# An Example of the Use of Standard Flammability Criteria for Performance Analysis of Materials: Polycarbonate and PMMA

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## ABSTRACT

A detailed flammability evaluation of two different materials is presented, as an example of how important is physical observation and detailed analysis in the interpretation of test data. The objective is to provide different criteria that could allow the use of standard test data in fire modeling. The tests used are the lateral ignition and flame spread test (ASTM-E-1321) and the oxygen consumption calorimeter (ASTM-E-1354). The materials evaluated are a polycarbonate (Lexan) and compared to a commonly studied ideal material, PMMA (i.e., Poly-methyl-methacrylate). Lexan is a solid plastic sheet, generally considered as fire resistant. The solid plastic sheet is proposed as an alternate to PMMA for use as containment windows for glove boxes containing radioactive components in nuclear facilities. For idealized materials, such as PMMA, heat transfer from the flame to the fuel controls flame-spread rates. This study shows that the behavior of the Lexan, in the case of a fire, will be first governed by melting. Furthermore, if the material is placed vertical, the results indicate that the motion of the molten fuel, rather than the transport of energy will control flame-spread rates. Additional medium-scale tests fully confirms the main results obtained by the small-scale experiments.

**KEYWORDS:** material flammability, ignition, PMMA, Lexan

## INTRODUCTION

Material flammability assessment is an area of increasing complexity mainly due to the development of new technologies and of new engineered materials. Traditional test methods give some indicators of the relative performance of materials but many times provide little or no information that could be used to predict the behavior of a specific material in the event of a fire. Currently, the information from standard test methods is used to define selection criteria for materials and cannot be directly incorporated in fire models and thus, cannot be used to estimate the impact that a particular choice of material can have in the potential growth of a fire. The evolution of fire regulations towards performance based engineering analysis and the increasing scientific basis that is being required for fire reconstruction makes necessary a more in depth definition of material flammability, one that relies more on physical properties and empirical observation and less on pre-defined selection criteria. Standard test methods are commonly used for material flammability assessment and can be crudely separated in two different categories. Those that provide a ranking based on a direct observation (i.e., floor radiant

panel, upward flame spread test, etc. [1-3]) and those that rely on a physical principle to rank the materials (i.e., Limiting Oxygen Index, Flash Point, Energy Release Rate, etc. [1-3]). Within the later group, some test methods provide information that could be incorporated into a fire model. The flash point or the critical heat flux for ignition (ignition temperature) could be used as an ignition criterion as well as an indicator of flame spread [1]. Also, the lateral ignition and flame spread test provides other thermal properties that can be linked to the material and could be used to model ignition and opposed flame spread [1]. These properties are mainly the thermal inertia ($k\rho C$) and the flame spread parameter ($\phi$). The energy release rate corresponds to the total energy delivered by the combustion reaction [1,4]. Finally, the limiting oxygen index can be used as an extinction criterion under conditions where the oxygen concentration changes are expected [1]. Together and within an adequate model, these parameters provide the necessary elements to model the growth of a fire. However, the quantitative data obtained from the standard tests corresponds only to the conditions which the tests are conducted. Many studies have attempted to separate the particular experimental conditions of the tests from the relevant material properties [5-8] but this work is far from being completed. A notable exception seems to be the energy release rate, where the presence of a cone shape heater in the standard test allows recreating conditions deemed representative of a real fire, thus the generalized use of data from this standard test in fire models [8,9]. The accuracy of this type of extrapolation has been questioned, leading to the development of larger scale calorimeters that provide direct estimation of the energy release rate [10,11]. In this study, the flammability of two different materials is evaluated. A solid plastic sheet, called Lexan, is currently proposed as an alternate to Plexiglas (i.e., Poly-methyl-methacrylate (PMMA)) for use as windows in glove boxes enclosing radioactive components in nuclear facilities. The catastrophic potential consequences of a fire in a nuclear facility demand an accurate definition of the material properties that will lead to failure of the system. Therefore, the present approach carries out a detailed analysis of the Lexan material properties that go beyond the standard tests.

## BACKGROUND

### The Materials

The solid material Lexan is a transparent thermoplastic sheet. Many thermoplastics are flammable and as a result flame-retardants are added to allow these materials in building construction [12]. Lexan, however, does not contain flame retardant additives. Instead, the thermoplastic is extruded from polycarbonate resin, which gives Lexan better impact resistance and fire performance than many other thermoplastic materials on the market [13]. Lexan has passed the Glow Wire test according to IEC695-2-1 for 850ºC. For this test, a glowing wire is applied near the lower edge of a vertical sample to see if the sample ignites and if so how fast the flame spreads. Furthermore, according to the manufacturer (GE Structured Products), Lexan will not ignite when exposed to temperatures under 426ºC. Poly-methyl-methacrylate (PMMA - Rohm and Haas, Type–G) is a commonly used reference material for fire tests. For detail description of its properties, flammability characteristics and application the reader can consult references [7,8,11,12,14].

### Test Methodologies

In this section, a brief description of the test methods is provided. Some details on variants of the standard tests used are also presented. The modifications were necessary

due to the specific constraints imposed by the materials tested, but were always accompanied by an in-depth analysis of the physics of the process. A preliminary test, similar to the glow wire test, was conducted for the Lexan sheet to show in detail the behavior of a vertical sample exposed to a glowing wire.

*Lateral Ignition and Flame Spread Test (ASTM-E-1321)*

The Lateral Ignition and Flame-Spread Test (LIFT) consists of two independent tests, a piloted ignition test and a flame spread test. Details of the procedures and methodology can be found in reference [1] and of the theoretical background in reference [14]. The standard test requires a vertical sample; for liquids and melting materials, the protocols need to be modified to conduct tests horizontally. Furthermore, thermal equilibrium cannot be attained since the fuel will be modified throughout the heating process. Details on the modifications required can be found in Wu *et al*. [15]. For material flammability evaluation, ignition tests have to be conducted for different external heat-fluxes and, as the heat-flux is reduced, the ignition delay time increases until ignition is not achieved. The maximum heat flux that does not lead to ignition is the critical heat flux. A total heat transfer coefficient, $h_T$, an ignition temperature, $T_{ig}$, and the "thermal inertia" (which corresponds to the products of "$k\rho C$") can be determined. Flame-spread takes place once the fuel is ignited and the flame spreads over the solid fuel once the surface attains the temperature for ignition, $T_{ig}$. The test measures the flame-spread velocity for different heat-fluxes and a fit of theory to the data permits the empirical determination of what is labeled the "flame spread parameter", $\phi$. The FIST apparatus is an alternate version of the LIFT as defined in ASTM E-1321 [1]. This alternate methodology follows the same principles of the LIFT but uses smaller samples, 30 mm x 30 mm for the ignition test and 30 mm x 100 mm for flame spread test. Details on the analysis that preceded the reduction of the sample size are described by Long *et al*. [16] and will not be repeated here. For the present study, the FIST will be used instead of the LIFT.

*Energy Release Rate*

The total energy release as a function of time and per unit area is calculated from the oxygen consumption calorimeter method (ASTM-E-1354 [1]). The method is based on the well-recognized assumption that approximately 13.1 *MJ* of energy is released per 1 kg of oxygen consumed [4] with an expected error band of +/- 5% (ASTM-E-1354 [1]). The test method can also be used to determine ignition delay time, mass loss rates and an effective heat of combustion. The cone calorimeter used in the present study is in conformity with ASTM-E-1354 [1].

## EXPERIMENTAL RESULTS AND DISCUSSION

### Preliminary Tests and Special Behavior of Lexan

A simple equivalent to the glow wire test (ICE 659-2-1) was performed to illustrate the behavior of the material under this particular test condition. A 40 mm x 143 mm x 9.5 mm slab of Lexan was subject to the heat insult from an electrically heated Kanthal wire. The glowing wire was placed under the slab and held there for 5 minutes. The test was repeated at a higher voltage until the wire melted. The melting point of Kanthal wire is rated at approximately 1100°C. No ignition was observed during any of the wire tests.

(a) (b) (c)

Fig. 1. (a) Piloted ignition of the melted and expanded plastic, (b) Full fire (~30 seconds after ignition), (c) The intumesced char matrix after the test and an unburned sample.

Nevertheless, it was observed that the material melted around the wire and dripped downwards until no contact existed between the heater and the Lexan. To provide a larger and more intense heat source, a propane flame generated by a Bunsen burner was used to try to ignite the sample. After the burner flame was applied for about five seconds to the lower part of the sample, the material ignited. As soon as the burner was removed, the flame died. This procedure was then repeated a few times until the sample started to melt. Once melting was observed, the flame became more persistent until a small flame was permanently observed at the lower edge of the plate. Periodically, the ignited material will drip downward supporting a small pool fire below the sample. The flame did not spread upwards but continued to drip downwards, forming a flaming pool below the original sample. Although the sample did not have any upward flame spread, and thus it is considered to pass the test, it was clear that this was not due to the non-flammable nature of the material, but to a combination of its fire, thermal and mechanical properties. Experiments with burning of thermoplastics have demonstrated that ignition of such materials is a very complex process [2,3,12,17,18]. The key factor, long recognized, is that most thermoplastics change shape with time as they are subjected to heat. The modeling of the burning process of such materials is very difficult [17] and a small number of studies are available in the literature [18]. Due to the melting behavior of the thermoplastics, the repeatability is often considered poor, and no single standard bench scale tests can be considered suitable for testing such materials [12]. When the plastic board was exposed to external radiation in the oxygen consumption calorimeter, it started to melt. After 30-60 seconds (depending on the heat flux), bubbles started to form on the surface. As the bubbles started to grow, the material expanded, causing the surface to rise. The state of the material changed from a solid to a highly viscous liquid embedded in a char matrix. Following the burst of a bubble, the vapor inside ignited, leading to a flame. Figure 1a and b- shows a sample with sustained flaming. The ignition of the samples did not follow a well-defined pattern. Generally, ignition occurs when the igniter touched and cracked the bubbles. Therefore, under the configuration of the cone calorimeter, the location of the pilot has a significant effect on the ignition delay time. The ignition delay times obtained following this methodology have to be looked upon with caution. For Lexan, the ignition protocol of the LIFT (FIST) was deemed more appropriate since the pilot is placed outside the fuel surface area in this test. The importance of bubble formation on ignition delay time was greatest close to the critical heat flux for ignition, i.e., below 30 $kW/m^2$. For the higher heat fluxes, the material ignited before the surface had risen to the level of the igniter. Therefore, ignition data from the oxygen consumption calorimeter will only be included for high heat fluxes. The ignition times and heat fluxes (Fig. 6) will be discussed in the context of the LIFT (FIST) tests. When the sample was ignited, the flame spread rapidly over the entire melted

surface. A char was formed at the center of the specimen. The char intumesces from the surface to form a cone shaped char matrix with its center in the middle of the sample (Fig. 1c). This phenomenon is a common behavior for engineered polymers [17,18]. It is important to note that this charring pattern is only observed after ignition occurs and was not present in the glowing wire ignition test. The melted material created seal that prevented gaseous products of the material degradation, located beneath the sample surface, to escape. This caused the gaseous products to accumulate below the sample surface. As a result, the central part of the charred sample was pushed upwards, creating the char matrix.

**Heat Release Rate**

Figure 2 shows how the heat release rate from the samples varies when the samples are exposed to different external heat fluxes. The results show comparable maximum heat release rates (approximately 300-400 kW/m$^2$) for the five different external heat fluxes. The peak occurred generally in the beginning of the tests, typically before the intumesced char matrix had reached a significant height, and thus blocked some of the heat flux from the flame and the cone. The presence of a char layer also explains why the external heat flux does not seem to have any particular influence on the peak heat release rate. Kashiwagi *et al*. [18] reported similar observations when testing two different samples of polycarbonates. It is important to note that, although the external heat flux has a negligible effect on the peak energy release rate, it does have a significant effect on the decay period. For 30 kW/m$^2$, burning lasted less than 300 seconds while, for 60 kW/m$^2$, the decay period continued for more than 800 seconds. The external heat flux served to support the evaporation of the fuel even in the presence of a thick char layer. After the flames extinguish, the char continues to smolder, this explains why the Heat Release Rate curves do not descend to zero at the end of the test. For comparison, Fig. 2 presents typical data for a PMMA sample of identical dimensions. It can be observed that both the peak heat release rate and the burning period are much smaller in the case of Lexan. The data for PMMA was obtained with an external heat flux of 50 kW/m$^2$ and a shift in time was introduced to bring ignition to $t$ = 0 sec.

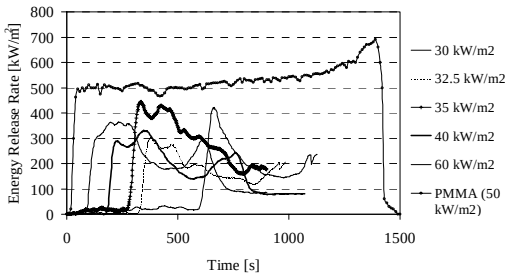



Fig. 2. Heat release rate as a function of time for different external heat fluxes. For comparison a similar test conducted for PMMA is presented, the data for PMMA was obtained with (50 kW/m$^2$) and has been translated in time to make ignition, $t$=0 sec.

From the curves in Fig. 2, the total heat release can be estimated (Fig. 3) and reveals to undergo a transition between 32.5 kW/m$^2$ and 35 kW/m$^2$. This transition shows that, after the initial period, burning has to be supported by an external heat-flux. If the external heat-flux is less than approximately 35 kW/m$^2$, Lexan will cease to burn after the peak energy release rate has been attained. This information provides a quantitative extinction criterion for modeling.

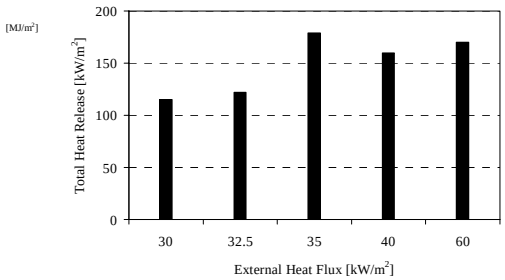



Fig. 3. Total heat release for different external heat fluxes.

**Qualitative Evaluation of Ignition and Flame Spread**

Piloted ignition and flame tests where conducted using the LIFT (FIST) protocol. An initial set of tests was conducted with the sample in the vertical position (as glove box walls). The samples were tested at eight different heat flux levels, ranging from 10 kW/m$^2$ to 32 kW/m$^2$. Bubbles started to form after 30-60 seconds, depending on the heat flux. As the bubbles grew in size, the plastic expanded, and started to melt. As a result, the upper part of the sample began to slide down and out of the frame. After about 120-180 seconds, the samples started to pyrolyze. At the higher heat fluxes (31 kW/m$^2$ and 32 kW/m$^2$), the sample ignited after 290 seconds and 420 seconds, respectively. During the 32 kW/m$^2$ tests, flashes were observed for 50 seconds before ignition was achieved. This phenomenon has been described previously for different materials [7,8] and will not be described in detail here. For the present tests, ignition is defined by the presence of a flame over the surface not by flashes emerging from the pilot. For the tests at lower heat fluxes (24 kW/m$^2$-30 kW/m$^2$), the tests had to be interrupted since all the plastic had slid out of the sample holder. No ignition or flash occurred during these tests. Further decrease of the heat flux restrained the movement of the material but still resulted in significant downward displacement. Only when the heat flux was reduced to 17 kW/m$^2$, the plastic started to melt, partly deformed but did not drip downwards. The material kept its integrity throughout the duration of the test (15 min). Nevertheless, melting close to the surface and deformation of the material shape was still observed. When tested at heat fluxes below 10 kW/m$^2$ the surface of the sample was observed to remain unaffected by the heat. Based on these observations, a minimum heat flux for melting can be established at approximately 10 kW/m$^2$ and a minimum heat flux for melting followed by dripping of the material can be established at approximately 17 kW/m$^2$. Between these two thresholds, the material melts but the viscosity is not sufficiently reduced to allow downward migration of the material due to gravity. Figure 4 shows a series of samples that correspond to the 10 kW/m$^2$ to 30 kW/m$^2$ pre-heating range. According to ASTM-E-1321, before conducting flame spread tests, pre-heating of the material is necessary to attain thermal equilibrium at the material surface. This protocol cannot be followed with Lexan because the sample will loose its integrity prior to the attainment of thermal equilibrium. Therefore, flame spread tests were conducted before attaining thermal equilibrium. The sample was allowed to preheat but ignition was induced before dripping started. Some deformation of the solid was allowed to obtain a broad surface temperature distribution. For these tests, the long samples were placed vertically and the flame is allowed to propagate downwards. Flame spread tests showed that ignition further contributes to the process of dripping. The plastic becomes less viscous at the top and starts to drip downwards as the flame attempts to propagate. Rapidly, the flame could be observed to spread almost instantaneously over the entire

sample. It is clear from these observations that the flame spread rate cannot be defined in the traditional manner for this material. If the material is placed vertically, the flame will not spread. Instead, within the modeling of the fire, if ignition is accomplished, it should be followed by a translation of the fuel to the floor allowing a small pool fire. The vertical tests were complemented with horizontal flame spread tests. For this purpose, the apparatus was rotated 90º so that the heating panel was above and parallel to the sample. To obtain good reproducibility of the results, a fan is used to induce a forced flow parallel to the surface [15]. The samples were tested at four different heat flux levels, 24 kW/m$^2$, 25 kW/m$^2$, 26 kW/m$^2$ and 27 kW/m$^2$. At 26 kW/m$^2$ and 27 kW/m$^2$, the samples ignited after 690 and 353 seconds respectively. At 25 kW/m$^2$ flashing was observed after 420 seconds and ceased at 600 seconds. However, the flashing did not lead to ignition and sustained flaming. No flames were observed at 24 kW/m$^2$.


(a)

(b)

Fig. 4. (a) A test sample placed in the sample holder, (b) Four samples tested in the Vertical FIST at different heat fluxes. From the bottom: 10, 17, 20 and 30 kW/m$^2$ and 10-15 minute exposures. None of those samples ignited.

The scenarios for the horizontal tests were the same as described for the vertical tests, but instead of sliding or flowing out of the frame, the sample continued to expand and formed large bubbles similar to the tests in the cone calorimeter. When the bubbles burst, flaming was observed. When the sample ignited, the melted plastic became less viscous and flowed over the sample and as a result a flame was rapidly spread all over the sample. Again, the deformation of the material and the low viscosity of the molten plastic preclude the determination of a flame-spread rate. Nevertheless, it is important to note that, once ignition occurs, the flames cover the entire sample area almost instantaneously. Although this might not be the case for larger samples, this information is important since it indicates that flame spread rates, for this material, are controlled by the motion of the molten fuel and not necessarily by the transport of energy. Therefore, geometrical considerations are of extreme importance.

**Quantitative Characterization of Piloted Ignition from Small Scale Tests**

The qualitative description of the flame spread phenomena show the difficulty in establishing quantitative criteria that can be use for modeling of fire growth in the presence of a material such as Lexan. The modeling of flame spread does not obviously correspond to the classical methodologies such as that proposed by Quintiere [14]. Flame spread rates can only be issued from a balance between buoyant, viscous and capillary forces associated to the molten material. In contrast, the ignition process is one that seems to conform the classical approach used in ASTM-E-1321 [1]. In this section, the ignition delay times will be analyzed according to this methodology. In Fig. 5, it can be observed that the ignition delay times are consistent between the different tests for heat fluxes above 30 kW/m$^2$. Below this value, the ignition results were deemed inaccurate since the igniter touched the emerging surface of the material. For the horizontal configuration,

ignition could not be achieved below 26 kW/m$^2$, therefore this value was deemed as the critical heat flux for ignition. For comparison, Fig. 5 shows the ignition delay times for PMMA obtained using the LIFT [14] and FIST [8]. It is clear that PMMA has a much lower critical heat flux (11 kW/m$^2$) and leads to much shorter ignition delay times. Nevertheless, it is important to note that melting of the Lexan was observed to start at 10 kW/m$^2$ while PMMA will not melt before ignition. Therefore, Lexan will ignite and contribute to the total energy release rate of a fire much later than PMMA, but its qualities as a barrier will be lost much earlier (because PMMA burning can continue for extensive periods of time before the surface regression can reach the back side of the material [8]).

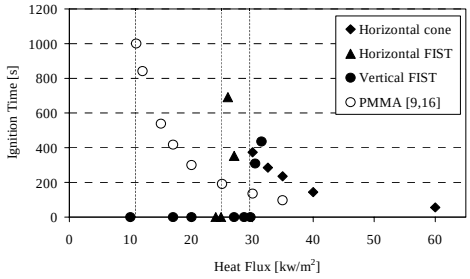



Fig. 5. Ignition delay time as a function of the external heat flux for different test methods and geometrical orientation. Some data for PMMA [8,14] is included for comparison. No ignition cases are noted as points at zero. This is done to visualize these data points that in reality correspond to ignition delay times that are greater than 1800 seconds.

To calculate the surface temperature, $T_{ig}$, a reasonable value for the total heat transfer coefficient, $h_T$, has to be found. $h_T$ consists of the radiative, $h_r$, and the convective, $h_c$, heat transfer coefficient. These values have been shown to vary with orientation and environmental effects. Olenick [19] suggested a value of the heat transfer coefficient based on a numerous experiments using the LIFT and FIST apparatus with PMMA as the reference material. The values suggested are; $h_c$ = 20 W/m$^2$K and, $h_r$ = 18 W/m$^2$K and are the ones to be used here. Other values are suggested in the literature [7,14] but are generally comparable to those presented by Olenick [19]. Figure 6 shows the inverse of the square root of the ignition delay time as a function of the external heat flux. By presenting the data in this way, theory predicts a linear correlation. Non-ignition data are presented on the heat-flux-axis since the time for ignition is assumed to approach infinity. The data follows well the linear trend, which shows that, despite of the endothermic nature of the melting process, it can be incorporated within the global value described as the thermal inertia ($k\rho C$). Table 1 provides a summary of the properties obtained for Lexan. In Table 2, the values for $k\rho C$ and $T_{ig}$ for the Lexan sheet are compared to other commonly used materials including PMMA. It can be observed that the ignition temperature, $T_{ig}$, for Lexan is very high compared to other materials [3,14,19], this is clearly an unrealistically high value that is a product of the methodology used that does not take into account the screening effect of the char. The thermal inertia for Lexan is comparable to the other materials (Table 2). This fact shows that the evolution of the surface temperature of Lexan will be very similar to the other materials presented. Therefore, Lexan will attain melting following a similar delay than that required for PMMA to attain ignition. The Glow Wire-test had no ignition for 850°C which, although higher than the temperature of 744°C calculated here, is closed. The discrepancy can be justified by the intrinsic differences of the tests.

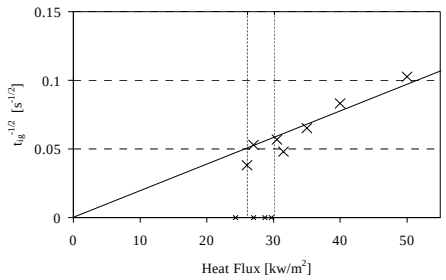



Fig. 6. The inverse of the square root of the ignition delay time as a function of the external heat flux.

Table 1. Fire properties for Lexan obtained using the methodology described in [1].

| **Material** | $\dot{q}''_{0,ig}$ [kW/m$^2$] | $h_T$ [W/m$^2$K] | $T_{ig}$ [ºC] | $t_{ig}^{-1/2}$ [s$^{-1/2}$] | $k\rho C$ [kW$^2$s / m$^4$K$^2$] |
|---|---|---|---|---|---|
| **Lexan** | 27 | 38 | 744 | 0.052 | 0.68 |

Table 2. Ignition temperatures and thermal heating properties for Lexan and other materials.

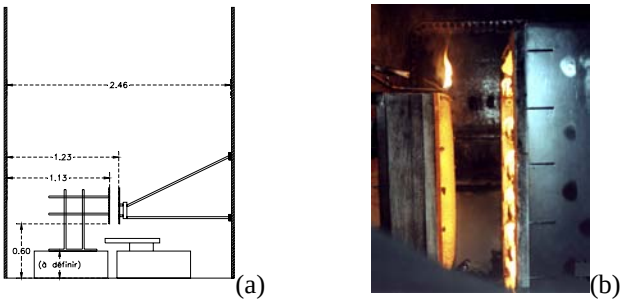
| **Material** | $T_{ig}$ **[ºC]** | $k\rho C$ **[kW$^2$s / m$^4$K$^2$]** |
|---|---|---|
| Lexan | 744 | 0.68 |
| Fire Resistant plywood [3,14] | 620 | 0.76 |
| Carpet (Nylon/wool) [3] | 412 | 0.68 |
| PMMA Polycast (1.59 mm) [3,8,14,19] | 278 | 0.73 |

**Medium Scale Test Results**

Some additional medium-scale experiments were carried out to characterize the flammability of Lexan at a representative scale of windows for glove boxes. These medium-scale experiments were carried out by the French "Institute for Radiological Protection and Nuclear Safety" (IRSN) within the framework of a cooperative safety research program with COGEMA. The experimental apparatus used for these medium-scale tests (Fig. 7) is composed by a thermally insulated black steel support on which a Lexan plate (0.4 m x 0.4 m x 9.5 mm) is fixed in a vertical position. A recuperation tray was also been installed to collect the Lexan material that may have melted and dripped down under the effect of the radiant heat flux. This Lexan plate was submitted to a radiant heat flux from a heating panel. The intensity of the radiant heat flux received by the sample ranged between 10 to 60 kW/m$^2$. The experimental setup was confined to a 22 m$^3$ steel vessel. Two series of experiments were conducted: piloted ignition tests and self-ignition tests (i.e., without pilot flame).

For the self-ignition tests, the samples were tested at eight different heat flux levels, ranging from 12.5 kW/m$^2$ to 61 kW/m$^2$. For low radiant heat fluxes (under 26 kW/m²), bubbles appeared in the Lexan material. Then, the Lexan will slowly loose its mechanical strength and melt into the recuperation tray. No ignition was observed. No more material remained on the vertical support after about 1800 seconds (end of the test). For 36 and 42 kW/m² self-ignition of the material was observed after 460 and 293 s respectively (Fig. 8, empty symbols). But, after video analysis, it was apparent that glowing thermocouples placed in front of the Lexan panel touched the dripping Lexan. These

thermocouples were deemed to be the origin of ignition. The same experiments were repeated without any thermocouples and no ignition was recorded. Further increase of the radiant heat flux (above 47 kW/m²) always resulted in ignition of the Lexan. As with the small-scale tests, the flames cover the entire sample area almost instantaneously once ignition occurred. From these results, the critical heat flux for self-ignition for Lexan material could be estimated to be around 45 kW/m² (Fig. 8). For the piloted ignition experiments, the Lexan panels were tested at four different heat flux levels, ranging from 26 kW/m$^2$ to 53 kW/m$^2$. As shown in Fig. 8, the material will always ignite for radiant heat fluxes above 28 kW/m$^2$ (ignition delay as 220 s and less).




(a) (b)

Fig. 7. (a) Experimental apparatus (medium scale tests); (b) Ignition with pilot flame.

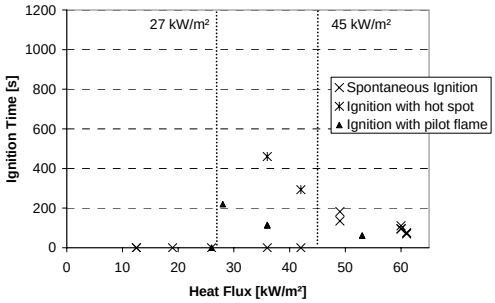



Fig. 8. Auto-ignition (with and without hot spot) delay time and ignition with pilot flame delay time as a function of the external heat flux from medium scale tests. No ignition cases are noted as points at zero (ignition delay times greater than 1800 seconds).

This result clearly shows that the medium-scale tests reproduce well the results of the small-scale tests. Thus, the calculated surface temperature, $T_{ig}$, has the same value than the LIFT test if you consider the total heat transfer coefficient $h_T$ as 38 kW/m²/K and the methodology described in [1] is used. The inverse of the square root of the ignition delay time and the thermal inertia ($k\rho C$) were also estimated according to the ASTM E 1321-93 method [1]. Table 3 provides a summary of the properties obtained for Lexan at the medium scale. It appears that the "fire properties" are consistent with those obtained with the small-scale experiments.

Table 3. Fire properties for Lexan estimated for the medium-scale tests.

| **Material** | $\dot{q}''_{0\,ig}$ [kW/m$^2$] | $h_T$ [W/m$^2$K] | $T_{ig}$ [ºC] | $t_{ig}^{-1/2}$ [s$^{-1/2}$] | $k\rho C$ [kW$^2$s / m$^4$K$^2$] |
|---|---|---|---|---|---|
| **Lexan** | 27 | 38 | 744 | 0.067 | 0.41 |

## SUMMARY AND CONCLUSIONS

A brief summary of the different observations and guidelines on the use of this data as input to design methodologies and fire models is provided in this section: **(1)** A simple ignition and spread test such as the glow wire test is not sufficient to properly evaluate the performance of Lexan under fire conditions. The behavior of the material in the case of a fire will be governed by melting; **(2)** Lexan does not ignite before the material has melted. The material starts to melt at a heat flux of approximately 10 $kW/m^2$. When mounted in a vertical position, the plastic starts to slide or move down at approximately 17 $kW/m^2$. To ignite the material, it has to be subjected to a heat flux of approximately 26 $kW/m^2$ when mounted horizontal, and 30 $kW/m^2$ when mounted vertically. For the medium scale tests, very similar results have been found, i.e., 27 $kW/m^2$ to ignite a vertical Lexan panel with pilot flame. For self-ignition experiments, the critical heat flux is estimated as high as 45 $kW/m^2$; **(3)** Flame spread modeling for Lexan is not necessary if placed vertically. The material has to melt before a flame can spread over its surface. In the vertical position, the downward flame spread is very fast because of dripping of molten material. For all practical considerations, the fuel can be transferred to the floor below and allowed to burn as a pool fire. The critical heat flux for dripping (17 $kW/m^2$) could be used as a criterion to transfer mass from the vertical sample to the floor. Nevertheless, it has to be noted that flames have a tendency to fall with the fuel, therefore the heat flux necessary to continue the transfer of fuel downwards needs to be modeled carefully; **(4)** Due to the char formation and melting behavior, Lexan will only ignite when exposed to heat fluxes above 27 $kW/m^2$, thus for fire modeling purposes, it should therefore be included into the fuel load, but the possibility of it being the "first burning item" should only be considered in the presence of sources that can generate these heat level of fluxes. If the fire can grow enough and Lexan reaches the melting/sliding temperature, the fuel should be transferred to a pool underneath the material, and an opening should be included where the Lexan sheet was. The material should be allowed to burn under a heat release rate curve corresponding to that of the tests presented in this paper. Spread can be considered as fast enough so as not to be included in the model; **(5)** The total heat release from Lexan will decrease by approximately 40% if less than 35 $kW/m^2$ of external heat flux are not supplied to the surface.

The test foundations for this paper have resulted in the identification of fire properties and recommendations for modeling of a fire growth scenario. These recommendations are based on physical principles but mostly on the observation of the different processes. This type of information is necessary when attempting modeling of a fire within the context of a compartment. With the limited information provided by the standard results of a test method, it is not possible to properly incorporate this data in a fire model. This study has only dealt with standard test methods as presented and does not question the validity of their assumptions. This work should be complemented with an in-depth analysis of the validity of the assumptions used in the standard methods to the proposed application.

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