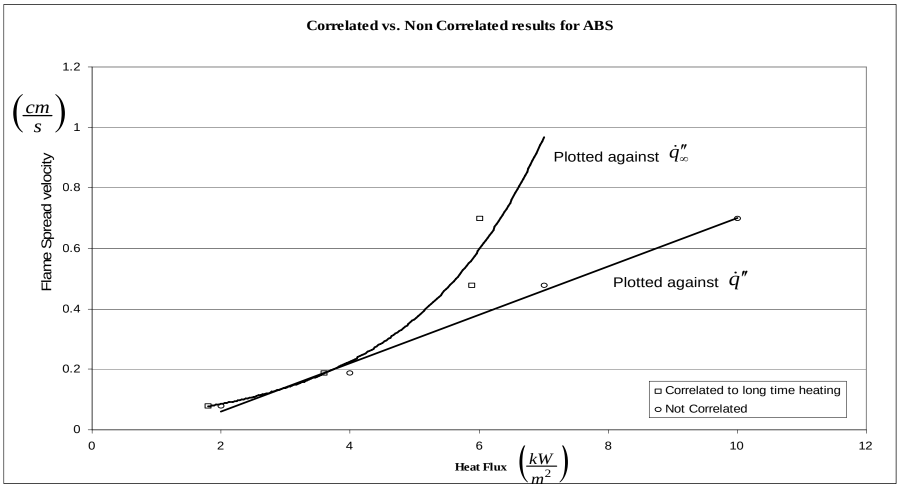
Overall the calculation of the flame spread velocity is straight forward. With a timer, the time for the flame front to travel from the point of ignition to the middle of the sample and then on to the end were recorded. Two velocities (beginning to middle and beginning to end) were calculated and averaged to give a final overall flame spread velocity over the sample's surface. This unfortunately was rather coarse and obscured any trends of acceleration. For example in downward spread, once the flame front reached the middle of the sample there would be considerable melting and the flame front would be carried by the flowing material increasing the velocity. Alternatively the "sooting" previously described, would slow down the upward flame spread.

To plot the flame spread velocity data versus the incident heat flux it was necessary to make an adjustment for the preheating time as previously mentioned. The data was correlated in the following manner. Once the critical heat flux for ignition was found from the calorimeter tests, the ignition data was plotted as $\frac{\dot{q}''_{critical}}{\dot{q}''} vs. \sqrt{t_{ig}}$. When the external heat flux was equal to the critical heat flux, $\frac{\dot{q}''_{critical}}{\dot{q}''} = 1$, then the time to ignition was the thermal response time of the material t^*. The graphical method to find t^* is shown in Figure 4. To adjust for preheating times less than the thermal response time, the function F (t) was used and the incident flux became

$$\dot{q}''_\infty = \dot{q}''F(t) \qquad [1]$$

Using this correction approach adjusted the data so it was representative of long time heating. An example of this is shown in Figure 3. Here ($\dot{q}''_\infty$) is the effective external flux ($\dot{q}''$) applied after a long time.

Figure 3 (effect of thermal response correction)



FLAMMABILITY DIAGRAMS

Since heat flux is the principal factor controlling early fire growth, it is incumbent on the engineer and safety regulator to understand a material's fire behaviour as a function of heat flux. Moreover theoretical relationships can be put forth for the fire phenomena ignition, energy release and spread in terms of flux, at least for sample materials. Effects of melting, dripping, thickness, sooting and other factors may not fully be described, but experimental renditions of the theoretical framework would suffice.

Theoretical Basis

Here we simply state some theoretical relationships. For thick or thin materials the time for ignition can be represented as

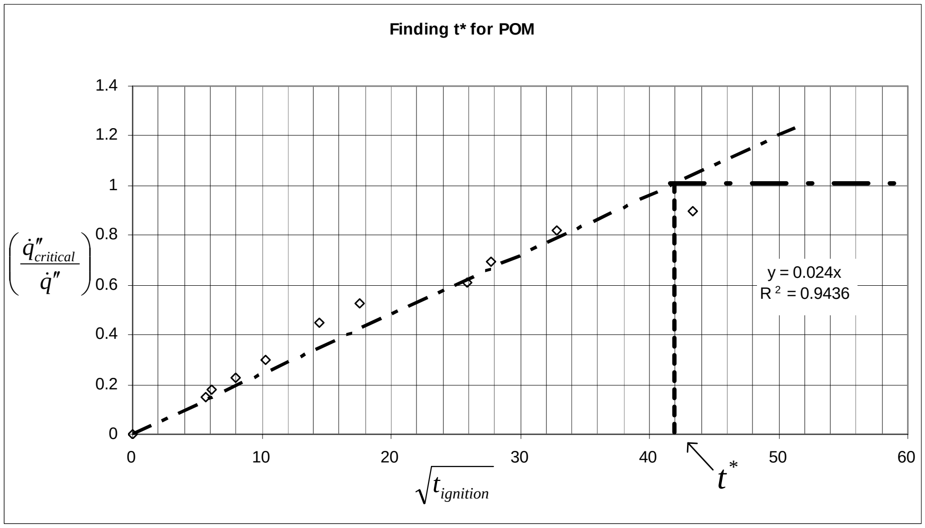
$$t_{ig} = \begin{cases} \rho c \delta \dfrac{(T_{ig} - T_o)}{\dot{q}''}, thin \\ \dfrac{\pi}{4} k \rho c \left(\dfrac{T_{ig} - T_o}{\dot{q}''} \right)^2, thick \end{cases} \quad [2]$$

where $\dot{q}''$ is the imposed (external) heat flux and T_o is the initial temperature. For thick materials an approximate result can be written as

$$\frac{\dot{q}''_{critical}}{\dot{q}''} = \begin{cases} b\sqrt{t_{ig}} \equiv F(t), t_{ig} < t^* \\ 1, t_{ig} \geq t^* \end{cases} \quad [3]$$

where $\dot{q}''_{critical}$ is the minimum flux below which ignition does not occur. The t^* is "the time to reach steady state" and was used as a guide in preheating the sample in flame spread experiments. It can be determined from data as illustrated in Figure 4.

Figure 4 (graphical determination of t^*)



By pre-heating the sample in flame spread experiments, the surface temperature achieved

$$T_s = T_o + \frac{\dot{q}''}{h_t} F(t) \quad [4]$$

Flame spread speed can then be described as

$$u = \frac{\delta_f}{t_{ig}} \quad [5]$$

where the flux to cause ignition on the surface is flame heat flux $\dot{q}''_f$, and δ_f is its heat transfer length.

Here for a thick sample:

$$t_{ig} = \frac{\pi}{4} k\rho c \left(\frac{T_{ig} - T_o - \frac{\dot{q}''}{h_t} F(t)}{\dot{q}''_f} \right)^2 = \frac{\pi}{4} \frac{k\rho c}{h_t^{\,2}} \left(\frac{\dot{q}''_{critical} - \dot{q}'' F(t)}{\dot{q}''_f} \right)^2 \qquad [6]$$

Also, if we desire the spread velocity after an indefinite heating time (∞) , then plotting u versus $\dot{q}''F(t)$ is the same as $\dot{q}''$ for $t \to \infty$. This gives velovity as a unique function of heat flux, and this is how the data for flame spread are presented. Furthermore the critical flux for ignition is also the limiting flux (at long time exposure) for infinite velocity.

From Tewarson[2], the steady burning rate per unit area can be expressed as

$$\dot{m}'' = \frac{\dot{q}''_f + \dot{q}'' - \dot{q}''_{rr}}{L} \qquad [7]$$

Then the energy release rate per unit area is

$$\dot{Q}'' = \dot{m}'' \Delta h_c \qquad [8]$$

Moreover conditions for ignition, spread and burning rate can also be shown as dependent on heat flux. It can be shown that the minimum mass flux for burning is greater than that for ignition and further, theoretically, they are inversely related to Δh_c .

With the ignition and flame spread data, plots giving a general description of the fire performance of the materials can be constructed. In these plots the critical heat flux is shown to be the asymptote of the time to ignition and the flame spread velocity for both upward and downward spread. This is what would be expected since at long time $(t_{ig} \to \infty)$ heating under the critical flux, the surface temperature would approach the ignition temperature (T_{ig}) . When the sample surface is at the ignition temperature the time for ignition approaches zero and the flame spread velocity would approach infinity from [5]. This is why both the ignition time and spread have the same asymptote as seen in the following Figures. Although the ignition times are quite similar, the critical heat flux for ignition varies for the different materials as does the energy release rate.

Figure 5 (HIPS Flammability diagram)

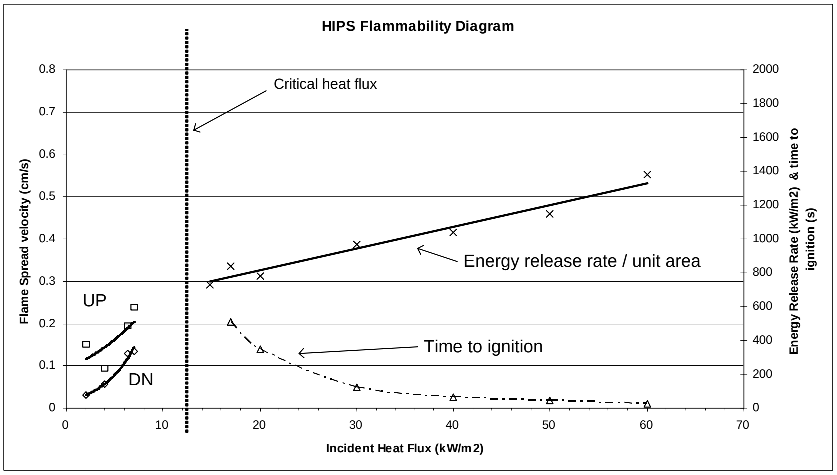


Figure 7 (ABS Flammability diagram)

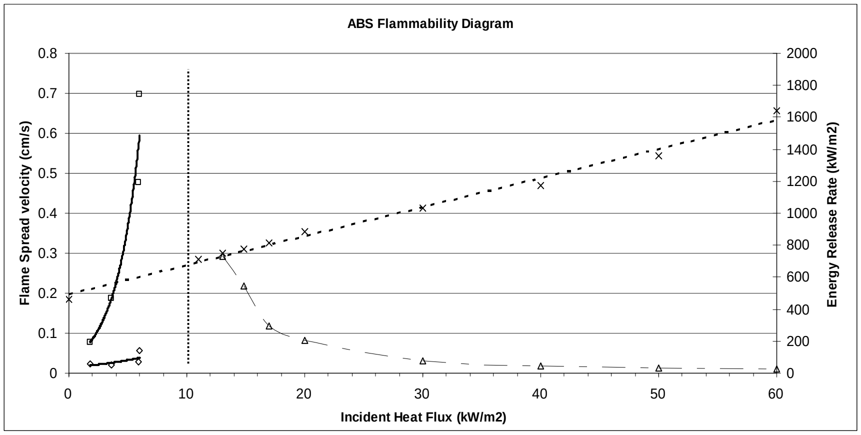


Figure 8 (POM Flammability diagram)

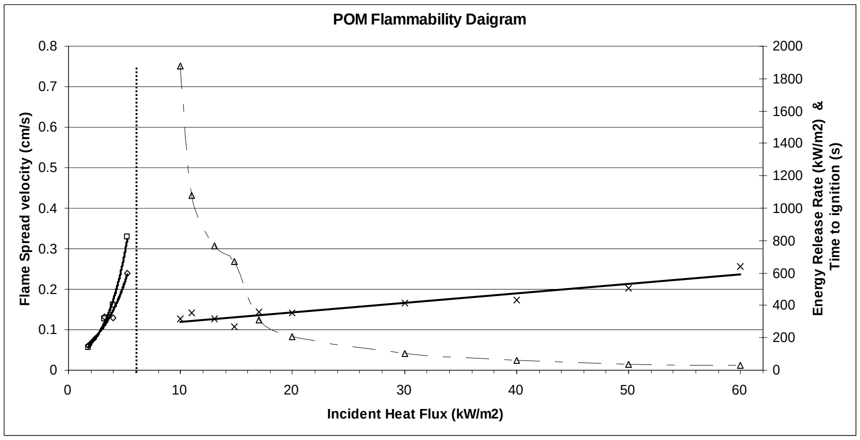
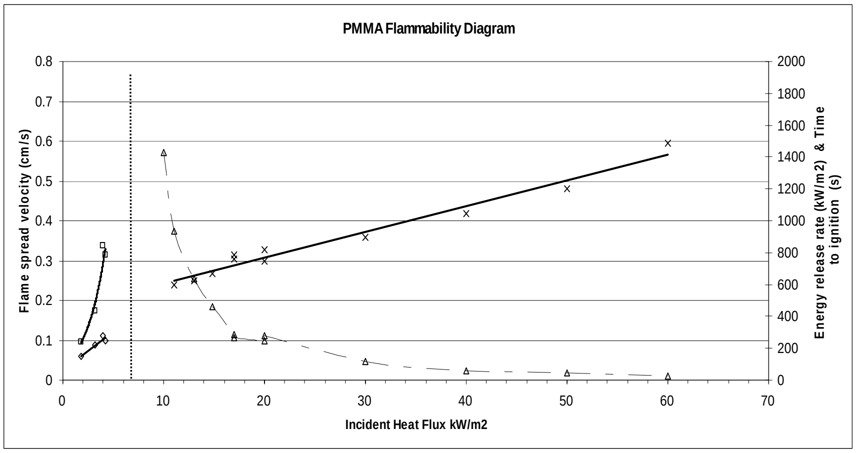


Figure 8 (PMMA Flammability diagram)



CONCLUSIONS

We have shown that the fire performance of materials is highly dependent on incident heat flux, a fact which is consistent with theory. Although tests using some of the standard test methods were not done with the materials used in this study, the results from the UL-94 Bunsen burner test for these materials happen to be publicly available. UL-94 classifies all of the materials as HB, meaning that the samples will show fire spread in the horizontal position not exceeding 76mm per minute (0.12 cm/s). This may be the spread rate in the horizontal position with no external heating, but as can be seen from the flammability diagrams this is no longer true with an applied heat flux greater than $5\frac{kW}{m^2}$. Additionally, although this was not specifically tested, judging from the low heat flux flame spread test of ABS it seems that upward flame spread on ABS may cease after a temporary forced ignition if there is no external heat flux applied. This is due to the sooting phenomenon previously described. Downward flame spread can be sustained with no external heating on ABS since the sooting does not occur. A similar behaviour is seen in HIPS but not POM and PMMA. These observations show that for these types of materials, tests in which only one orientation is examined can give misleading results. From the Flammability diagrams it is evident that a single classification can do little in describing the true nature of these materials. Their performance is not identical and can not be accurately accounted for by a singular test. Even though difficulties such as melting, sooting etc. could use special handling or a different test setup, meaningful flammability diagrams can be produced despite these effects and they depict a comprehensive overall fire response for the material.

ACKNOWLEDGMENTS

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