FLAMMABILITY CHARACTERIZATION WITH THE LIFT APPARATUS AND THE CONE CALORIMETER

Thomas G. Cleary
Building and Fire Research Laboratory
National Institute of Standards and Technology
Gaithersburg, MD 20899

ABSTRACT

Two small-scale test apparatuses, the LIFT apparatus and the Cone Calorimeter provide ignitability, flame spread, and heat release rate data for combustible solid materials. Data gathered with these apparatuses can be reduced to a limited number of key flammability or fire properties for a particular material. These key properties, in conjunction with the appropriate modelling equations, characterize the time to ignition, flame spread rate, and heat release rate over the range of applicable heating conditions and surface temperatures likely in full-scale fires. These key properties may be used as input parameters in a fire model that predicts flame spread and heat release rates for certain full-scale fire scenarios.

INTRODUCTION

A new generation of fire tests has been developed that yield data which can be used to assess the hazards associated with combustible materials. Many of the existing fire test methods still in use today rank materials by an arbitrary index. A problem associated with such a methodology is that results from such tests are not general, but hold only for the test conditions that prevail. This leads to situations where different test results could imply different levels of hazard for the same material, and it may not be obvious how to reconcile such differences. **A** classic example is that some foamed plastics yield good flame spread results in the Steiner Tunnel test (ASTM E 84), but if tested in a room configuration with the foam lining walls and ceiling, flames spread rapidly to the point where flashover occurs (essentially all material in the room would be burning) [1]. Fortunately, over the years, fundamental research in combustion processes has lead to the development of bench-scale fire tests that measure the important aspects of flammability and can be interpreted in terms of underlying theories of combustion. These developments afford the opportunity of characterizing flammability in a more scientifically acceptable manner.

The key aspects of flammability that control the fire hazards related to the size of the fire are ignitability, flame spread, and heat release rate. Ignitability is the propensity of a material to ignite in the presence of a heat source. Ignitability addresses the questions, "Will it ignite?" and if so "How long will it take to ignite?" given a known heat source. Flame spread influences the fire growth rate. In characterizing flame spread, answers to the following questions are sought: "Under what conditions will flame spread occur?" and given a specific scenario "What is the flame spread rate?" Heat release rate is the amount of energy released from a fire per unit time and is directly related to the fire hazard. This overall rate of heat release is a measure of the force pumping combustion gases and heat outward from a fire. The answer to the question " What is the heat release rate of a burning object?" must be provided to quantify hazard. To answer the questions posed above for any number of specific scenarios requires testing over a range of controlled heating conditions and that is what the bench-scale test methods described below seek to do.

The apparatuses considered here are the LIFT (Lateral Ignition and Flame Spread Test) [2] and the Cone Calorimeter [3]. Together they are capable of providing the data needed to characterize most, and perhaps all, of a material's flammability. The component parts of flammability considered by these tests are ignitability, flame spread, and heat release rate. Other issues like smoke production and toxicity are important for a hazard assessment, but are not addressed in the analysis presented here. Both of these test methods have been accepted by the **ASTM** as standard test methods. Below, a brief description of each apparatus is given, more detailed descriptions of each can be found in references **[4]**(LIFT) and [5] (Cone Calorimeter).

It must be pointed out that bench-scale testing alone is presently insufficient for fire hazard assessment, since such test results do not necessarily directly correlate to full-scale results. But the data generated can be used in an analysis that is part of a hazard assessment. Here, the data from the LIFT and Cone Calorimeter are reduced to key fire properties which are indicative of some specific aspects of flammability. The fire properties are parameters obtained from correlating the test data with simplified models of the phenomena. They can be used as inputs into a recently developed computer fire model capable of predicting large-scale wall and ceiling fire test results [6]. ***As*** input data, the fire properties reproduce the flammability phenomena at a sophistication level consistent with the computer fire model's inherent assumptions and simplifications.

IGNITION

To ignite a solid, it must be heated to such a temperature and at such a rate that the volatile products released will form a mixture with air in the flammability range. Relatively low heating rates will not be sufficient to produce such a mixture, but at a some elevated heating rate such a mixture will form given a long enough exposure to an adequate heat source. At higher heating rates, a flammable mixture will form in less time.

In the LIFT and in the Cone calorimeter, time to ignition data can be gathered over a range of specified constant heat fluxes typical of fires, thus characterizing ignitability as a function of heat flux. In most cases, a small pilot flame or spark is present to ignite the flammable

mixture once it forms. In the absence of a pilot, the heat flux required to ignite a material is typically much higher. Piloted ignition is most often specified in flammability testing since it is more conservative to assume that an ignition source is always available. Furthermore, flame spread can be thought of as a series of continuous piloted ignitions, thus it is desired to characterize the piloted form of ignition.

The LIFT apparatus provides ignitability and flame spread information on, typically, vertically oriented samples. A schematic of the LIFT is shown in Figure 1. The heat source is a gas-fired radiant panel. The face of the panel is a ceramic honeycomb where a gas-air mixture burns, heating up the panel. The panel radiates heat to the sample surface. The sample is placed in a holder which is at a 15° angle from the radiant panel. This configuration provides a varying external heat flux along the length of the sample. Separate ignition and flame spread tests are performed.

Ignition tests use small 15 X 15 cm samples up to 50 mm thick. The ignition samples are placed in the holder at the end nearest the radiant panel. The external heat flux exposure over this short distance is essentially constant, thus ignition tests are performed at constant heat flux conditions. The sample edges and back surface are wrapped in aluminum foil and an insulating board is placed behind the sample to minimize heat losses. A small pilot flame located above the sample will ignite the sample when a flammable mixture is achieved. The external heat flux from the radiant panel is adjusted to the desired level by setting the gas and air flow rate. After fixing the external heat flux level, the sample is inserted and the subsequent time to ignition is recorded. A minimum external heat flux for ignition is obtained by bracketing the flux level where the sample will just ignite to within approximately ± 2 kW/m^2. A number of ignition tests are performed over a range of external heat flux levels to provide the data necessary to characterize ignition.

Most thermally thick materials are adequately characterized by a simple, inert, one-dimensional heating model. A material can be considered thermally thick if the heat flow in-depth does not penetrate so far into the sample that the back surface experiences a significant temperature rise. It has been shown that time to ignition for thermally thick materials can be correlated by,

$$\frac{\dot{q}''_{ig}}{\dot{q}''_{e}} = \begin{cases} b\sqrt{t}, & t \le t^* \\ 1, & t \ge t^* \end{cases} \qquad (1)$$

where $\dot{q}''_{ig}$ is the minimum flux for ignition, $\dot{q}''_{e}$ is the external heat flux . The left-hand side is plotted against the square root of time to ignition. The slope of a best fit line that passes though the origin provides the value of the parameter b. For a particular material, b is a constant. t^* is given by the intercept of the fit line with $\dot{q}''_{ig}/\dot{q}''_{e}$ equal to one. It is a characteristic time indicative of the time for the surface temperature to approach a steady state. The coefficient b can be related to a material property called the thermal inertia (kpc) which is a product of the thermal conductivity (k), the material density (p), and the heat capacity (c) of the material. In this case kρc is an effective value which includes temperature effects, phase changes, and other effects. Thermal inertia dictates how fast the surface

temperature rises for a specific external flux; the lower the thermal inertia, the faster is the temperature rise. A characteristic surface temperature that signifies intense volatilization of a material, such that piloted ignition occurs, is deemed a material's ignition temperature, T_{ig}. This is the temperature of the exposed surface of the material; a temperature gradient still exists in-depth. In this analysis, the ignition temperature is assumed to be a unique value, but in reality it can be expected to depend on the heating rate and other factors to some extent. Ignition temperature is not directly measured in the tests, but is found from the following heat balance applied to the minimum ignition flux condition;

$$\dot{q}''_{ig} = \epsilon \sigma (T_{ig}^4 - T_\infty^4) + h_c (T_{ig} - T_\infty) \qquad (2)$$

where h_c is average convective heat transfer coefficient approximately equal to 0.015 (kW/m^2 K) for vertically oriented samples. ϵ is the surface emissivity which is assumed to be unity, σ is the Stefan-Boltzmann constant, and T_∞ is the ambient temperature. In Equation (2), T_{ig}, and T_∞ must be expressed on an absolute temperature scale, i.e. Kelvin.

Time to ignition can be approximately expressed as

$$t_{ig} = \frac{\pi k \rho c (T_{ig} - T_\infty)^2}{4 (\dot{q}''_e)^2} \qquad (3)$$

Here it can be seen how kpc, T_{ig}, and $\dot{q}''_e$ influence time to ignition. In this model the chemistry of the material is all contained in T_{ig}.

An example of the ignition data correlation is shown in Figure 2. The accuracy of this simple model is indicated by its ability to fit the data.

FLAME SPREAD

In general, flame spread on flat surfaces can progress in distinctly different modes, lateral, horizontal or downward flame spread which are all examples of spread against a self-induced buoyant air flow, and upward or wind-aided flame spread. Fire growth can involve one or both modes depending on material orientation and air flow direction. Each mode of flame spread is examined below.

Lateral Flame Spread

The LIFT apparatus is designed to measure lateral flame spread rates. This mode of flame spread is also termed opposed flow flame spread since the local induced air flow is in the opposite direction of the flame spread direction. Lateral and downward spread on vertical surfaces, and horizontal spread are all Characterized as opposed flow flame spread and should

be essentially equivalent [7]. Opposed flow flame spread is a function of external heat flux or surface temperature this flux produces. The LIFT apparatus measures the flame spread rate over the range of applicable fluxes or surface temperatures typical of fires.

The LIFT flame spread sample is a full size 150 X 800 mm sample. Recall that the flux level varies along the length of the sample from a high value at the end closest to the radiant panel to a low value (a few percent of the high value) at the end furthest from the radiant panel. First, ignition tests are performed and the data reduced. For flame spread tests, the radiant panel is set to an external flux 5 to 10 kW/m^2 above the minimum flux for ignition at the reference position which is located 50 mm down from the end of the sample holder closest to the radiant panel (this is the location where the external heat flux for the ignition tests is specified). A flame spread sample is inserted and allowed to preheat until the sample surface temperature profile approaches steady state. This preheat time is available from the ignition data analysis (t^*). After preheating the sample, a pilot flame is used to ignite the end of the sample closest to the radiant panel. Since the temperature of this end of the sample is above the ignition temperature, a flame will immediately flash across the surface until a point where the surface temperature just drops below the ignition temperature. The flame then starts to spread across the sample face. The times for the flame front to reach specified positions on the sample face (typically every 25 mm) are recorded. In addition, the position where the flame front stops advancing is recorded. With the position and time data, a running-three-point average is used to calculate the flame front velocity at each position. Three identical flame spread tests are performed to improve measurement statistics.

Since each position along the sample surface corresponds to a known external flux at that position, the flame front velocity as a function of external flux is obtained. These data can be correlated by plotting the inverse of the square root of velocity versus external flux. A straight line is fitted through these data. An example of flame spread data plotted in this manner is given in Figure 3. The intercept with the x-axis corresponds to the minimum flux for ignition. This value should correspond to the minimum flux for ignition obtained from the ignition tests. The external flux at the position where the flame stops progressing is termed the minimum flux for spread. In terms of surface temperature, flame spread rate is given by the following equation

$$V_L = \frac{\Phi}{k\rho c\,(T_{ig} - T_\infty)^2} \qquad (4)$$

Φ is obtained from the slope of the fitted data and is related to the heat flux from the flame. Thus spread rate depends not only on the chemical stability of the solid through T_{ig}, but also the kinetics and energetics of the flame. A surface temperature (produced by the external heat flux) is associated with the minimum flux for spread, therefore, the range of surface temperatures for opposed flow flame spread extends from the minimum temperature for spread to the ignition temperature for a particular material.

The results from the LIFT can be presented on a flammability diagram. Figure 4 shows such a diagram. The x-axis is the external heat flux, the left-hand ordinate gives spread rate, and

the right-hand ordinate gives time to ignition. The curves are the model fits of the data. In general, a shift to the right indicates better performance since ignition takes longer and spread rates are lower for a given incident heat flux.

Some results from LIFT tests are shown in Table 1. The polystyrene **was** tested in the horizontal orientation to limit melting and dripping effects.

Table 1. Ignition and Flam Spread Properties'

MATERIAL	$\dot{q}''_{ig}$ (kW/m^2)	T_{ig} (°C)	$k\rho c$ $(kW/m^2K)^2s$	(kW^2/m^3)	$T_{s,min}$ (°C)
Particle board	17	405	0.63	8	180
Insulating fiberboard	15	381	0.29	14	90
Gypsum board	23	469	0.52	14	380
Extruded polystyrene foam (2 lb/ft^3)	15	376	0.91	31	133
Fire retarded rigid polyurethane foam (2.4 lb/ft_3)	15	376	0.037	4	224
Non-fire retarded polyurethane foam (3.2 lb/ft^3)	14.5	370	0.036	3	65
Polyisocyanurate foam (1.6 lb/ft^3)	21	445	0.030	5	307

The particle board and the insulating fiberboard are both wood based products. Differences in ignitability are readily apparent since both T_{ig} and kpc values are higher for the particle board, indicating that the insulating fiberboard would ignite first at any heat flux above the minimum flux for ignition. **Also,** the spread rate would be higher €or the insulating fiberboard at a given external flux, and the minimum flux for spread for the fiberboard is lower than the value for the particle board. The polystyrene foam collapsed to a thin melt prior to ignition and subsequent spread. For the two rigid polyurethane foams, the main difference appears to be in the minimum temperature for spread. The fire retarded foam yields slightly higher spread rates than the non-fire retarded foam at specific external fluxes, but the temperature for spread is much higher €or the non-fire retarded foam.

'The **values** in this table were obtained from references [6] and [8].

Wind-aided Flame Spread

Wind-aided or upward flame spread is characterized by flame spread in the direction of flow of the hot fire gases and flames. Un-burned material ahead of the pyrolyzing fuel is heated by the flames which are swept ahead by the induced buoyant flow or forced flow. Wind-aided flame spread is somewhat more difficult to measure than lateral flame spread since the flame ahead of the pyrolysis front obscures the front's position. In addition, wind-aided flame spread is usually acceleratory or deceleratory by nature. But, given the data collected from the LIFT and Cone Calorimeter, an approximate model can be used to estimate wind-aided spread rates without having to rely on a separate wind-aided flame spread test [6,9].

Wind-aided flame spread is expressed by the approximate formula

$$\frac{dy_p}{dt} = \frac{y_f - y_p}{t_{ig}} \qquad (5)$$

where y_f is the visible flame tip position which represents the length of material exposed to a significant flame heat flux; y_f is a function of the heat release rate and correlations for this are available [10]; y_p is the pyrolysis front position and t_{ig} is **a** characteristic ignition time dependent on the material properties and the external heat flux to the sample surface. **A** similar formula for the burn-out front, which follows with some delay behind the pyrolysis front, **is** given as

$$\frac{dy_b}{dt} = \frac{y_p - y_b}{t_b} \qquad (6)$$

Here y_b is the burn-out front position and t_b is a burn time of the material which can be obtained from Cone Calorimeter data. These equations were solved analytically **[6]** to yield two dimensionless parameters, **a** and **b,** which indicate a material's propensity to spread flames upward or in a wind-aided configuration. **a** and **b** are given by

$$a = k_f \dot{Q}'' - 1 \qquad (7)$$

$$b = a - \frac{t_{ig}}{t_b} \qquad (8)$$

$\dot{Q}''$ is a constant heat release rate value estimated from the Cone Calorimeter, k_f is a constant approximately equal to 0.01 m^2/kW. **a** applies alone when there is no burn-out front advancing and **b,** which incorporates **a,** applies when a burn-out front is present. Material

bum-out is an important behavior for thin materials such as textile wall-coverings or chzrring materials.

The solutions to the equations yield the results shown in Figures 5 and **6.** Before a bum-out front develops, the fire size can grow in an acceleratory manner, at a steady (linearly increasing) rate, or in a deceleratory manner depending on the value of **a as** shown in Figure 5. After a burn-out front appears, the fire can either still accelerate (pyrolysis front advancement is faster than bum-out front advancement), yield a steady fire (pyrolysis and bum-out front advancement are equal) or decelerate (burn-out front catches up to the pyrolysis front, shrinking the fire size) depending on the value of **b,** as shown in Figure 6.

An indication of the sensitivity of flame spread to external heat flux is seen by evaluating **a** and **b** at different Cone Calorimeter external heat flux levels. Figures 7 and 8 show, for a few materials, how these two parameters can change as a function of external heat flux. The time to ignition (t_{ig} in Equation 8) **was** evaluated at the flame heat flux of 25 kW/m^2 plus the additional external heat flux. For a particular scenario, the proper external heat flux must be specified. For example, the proper external heat flux for a free-standing wall may be 0 kW/m^2, since no external heat flux is present. By contrast, in a room corner fire, an external heat flux of 25 kW/m^2 or greater may be more appropriate due to configuration effects and radiation from the hot smoke layer. Specifying a constant external heat flux is an approximation, but was shown to yield good predictions of room corner fire tests [6]. Quintiere has formulated a model which is an extension of the work in reference [6] that does not require a specified constant external heat flux, but calculates the time varying external heat flux based on the configuration of the burning material and the fire conditions in the room.

HEAT RELEASE RATE

The Cone Calorimeter yields heat release rate information on small 10 X 10 cm samples. Figure 9 is a schematic of the Cone Calorimeter. The apparatus employs the principle of oxygen consumption calorimetry. The basis of oxygen consumption calorimetry is that it has been observed that the heat release rate for a wide variety of fuels is approximately equal to $13.1 \pm 5\%$ kJ/g O_2 consumed [11]. The Cone Calorimeter measures the mass of O_2 consumed as a function of time throughout the test. The heat source of this apparatus consists of an electrical resistance heater wound into the shape of a truncated cone. This configuration can produce a nearly uniform heat flux across the sample face. The external heat flux is set by fixing the temperature of the heating element to the desired level; the temperature in turn is controlled by the electrical power to the element. The sample is placed on a load cell under the heating element to monitor the sample mass loss. An electrical spark ignitor is used to ignite the sample then it is withdrawn. The Cone Calorimeter is capable of providing time to ignition data comparable to the LIFT time to ignition data. The combustion products are collected in a exhaust hood. Gas composition is analyzed and light extinction measurements are performed on the products in the exhaust stream.

The results of a Cone Calorimeter test include the heat release rate versus time at a specified external heat flux. Heat release rate is the product of the heat of combustion and mass loss

rate thus it is influenced by the chemical stability of the solid and the energetics of the flame. A current topic in fire research focuses on finding correlations between this type of bench-scale data and full-scale test results. Here the data is approximated to serve as input into a fire model that calculates the fire growth rate of room comer fires. The heat release rate is approximated by a square wave starting at t_{ig} with an amplitude equal to 90 % of the peak heat release rate, and enclosing an area equivalent to the area under the curve. The effective bum time (t_b) is the width of the enclosing box. Figure 10 shows how a heat release rate curve is approximated. The percentage of the peak selected must be investigated €or sensitivity; Cleary and Quintiere [6] used 90 % of the peak in their study. In any case, it appears that the actual peak value must be emphasized when examining fire growth rates.

A plot of the peak heat release versus external heat flux typically can be fitted well with a straight line. Figure 11 shows an example of such a plot. This relationship can be used to interpolate between experimentally measured points. A physical basis for this linear relationship was proposed by Quintiere [12]. The equation below shows the relationship between the heat release rate and the heat fluxes that influence a material's burning behavior.

$$\dot{Q}'' = \frac{H_c}{L_g} (\dot{q}_e'' + \dot{q}_f'' + \dot{q}_L'') \qquad (9)$$

The terms $\dot{q}_f''$, and $\dot{q}_L''$ are the heat flux from the flame, and the heat losses term which includes surface re-radiation and conductive heat losses. At the peak heat release rate the heat losses term reaches a minimum value. Thus at the peak heat release rate the combination of $\dot{q}_f''$ and $\dot{q}_L''$ can be considered a constant and independent of the external heat flux. Therefore, the slope of the line in Figure 11 is related to the ratio of the heat of combustion (H_c) to an effective heat of gasification (L_g) of the material. The heat of combustion is available from the Cone Calorimeter by dividing the heat release rate by the mass loss rate. The effective heat of gasification is given by the inverse of the slope of the line multiplied by the heat of combustion. This value is a lower limit or asymptotic limit of the heat of gasification which for solid materials is a time varying value. There is no simple way of obtaining the time varying heat of gasification because of the difficulty in measuring the flame heat flux and heat losses term in Equation 9. The effective heat of gasification obtained here does give an indication of the thermal stability of a material. Table 2 shows some values of the heat of combustion and effective heat of gasification for various materials.

The heat release rate was shown above to be important in predicting upward flame spread propensity through the a and b parameters. In addition, the heat release rate per unit area times the area of the fire gives the heat release rate of the fire.

Table 2. Heat of Combustion and Effective Heat of Gasification for Various Materials[2]		
MATERIAL	H_c (kJ/g)	L_g (kJ/g)
Extruded polystyrene foam (2 lb/ft^3)	34	2.7
Fire retarded polyurethane foam (2.4 lb/ft^3)	12	2.6
Non-fire retarded polyurethane foam (3.2 lb/ft^3)	21	4.1
Polyisocyanurate foam (1.6 lb/ft^3)	10	7.7
Particle board	14	5.4
Gypsum board	7	4.8

SUMMARY

It has been shown that the LIFT and Cone Calorimeter can provide ignitability, flame spread, and heat release rate data. The data are reducible to key fire properties. The ignition temperature (T_{ig}), the effective thermal inertia (kpc), and the minimum flux for ignition ($\dot{q}''_{ig}$) are obtained from ignition data. Φ and the minimum temperature for spread ($T_{s,min}$) are obtained from lateral flame spread tests. Heat release rate data are approximated by a square wave with the height given by the peak heat release rate, with the length of the square wave equal to the effective burn time. Thus two important properties, the peak heat release rate and the effective burn time which are functions of external heat flux, are obtained. In addition, the heat of combustion and the effective heat of gasification give an indication of the energetics and thermal stability of a material. *Also,* for wind-aided or upward flame spread, the two dimensionless parameters **a** and **b,** which incorporate rate of heat release and ignition delay time, indicate a materials propensity to spread flame.

These fire properties can be used as inputs into a fire model that successfully predicts room corner fire tests. Such a relationship between the bench-scale tests and full-scale fire scenarios is the key to evaluating material flammability through bench-scale test methods.

[2]The values in this table are from references [6] and [8].

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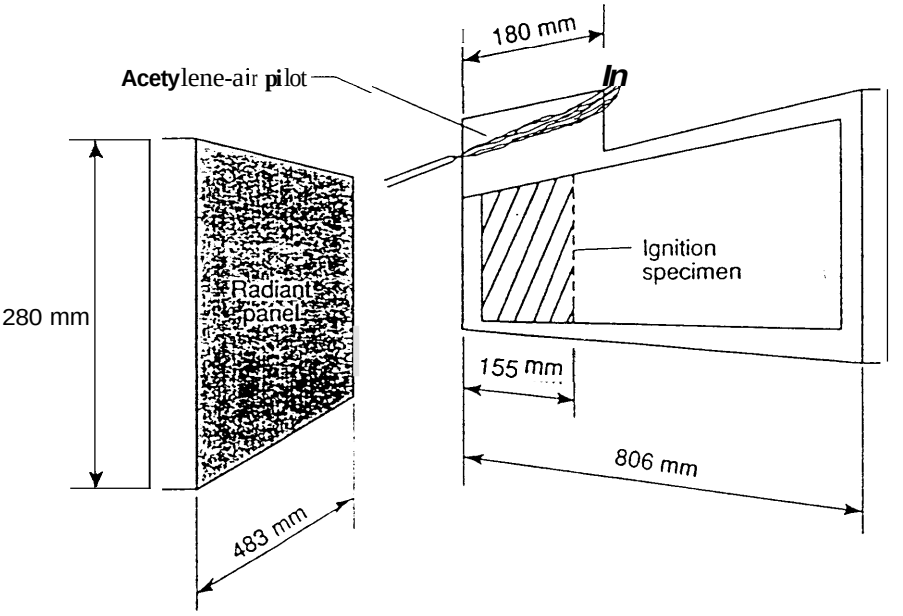

Figure 1. Schematic of LIFT apparatus.

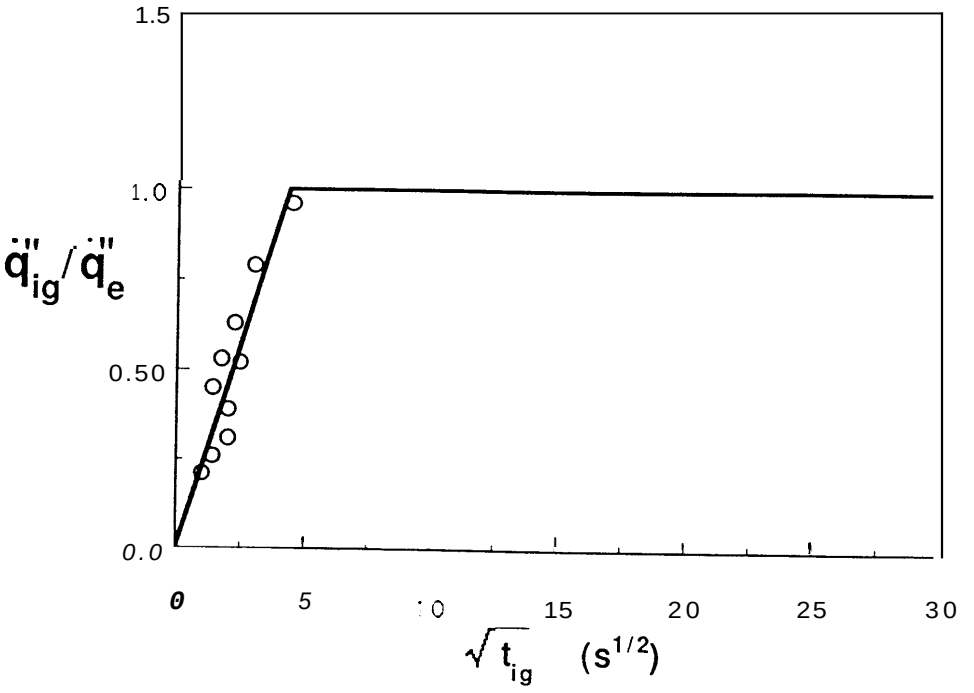

Figure 2. ignition data correlation for rigid polyurethane panel foam

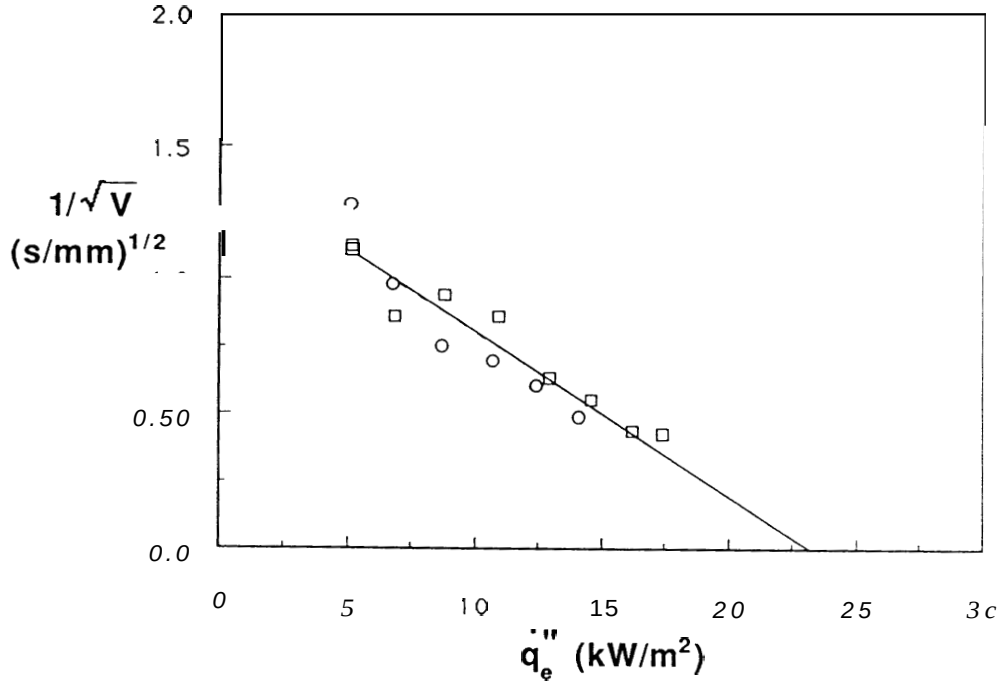

Figure 3. Lateral flame spread correlation for rigid polyurethane foam **(spray).**

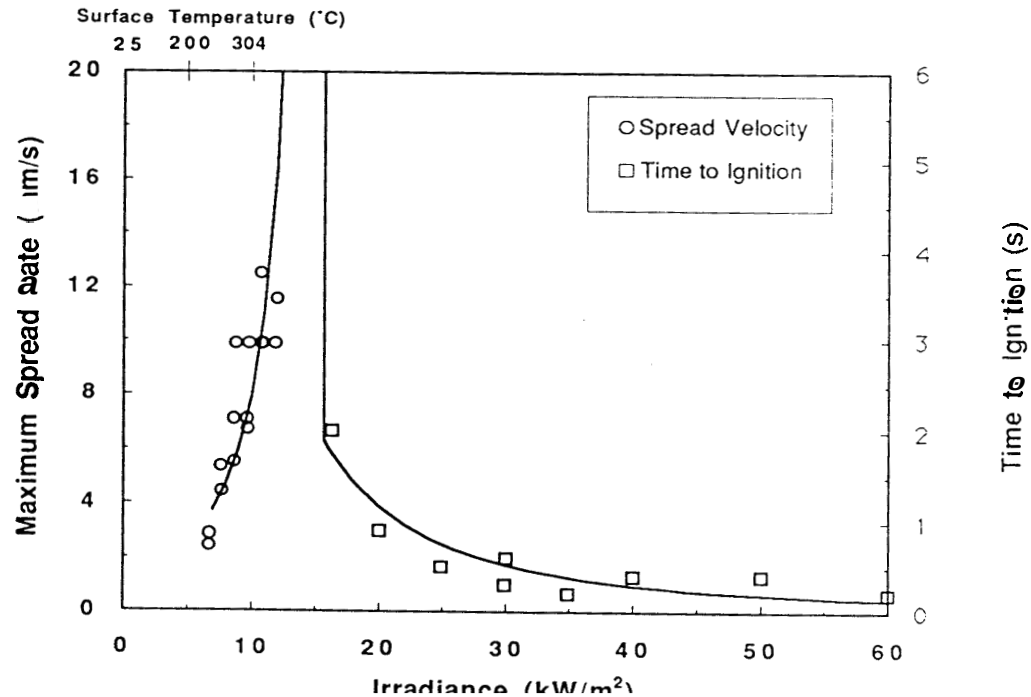

Figure 4. Spread and ignition results for rigid polyurethane panel foam.

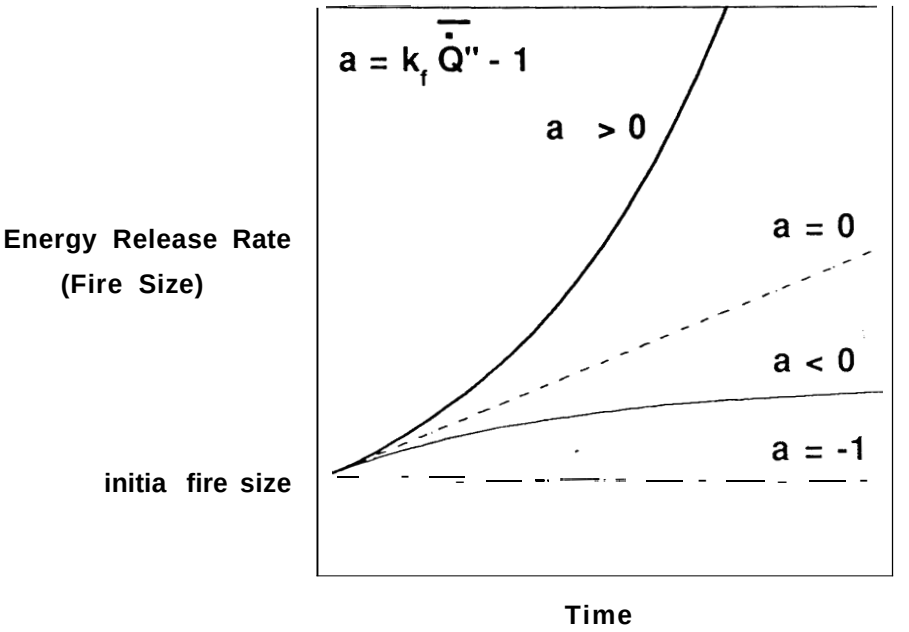

Figure 5. Dependence of a on the fire growth potential.

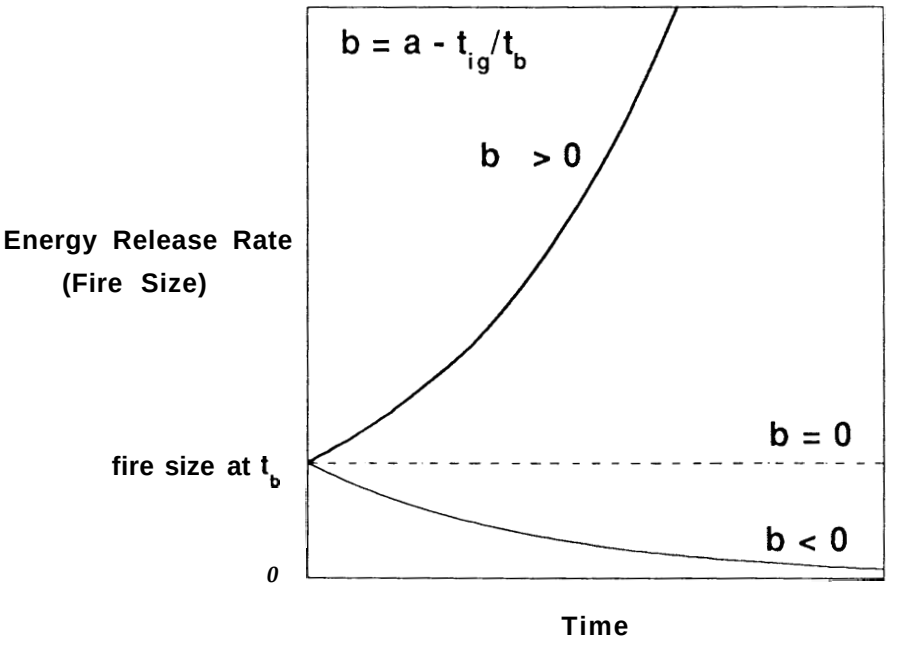

Figure 6. Dependence of b on the fire growth potential.

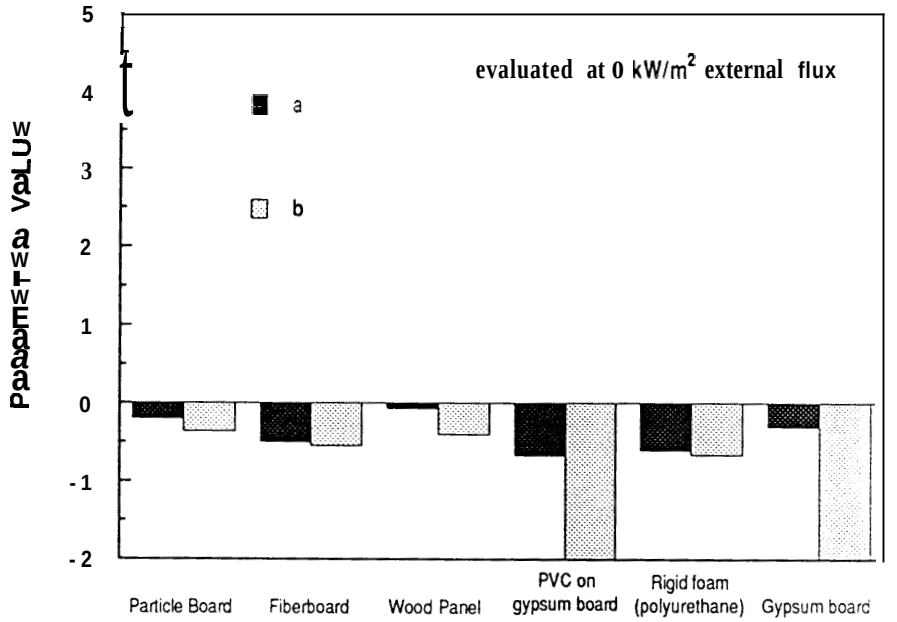

Figure 7. a and b values for various materials.

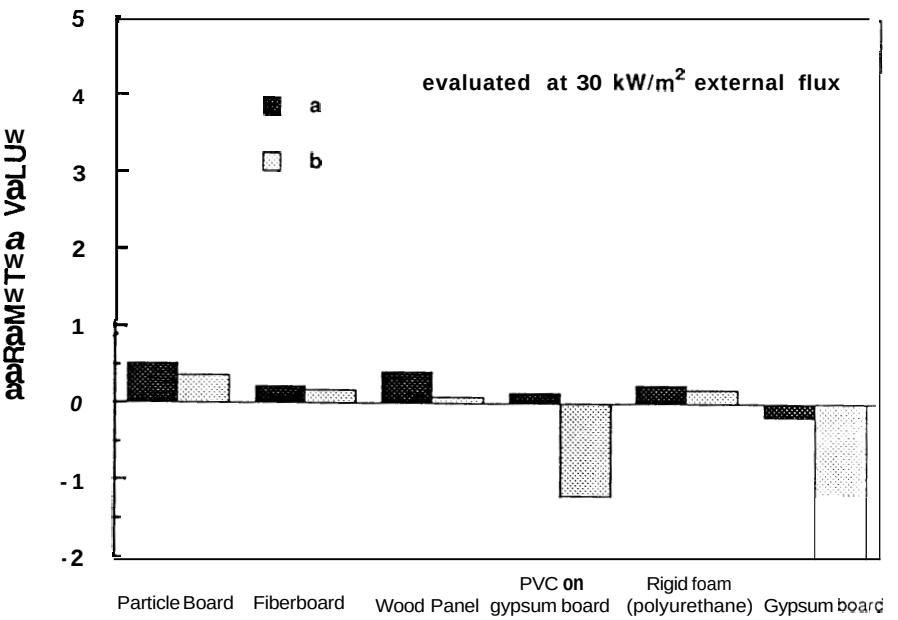

Figure 8. a and b values *for* various materials.

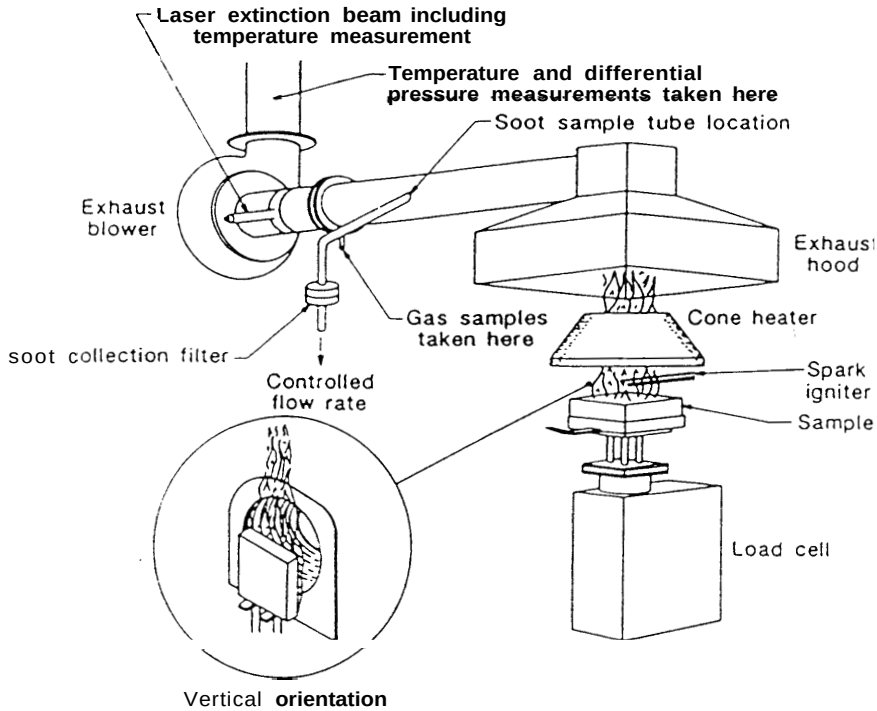

Figure 9. Schematic of the Cone Calorimeter

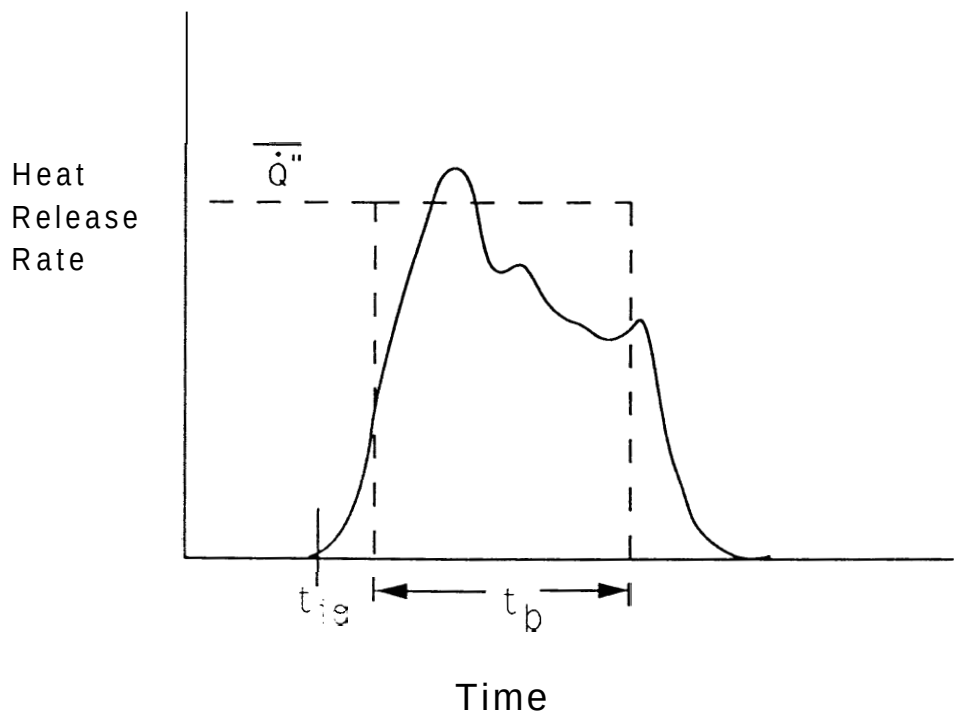

Figure 10. Heat release rate property data.

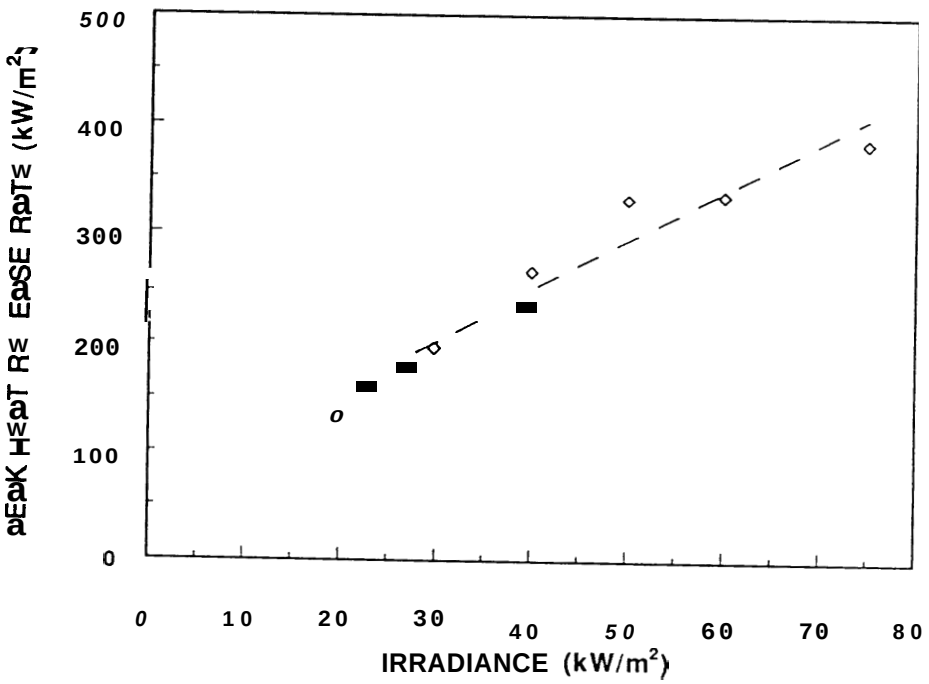

Figure 11. Peak rate of heat release versus irradiance for rigid polyurethane foam (spray).