BASIC PRINCIPLES FOR AN ADEQUATE PERFORMANCE ASSESSMENT STANDARD

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ABSTRACT

Performance assessment standards need to be developed on the basis of proper physical understanding. The objectives need to be established and accessory variables need to be separated from the critical variables determining the behaviour of the system or element. This paper explores the different requires to define a proper standard for fire applications.

INTRODUCTION

Many standards have been developed to normalize performance assessment. These standards have been compiled in many documents and are an integral part of our codes and regulations. This paper concerns mainly fire related standards but emphasizes principles that are applicable to any other discipline.

Fire related performance assessment standards cover a broad range of areas, from those that establish the reliability and effectiveness of components and systems such as smoke detectors [1,2], sprinklers or water supply systems [3] to those that address specific properties of materials [4] or construction element [5]. Component and system performance assessment can follow simple practises when the process to be assessed is very well understood. This is the case of water based systems, where performance assessment simply establishes the capability of the system to provide the desired amount of water. A simple flow measurement that can be executed with well validated tools serves as the indicator of performance, and repeatability and error bars can be clearly established. The performance metric is clear and directly measured. Activation of a sprinkler system introduces more complex phenomena that cannot be quantified in as easy of a manner. The mechanisms of activation is well understood, the heating of the fusible link to a failure temperature, and can be quantified with a single, easy to measure variable. Nevertheless, the source of heat is convective heat transfer from the fire. The source is therefore and undefined variable that cannot be standardized. The acceptable practise, in this case, is introducing standardized flow conditions to define the Response Time Index (RTI), these flow conditions can be deemed as “typical” of a fire [6]. The analysis supporting the RTI shows that its value is independent from the source variables and can be assumed as simply a property of the fusible link. This standard is therefore a well defined performance assessment metric, nevertheless using the RTI to predict sprinkler activation still requires the proper definition of the source which is not the same as the characteristic source term used for the standard. Furthermore, the characteristic source of the standards partially omits physical processes such as evaporative cooling. Different analysis have been done to improve on the concept of the RTI and to attempt its use for activation prediction [7,8].

Most other processes associated to fire are not as clearly understood. In the case of smoke detectors, the interaction of the detector and the smoke is not very well understood therefore the definition of a performance metric is not as clear. Furthermore, the metric used (light extinction) can only be loosely linked to the relevant performance metrics for which the detector was designed (i.e. tenability criteria). In the case of smoke detectors, UL-217 and UL 268 A [1,2] use a standardized source, like in the case of sprinklers, nevertheless the physical variables linking the source with the activation cannot be defined, therefore the outcome is inevitably a combination of the source and the hardware. Tenability criteria are simplified to a single metric, white light attenuation. The problem is so complex in this particular case that standardized detector is used as the metric, thus smoke detector activation can only be assessed in a relative manner. The outcome of these standards cannot be used for prediction and are limited to sources that produce smoke similar to that prescribed by the standard. Error bars and repeatability are therefore only associated to the protocols of the standard but cannot be linked to the required performance metric.

An area where there are multiple performance assessment standards is the area of material flammability. In this case the objective is to assess the potential of a material to contribute to fire growth. Fire growth is a complex process where environmental variables are intimately linked to material properties. Numerous attempts have been made to simplify and reduce fire growth to a single variable, the most notable is the Heat Release Rate [9] that justified the development of the cone calorimeter [10]. Other standards emphasize ignition or flame spread [11]. Material flammability standards cover a wide range of sophistication and have been the subject of great criticism. This paper will centre on the discussion of what makes an adequate material flammability standard.

Fire resistance standards are also based on an attempt to establish a standardized source. The standard source has then been used to define a boundary condition for individual structural elements. These simplifications omit the combined behaviour of different structural elements [12] and the broad range of variation of the source [13]. Many studies have emphasized the limitations of fire resistance standards and their failure to provide an adequate performance metric.

This paper will focus on material flammability standards and attempt to provide some indication of the key criteria that should be respected in the development of a standard.

MATERIAL FLAMMABILITY

Material flammability is difficult to define. A recent study provided a detailed analysis of the different components to be considered when discussing material flammability [14]. The consensus is that fire growth is controlled by the Heat Release Rate (HRR). The HRR can then be assessed by the Heat Release Rate per Unit Area (HRRPUA). The HRRPUA is a function of the heat of combustion and the burning rate, while the area of the fire is intimately linked to ignition and flame spread. Material flammability can therefore be established as the material properties that control ignition, flame spread and the HRRPUA. Many attempts have been made to establish the material properties that control these processes but this remains an unresolved problem.

The second analysis that is necessary is to define the consequences of fire growth. In many cases, the consequences are the relevant parameters whose performance needs to be assessed.

This is generally translated in terms of tenability criteria and could include temperatures, heat fluxes, concentrations (carbon monoxide, soot, etc.). The consequences are once again a result of the relevant material properties and of environmental variables. Usually these properties are described in terms of yields and the HRRPUA [15].

A detailed analysis of the process of ignition shows that the material properties associated to ignition are of several types, there are the thermal properties (thermal conductivity, specific heat, density), the characteristics of the chemical decomposition process (chemical reactions, kinetic constants) and the physical transformations (melting, charring, etc.). Flame spread is controlled by similar parameters with the addition of the heat flux from the flame to the material. This incorporate gas phase parameters such as the heat of combustion, soot production, etc. and inevitably links the source with the material.

REQUIREMENTS FOR A MATERIAL FLAMMABILITY STANDARD

Material flammability standards need to focus on material properties, thus should attempt to isolate the source from the material. For this purpose it is necessary to understand the variables associated with the source and formalize their interaction with the material.

A detailed analysis of ignition, flame spread and HRRPUA shows that in all cases the number of variables involved is large enough that a single test can not define them all. Conducting a multiplicity of tests and providing a broad array of material properties could potentially serve to produce the required inputs for models but is not a practical solution for performance assessment. Performance assessment aims to provide a ranking, so isolating all relevant variables implies a multiple-tier ranking that can lead to confusion.

A performance assessment standard need to reduce the number of variables involved to the minimum number of material parameters that will adequately describe the process through the entire range of environmental conditions. Thus a detailed analysis of the process is necessary and an assessment of the controlling parameters and those that can be neglected. Once this assessment has been made then the negligible variables can be ignored and a test developed to optimise the assessment of the dominant parameters. The assessment of the dominant parameters has to be made on the basis of measurements that adequately quantify these parameters (directly or indirectly) and allows for the quantification of the errors and repeatability.

The main risk of this process is to oversimplify the standard and ignore relevant variables, or to attempt compounding too many variables that need to be presented separately. Currently many tests suffer from these deficiencies, this will be discussed by other papers thus will not be presented here. The standardization of ignition as per ASTM E 1321 [11] will be presented here as an adequate example of how to isolate these variables.

IGNITION OF A THERMALLY THICK SOLID

A number of authors have attempted the solution to complex formulations for the ignition of thermally thick materials. Extensive reviews of these modelling efforts can be found in references [16-20]. In most cases some simplifications have been necessary and in general the critical limitation of these models is associated to the inadequate definition of many of the relevant variables and parameters. This section will suggest simplifications that will lead to models commonly used in the analysis of standard test methods evaluating the flaming ignition of solid fuels.

The assumption that the solid remain inert until ignition is probably the most far reaching of all proposed simplifications. As a result of this assumption the energy equation is dramatically simplified. Despite the far reaching implications of assuming that the solid remains inert until ignition there is very limited work that assesses the validity of this assumption.

To the knowledge of the author, the only explicit studies that discuss the importance of assuming that the material is inert are those by Cordova et al. [21], Dakka et al. [22] and Beaulieu and Dembsey [23]. In the first two studies transparent Poly(methyl methacrylate) (PMMA) was used while on the latter work the detailed analysis is done with black PMMA but a number of other materials serve to confirm the conclusions. Despite the bias towards PMMA, the discussion is appropriate here to illustrate the potential errors associated to this simplification.

Figure 1 presents characteristic ignition delay times (t_{ig}) and pyrolysis dely times (t_P) for PMMA. The ignition delay time was recorded as the first flash while the pyrolysis delay time as the moment when the fuel initiates its endothermic degradation. The onset of pyrolysis was characterized by means of mass loss measurements, flow visualization and IR-Thermography. These results show that for these particular experiments there is a significant difference between the “flash point” and the onset of pyrolysis (could be up to 100%) therefore the assumption that the fuel remains inert until ignition might not be justified.

The breakdown of the inert solid heating assumption is further discussed by Beaulieu and Dembsey [23] who show that an analysis following this approximation will lead to shorter ignition delay times for realistic heat fluxes. The biggest errors were observed at the higher heat fluxes. Their tests were done for a comprehensive array of materials and with heat fluxes up to 200 kW/m^2.

This assumption still remains the backbone of all standard test method analyses for ignition [11]. If this approach is followed and the regression rate is assumed to be negligible, the energy equation is reduced to

$$\frac{\partial[\rho_S C_S T]}{\partial t} = -\frac{\partial}{\partial x}\left[-k_S\frac{\partial T}{\partial x}\right] + \dot{q}'''_{RAD} \qquad (1)$$

And the boundary conditions to

$$x=0 \qquad 0 = k_S \left.\frac{\partial T}{\partial x}\right|_{x=0^+} - \varepsilon_S(0,t)\sigma(T^4(0,t) - T_0^4) - h_{Cv}(t)(T(0,t) - T_0) \qquad (2)$$

$$x=L \qquad 0 = -k_S \left.\frac{\partial T}{\partial x}\right|_{x=L^-} + k_B \left.\frac{\partial T_B}{\partial x}\right|_{x=L^+} \qquad (3)$$

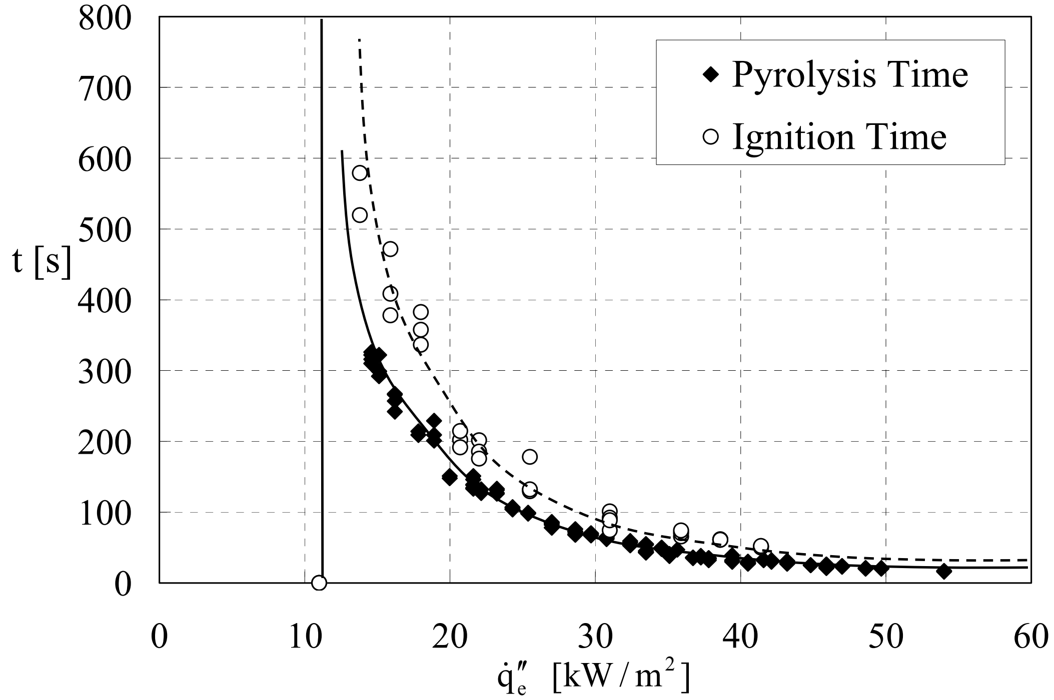

Figure 1 Characteristic ignition delay times (t_{ig}) and times to the onset of pyrolysis (t_P) for PMMA and a wide range of external heat fluxes extracted from reference [22]. Onset of pyrolysis or ignition did not occur below 11 kW/m^2.

The next major simplifications that are commonly accepted are to assume that most of the incident heat flux is absorbed at the surface ($\alpha(t)\approx 1$) and that the thermal properties of the solid can be considered invariant ($\rho_S(x,t)\approx\overline{\rho}_S$, $C_S(x,t)\approx\overline{C}_S$, and $k_S(x,t)\approx\overline{k}_S$). These assumptions further simplify Equation (1) because it allows neglecting in-depth radiative absorption. The thermal properties can then be extracted from the differential terms and external radiation now appears in the exposed boundary condition:

$$\overline{\rho}_S\overline{C}_S\frac{\partial[T]}{\partial t}=\overline{k}_S\left[\frac{\partial^2 T}{\partial x^2}\right] \tag{4}$$

$$x=0 \qquad 0=\overline{k}_S\left.\frac{\partial T}{\partial x}\right|_{x=0^+}+\dot{q}''_e-\sigma(T^4(0,t)-T_0^4)-h_{Cv}(t)(T(0,t)-T_0) \tag{5}$$

$$x=L \qquad 0=-\overline{k}_S\left.\frac{\partial T}{\partial x}\right|_{x=L^-}+\overline{k}_B\left.\frac{\partial T_B}{\partial x}\right|_{x=L^+} \tag{6}$$

There is little true justification in the literature to support these assumptions, nevertheless they are of practical use since for many fire related materials the absorptivity (or emissivity) will approach unity [22], or in the case of testing the material surface can be treated with a coating that has these properties [24]. Furthermore, thermal properties vary with temperature, but a global set of properties can be established to provide a good fit to ignition data. An example of a comprehensive assessment of the impact of variable thermal properties is provided by Steinhaus [25].

To standardize the ignition process it is important to provide a controlled environment, so that test results can be consistent between laboratories and different users of the standard. Therefore, standard test methods provide clear definition of the environmental conditions, thermal characteristics of the backing material and pilot location [11, 24]. Equations (4), (5) and (6) do not have to be solved to obtain the fuel concentration at the pilot location. Instead the impact of the gas phase on the results is ignored. This is done on the basis that flow conditions are the same between tests thus their impact on the transport of fuel and oxidizer to the pilot is the same.

Standardization of the flow conditions has a deep effect on the meaning of the results. The thermal properties associated to the analysis are no longer true thermal properties of the material but global properties that are a combination of the solid and the standardized gas phase conditions. This is of critical importance, because, as a product of standardization, test results can be compared among themselves (if the same method is used), nevertheless cannot be extrapolated to conditions different to those of the test. This applies to other standard tests or to real fire conditions. Cordova et al. [26] provides a graphical assessment of the effect of varying the flow conditions on the resulting thermal properties showing that small variations in the flow field can result in drastic variations of the resultant thermal properties.

Different test methods will use different flow fields therefore values for the convective heat transfer coefficient vary with the authors. A commonly cited value is 15 W/m^{2}K. Furthermore, it is common to linearize surface radiation to define a single total heat transfer coefficient ($h_T \approx 45$ W/m^{2}K).

Most test methods define the backing material as a good insulator ($\overline{k}_B \to 0$) neglecting heat losses through the back end of the sample. Finally, characteristic ignition delay times can be considered much shorter than the time required for the thermal wave to travel through the sample therefore $L > \varepsilon_T$ and the solid is generally assumed as semi-infinite.

If all these assumptions are made, Equations (4), (5) and (6) can be reduced to:

$$\overline{\rho}_S \overline{C}_S \frac{\partial T}{\partial t} = \overline{k}_S \left[\frac{\partial^2 T}{\partial x^2} \right] \qquad (7)$$

$$x=0 \qquad 0=\bar{k}_S \left.\frac{\partial T}{\partial x}\right|_{x=0^+} + \dot{q}''_e - h_T(T(0,t)-T_0) \tag{8}$$

$$x\rightarrow\infty \qquad 0=-\bar{k}_S \left.\frac{\partial T}{\partial x}\right|_{x=L^-} \tag{9}$$

If the solid is assumed to be inert until ignition and the gas phase can be summarized into a single total heat transfer coefficient (h_T) this amounts to the assumption that ignition will occur at the onset of pyrolysis and that these process can be simply characterized by the attainment of a characteristic surface temperature that is commonly labelled the ignition temperature, T_{ig}. If the sample is suddenly exposed to an external heat flux, then the time delay between exposure and ignition is named the ignition delay time, t_{ig}. These two parameters represent then the entire process of ignition.

A final link can be made to establish a critical ignition condition. If the ignition delay time is infinitely long, then there will be no gradients of temperature within the solid and surface heat losses will be equivalent to the heat input. This represents the minimum heat flux required to achieve T_{ig}, and thus flaming ignition of the solid fuel. This heat flux is named the minimum heat flux for ignition, $\dot{q}''_{0,ig}$. Since surface temperatures are more difficult to measure than heat fluxes, the minimum heat flux for ignition can be used to establish the ignition temperature. Equation (8) can then be re-written to

$$T_{ig} = T_0 + \frac{\dot{q}''_{0,ig}}{h_T} \tag{10}$$

Equation (10) is an idealized expression that assumes that no temperature gradients exist in the solid, this can lead to errors in the calculation of T_{ig}. To establish a relationship between external heat fluxes and surface temperature that includes in-depth heat transfer a sample can be allowed to reach thermal equilibrium and the surface temperature recorded. The obtained relationship represents a more accurate representation of equation (10) and can be used to extract ignition temperatures from measured heat fluxes. A graphic representation of this relationship can be found in reference [11].

Again, both minimum heat flux for ignition and ignition temperature are not material properties but a combination of the material and the specific environmental conditions associated to the test. Extrapolation to realistic scenarios and fire models has to be done with significant care.

Imposing a constant external heat flux ($\dot{q}''_e$=constant) and using all the above assumptions allows for an analytical solution to equation (7). This solution establishes the evolution of the solid temperature as a function of time. This solution can be found in any heat transfer book but was first postulated for the flaming ignition of a solid fuel by Quintiere [27] and incorporated in ASTM E-1321 [11]. More detailed discussion of methodologies and nomenclature can be found in the description of the standard tests [11].

The solution for T(x,t) is given by

$$T(x,t)-T_0=\frac{\dot{q}''_e}{(h_T)}\left[\operatorname{erfc}\left(\frac{x}{\sqrt{4\overline{\alpha}_D t}}\right)-e^{\frac{(h_T)}{\sqrt{\alpha_D}\sqrt{\overline{k}_S\overline{\rho}_S\overline{C}_S}}x+\frac{(h_T)^2}{\overline{k}_S\overline{\rho}_S\overline{C}_S}t}\operatorname{erfc}\left(\frac{(h_T)}{\sqrt{\overline{k}_S\overline{\rho}_S\overline{C}_S}}t^{\frac{1}{2}}+\frac{x}{\sqrt{4\overline{\alpha}_D t}}\right)\right] \quad (11)$$

Where $\overline{\alpha}_D = k_S/\rho_S C_S$ is the global thermal diffusivity and "erfc" is the complement to the error function. To obtain the surface temperature (T_s), x is set equal to 0 and $T = T(0,t) = T_s$. Therefore equation (11) simplifies to:

$$T_s = T_0+\frac{\dot{q}''_e}{(h_T)}\left[1-e^{\left(\frac{(h_T)^2}{\overline{k}_S\overline{\rho}_S\overline{C}_S}\right)t}\operatorname{erfc}\left(\frac{(h_T)}{\sqrt{\overline{k}_S\overline{\rho}_S\overline{C}_S}}t^{\frac{1}{2}}\right)\right] \quad (12)$$

from equation (12),

$$\overline{T}=\frac{\dot{q}''_e}{(h_T)} \quad (13)$$

can be defined as a characteristic temperature and,

$$t_c=\frac{\overline{k}_S\overline{\rho}_S\overline{C}_S}{(h_T)^2} \quad (14)$$

is defined as a characteristic time. Equation (14) is the general solution to the surface temperature at all levels of incident heat flux. To obtain the ignition delay time (t_{ig}) the surface temperature (T_s) is substituted by T_{ig} and equation (14) can be rewritten as:

$$T_{ig} = T_0 + \overline{T}\left[1 - e^{\frac{t_{ig}}{t_c}}\operatorname{erfc}\left(\left(\frac{t_{ig}}{t_c}\right)^{\frac{1}{2}}\right)\right] \tag{15}$$

To avoid the complex form of the error function simplified solutions have been proposed in the literature [11,27]. In order to solve for the ignition delay time (t_{ig}) a first order Taylor series expansion of equation (15) is conducted. The range of validity of this expansion is limited, thus cannot be used over a large range of incident heat fluxes. Thus, the domain has to be divided at least in two.

The first domain corresponds to high incident heat fluxes where the ignition temperature (T_{ig}) is attained very fast, thus $t_{ig} << t_c$. Application of the first order Taylor Series Expansion to equation (15) around $t_{ig}/t_c \rightarrow 0$ yields the following formulation for the ignition delay time (t_{ig}):

$$\frac{1}{\sqrt{t_{ig}}} = \frac{2}{\sqrt{\pi}\sqrt{\overline{k}_S\overline{\rho}_S\overline{C}_S}}\frac{\dot{q}''_e}{\left(T_{ig} - T_0\right)} \tag{16}$$

As can be seen from equation (16), the short time solution for the ignition delay time (t_{ig}) is independent of the total heat transfer coefficient term (h_T). Thus the ignition delay time (t_{ig}) is only a function of the external heat flux ($\dot{q}''_e$) and the global properties ($\overline{k}_S$, $\overline{\rho}_S, \overline{C}_S$) of the solid fuel and the ignition temperature (T_{ig}).

For low incident heat fluxes $t_{ig} \geq t_c$, the Taylor series expansion is made around $t_{ig}/t_c \rightarrow \infty$, where the first order approximation yields:

$$\frac{1}{\sqrt{t_{ig}}} = \frac{\sqrt{\pi}\sqrt{\overline{k}_S\overline{\rho}_S\overline{C}_S}}{h_T}\left[1 - \frac{h_T\left(T_{ig} - T_\infty\right)}{\dot{q}''_e}\right] \tag{17}$$

Equations (16) and (17) establish the relationship between ignition delay time and external heat flux. It is convenient to express the ignition delay time data presented in Figure 1 as $1/\sqrt{t_{ig}}$ where T_{ig} is obtained from the experimental minimum heat flux for ignition and Equation (22). Such a plot is presented in Figure 2. Substituting T_{ig} in Equation (16) allows extracting the product of the three thermal properties ($\overline{k_S\rho_S C_S}$) as a single experimental parameter representing the global material properties controlling flaming ignition of solid fuels that can be considered semi-infinite. Quintiere terms this product the thermal inertia [27].

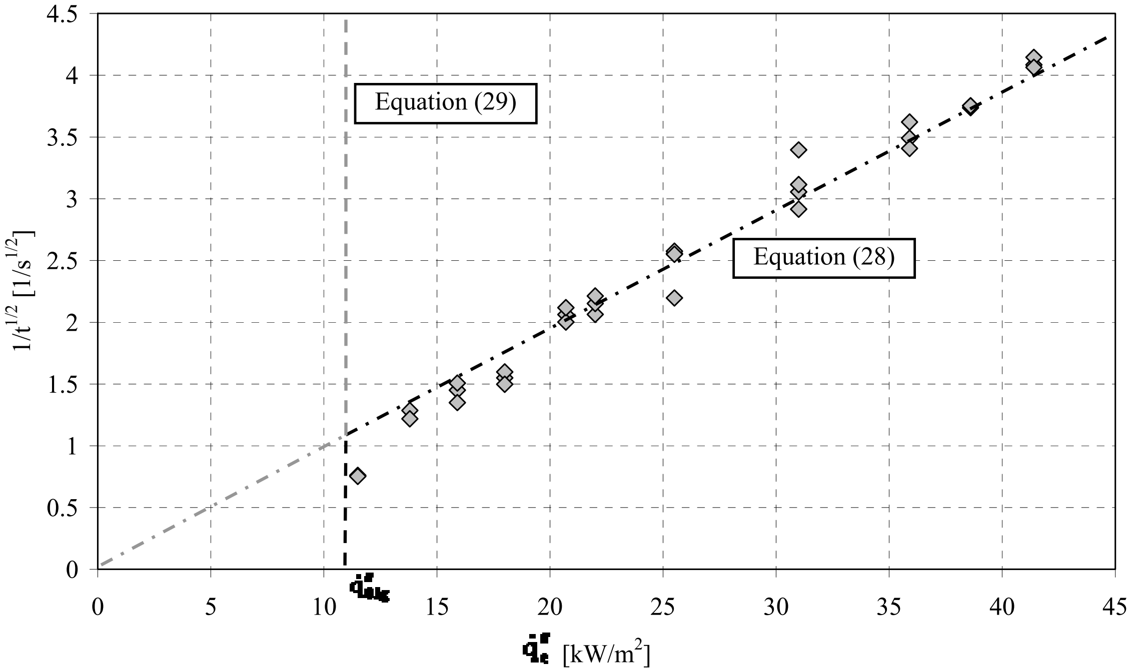

Figure 2 Ignition delay time ($1/t_{ig}^{-0.5}$) for different external heat fluxes using PMMA as a solid fuel. Data extracted from reference [40].

When describing ignition propensity of solid fuels is customary to summarize the description of the materials on the basis of only two parameters, the ignition temperature, T_{ig}, and the thermal inertia, $\overline{k_S \rho_S C_S}$. Several tables have been produced in the past with comprehensive lists of materials typical of fires. As an example, Table 1 presents the data as compiled by Quintiere [27].

Material	T_{ig} [°C]	$\overline{k_S \rho_S C_S}$ [(kW/m^{2}K)^2.s]
Wood fiber board	355	0.46
Wood hardboard	365	0.88
Plywood	390	0.54
PMMA	380	1.00
Flexible Foam Plastic	390	0.32
Rigid Foam Plastic	435	0.03
Acrylic Carpet	300	0.42
Wallpaper on Plasterboard	412	0.57
Asphalt Shingle	378	0.70
Glass Reinforced plastic	390	0.32

Table 1 Ignition Data from ASTM E-1321 per Quintiere [27].

CONCLUSIONS

This paper has established the principles behind developing a proper standard. It requires a clear definition of the physics and the separation of environmental variables from the properties that are being assessed. The complexity of the fire problem makes this problem a difficult one, but the ignition example has been used to show that even after many simplifications a proper standard can be obtained.

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