

A PROFILE OF THE HEAT-RELEASE RATE CALORIMETER

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ABSTRACT

This paper explores the potential of the heat-release rate calorimeter as a tool to develop information useful in assessing fire hazard of materials as they are used in construction. Details are given of concepts for deducing from a typical heat-release rate versus exposure time curve, a variety of basic and applied physicochemical properties of materials in fires. The practical significance of these properties is discussed in relation to the combustion processes occurring in a fire. Among the properties considered are: thermophysical properties of the tested material, time of piloted and spontaneous ignition, fire spread with external radiation, fire endurance of slabs, rate of heat-release, extinguishability, B-number, self-heating and smoke production.

INTRODUCTION

The quest for meaningful fire and flammability tests that bear some quantifiable relation to actual fires has led to the development of the heat-release rate calorimeter (HRRC). Development of a wide variety of calorimeters followed especially in the United States. Data have been generated, interpretations offered, conclusions drawn, and guidelines postulated, but seldom with sufficient scientific insight into the physics and chemistry of the fire processes under scrutiny. A strong movement is under way to adopt the HRRC as a standard. Premature standardization of the HRRC without full quantitative exploration of its capabilities and deficiencies might lead to a repetition of the technical ambiguity, political controversy, and emotional dialogue surrounding other existing standard test methods. This paper is intended to scientifically explore the potentials and limitations of the HRRC.

BACKGROUND

In a typical heat-release rate calorimeter, a material specimen is exposed to a prescribed air flow and external radiant flux. A pilot ignition source may or may not be provided in the vicinity of the heated specimen surface. The back face of the specimen, of known physical and chemical structure and thickness, must be kept at a well-defined (insulated, constant flux or constant temperature) thermal condition. A secondary gas burner or electrical heater may be present in the flue stack. As the exposed specimen is ignited, and as burning occurs, heat is released as a function of time. This heat-release may be measured by operating the calorimeter in either isothermal mode or adiabatic mode. In the isothermal mode, the flue gas temperature, as monitored by thermocouples, is kept constant by cutting down the energy input to the secondary heater in

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proportion to the unknown heat-release rate. In the adiabatic mode, the secondary heat input is absent, and the heat-release rate is indicated by the rise in flue gas temperature. Whereas, both modes of operation have their practical advantages and disadvantages, the isothermal mode is basically superior for measuring a fire-extensive thermochemical property and to ensure a constant volumetric flow rate in the flue stream.

The conventional calorimetry (e.g., the Parr Bomb) measures the thermochemical quantity of heat released when a known small quantity of fuel is made to combust in oxygen nearly completely at constant temperature. The heat-release rate calorimeter, on the other hand, expands the time-scale over which the heat is released under nonisothermal, nonequilibrium conditions. The effects of geometry, orientation, flow, and external heating are thus accentuated, with the aim of duplicating the path taken by materials in their consumption by a fire. The heat-release rate measured with the HRRC is an extrinsic property of the test material because of the intruding factors, characteristic of combustion in a large fire, such as incompleteness of pyrolysis and combustion; inadequate equilibration of the products released; heat losses to the bounding walls; external energy impetus; dripping, charring, sputtering, and other thermomechanical effects; constrained ventilation and boundary layer effects; self-radiation characteristics. In fact, a more precise name might be "path calorimeter." An example HRRC output curve is illustrated for the heat-release rate calorimeter in Fig. 1.

SCOPE

Theoretically, some of the physicochemical properties related to the fire behavior that are obtainable in a typical HRRC experiment are: thermophysical properties of the tested material; time to piloted and spontaneous ignition and ignition mechanisms; fire spread with external radiation; basic mechanism of flashover; fire endurance of material slabs; rate of heat release as a function of the scale and configuration; heat content or energy potential (i.e., integrated heat release rate); limiting thermal index and extinguishability; thermal sensitivity index and B-number; self-radiance of flames of isolated fuel elements; release rate and potential of smoke for the variable scale and configuration; degree of completeness of combustion; rate and yield of combustion products. In fire hazard assessment, these properties are clearly significant. In this paper, the details by which they are deduced from the heat-release rate calorimeter output will be considered in some depth. The possible useful concepts will be explored, but not necessarily with emphasis on explicit mathematical rigor. We have chosen this approach because we believe that the concepts deserve as lucid a presentation as possible without being obscured, at present, with the imminent nonlinearities and other mathematical complexities.

THERMOPHYSICAL PROPERTIES

Under the well-defined boundary conditions on a slab of finite thickness l , i.e., prescribed radiant flux I on the front-face ($x = 0$) and constrained loss rate on the back-face, manipulation of the transient conduction solutions^{1*} leads one to deduce, in the preheat phase, the material's effective thermal diffusivity, α_s , conductivity, K_s , responsiveness $K_s \rho_s C_s$, and volumetric heat capacity, $\rho_s C_s$, from the measured time (t)-temperature (T) records pertaining to two different depths (x) beneath the exposed surface. Denoting the spatial locations by subscripts a and b and two time instants by 1 and 2 if $\alpha_s t/l^2 \gtrsim 0.25$, one obtains for the insulated back-face condition,

$$K_s \approx \left(1 - \frac{x_a + x_b}{2l}\right) \left(\frac{x_b - x_a}{T_{a1} - T_{b1}}\right) I$$

$$\alpha_s \approx \left(1 - \frac{x_a + x_b}{2l}\right) \left(\frac{T_{a1} - T_{a2}}{T_{a1} - T_{b1}}\right) \left(\frac{x_b - x_a}{t_1 - t_2}\right) l$$

$$K_s \rho_s C_s \equiv K_s^2 / \alpha_s$$

$$\rho_s C_s \equiv K_s / \alpha_s \quad (1)$$

It is critical to specify the boundary conditions unambiguously in a HRRC experiment. If the test material ignites very rapidly, the preceding equations may be of little help and resort might have to be taken to the solutions of a semiinfinite slab conduction problem.

IGNITION

Although a slight release of heat may be noticeable due to preignition oxidation, ignition is expected to mark the onset of significant heat-release. The time for this to occur depends on the imposed heat flux, material properties--physical and chemical--flow and mixing in the calorimeter chamber, location of pilot source, if one is used, and other variables. If * denotes the state of ignition, the ignition time, t^* , is predictable (when the back-face is insulated) from

$$t^* \approx \frac{\rho_s C_s l (T^* - T_i)}{I} - \frac{l^2}{3\alpha_s} \quad (2)$$

*References are listed at the end of the paper

where T^* is the surface temperature at ignition. A plot of t^* versus $1/I$ is thus expected to be a straight line (see Figure 2) with a slope, $\rho_s C_s \ell (T^* - T_i)$, and a negative intercept, $\ell^2 / 3\alpha_s$. Knowing $\rho_s C_s$ from the pre-heat problem, one can also obtain T^* for various materials, with or without pilot ignition source. This T^* is useful in classifying materials as to their "ignitibility". Also, the $t^*(I)$ measurements offer an independent way of calculating the thermal diffusivity, α_s .

The intensity and location of the pilot light² significantly influence the time to ignition and exposed surface temperature at ignition, and all the while, the impressed radiation heats the solid. It is, therefore, imperative to choose the type and location of pilot source judiciously.

Furthermore, inasmuch as ignition is associated (a) with some sort of thermal (im)balance between the oxidative heat generation and the convective-conductive heat dissipation, and (b) with the formation of a flammable mixture in the boundary layer, taller panels tend to ignite sooner,³ and ignition is better facilitated by a pilot source at the top⁴ of the panel rather than at the bottom.⁵

FLAME SPREAD

When the specimen, which is exposed to low to moderate external radiation fluxes is pilot-ignited, the flame quickly spreads vertically upwards if the pilot is at the bottom,⁵ and horizontally along the top if the pilot is at the top.⁶ In both cases, the flame edge becomes flat, spreading (laterally in the first case and downwards in the second case) at a more or less uniform rate, V . The heat release rate \dot{q}_G'' becomes measurably large and increases with time rather rapidly. deRis⁷ derived an equation for this flame spread on a thick fuel element. Assuming that the radiant heating intensity ahead of the leading edge of the spreading flame is the same as that behind, the deRis result could be modified to the following form.

$$V = \tilde{a} + \tilde{b} I^2 \quad (3)$$

$$\tilde{a} \equiv \left(g\alpha_g \frac{T_f - T_\infty}{T_\infty} \right)^{1/3} \left(\frac{\rho_g C_g K_g}{\rho_s C_s K_s} \right) \left(\frac{T_f - T_p}{T_p - T_\infty} \right)^2$$

$$\tilde{b} \equiv \left(2\delta + \frac{4\alpha_g}{\pi} \left[g\alpha_g \frac{T_f - T_\infty}{T_\infty} \right]^{-1/3} \right) \left(\rho_s C_s K_s (T_p - T_\infty)^2 \right)^{-1}$$

At the considered low-to-moderate external radiant fluxes $V \approx \tilde{a}$, so that the height H' of the upper part of the panel covered by the spreading flame (for top-ignition) is given by $H' \approx \tilde{a}(t-t^*)$. The fuel generation rate under this flame is

$$\dot{m}'' = \frac{h (T_f - T_p) + I}{L} \quad (4)$$

where L is the latent heat of pyrolysis, and h is the heat transfer coefficient for the convective feedback between the flame and the fuel

surface; h is proportional to $\rho u C$, where u is the velocity induced in the flame gases under the influence of the buoyant and viscous forces, $u_g \propto gH'^2/\nu_g$. Hence, the mass transfer rate becomes

$$\dot{m}'' \approx \left[I + \kappa_1 \rho_g C_g (g/\nu_g) (T_f - T_p) \tilde{a}^2 (t - t^*)^2 \right] / L$$

Furthermore, $\dot{m}'' H' W \Delta H_b \equiv \dot{q}_G'' HW$ so that

$$\dot{q}_{GT}'' \approx \omega_T I (t - t^*) + \Omega_T (t - t^*)^3 \quad (5)$$

where

$$\omega_T \equiv \left(\frac{\Delta H_b}{L} \frac{\tilde{a}}{H} \right); \quad \Omega_T \equiv \left(\frac{\Delta H_b}{L} \frac{\tilde{a}^3}{H} \kappa_1 \rho_g C_g (g/\nu_g) (T_f - T_p) \right)$$

For bottom-ignition, with lateral flame spread, we can deduce a similar expression (note that there are two spreading fronts, and the flame gas velocity is independent of time),

$$\dot{q}_{GB}'' \approx \omega_B I (t - t^*) + \Omega_B (t - t^*)^3 \quad (6)$$

where

$$\omega_B \equiv \left(\frac{\Delta H_b}{L} \frac{2\tilde{a}}{W} \right); \quad \Omega_B \equiv \left(\frac{\Delta H_b}{L} \frac{2\tilde{a}}{W} \kappa_1 \rho_g C_g (gH^2/\nu_g) (T_f - T_p) \right)$$

Note the strong differences in the dependency of the heat-release rate on time. These strong differences require a judicious and consistent choice of location of the pilot flame in an experiment. Further, note the way the flame velocity \tilde{a} enters into the two definitions of Ω . Also note that the ratio $\Delta H_b/L$ appears in all the coefficients. If convective feedback is negligible compared to the externally impressed radiation, then both the cases reduce to give similar time dependency of heat-release rate.

$$\dot{q}_{GT}'' = \frac{\Delta H_b}{L} \frac{\tilde{a}}{H} I (t - t^*) = \frac{W}{2H} \dot{q}_{GB}'' \quad (7)$$

For correlation of experiments with varying panel geometry and with varying pilot source location, this relation is crucial.

FIRE ENDURANCE

The fire endurance of a slab construction assembly simulating a door, wall, window, floor, or ceiling may also be studied by either monitoring the back-face temperature and noting the time when it reaches a pre-chosen critical value, or by observing the arrival of decomposition to the the back-face. The first criterion is fairly straightforward; the second is more subtle. It may be possible to relate the second criterion to the period of active flaming, which is expected to exceed the endurance time but little.

Ignoring the reduction in thickness of the specimen from burning, the endurance time by the first criterion may be deduced from the conduction solution (for insulated back-face condition) as

$$t_e \approx \frac{x^2 \rho_s C_s}{6K_s} + \frac{\rho_s C_s x}{I} (T_e - T_i) \quad (8)$$

FULLY DEVELOPED FLAMING

Three things are crucial in the heat-release rate versus time record obtained on a given material exposed to a given irradiance; these are the shape of the curve, the maximum release rate, and the average rate. Some significant time characteristics may be deduced from the shape; for example, time to ignition, time to complete flame spread, time to maximum release rate, time to complete flaming, and time to complete glowing. From the maximum rate, the expectable fire severity may be deduced. The total area lying under the $\dot{q}_G''(t)$ curve is a measure of the heat load (per unit area) of the tested specimen. If divided by the total mass lost (per unit area) by the specimen, the heat load gives the heat of burning, ΔH_b .

$$\Delta H_b \equiv \frac{\int_0^{\infty} \dot{q}_G''(t) dt}{\Delta m/WH} \quad (9)$$

ΔH_b is usually much lower than the thermochemical heat of combustion because of incompleteness of combustion and other fire-extrinsic effects. If a calorimeter is equipped to continuously monitor the sample mass loss with time, then it will be possible to delineate the relative contributions of flaming and glowing to ΔH_b . For the time being, we define ΔH_b by $\dot{q}_G'' = \dot{m}'' \Delta H_b$ for the fully developed stage. The mass loss rate itself is roughly

$$\dot{m}'' \approx \left[\dot{q}_{cfw}'' + \dot{q}_{rfw}'' - \dot{q}_{lwo}'' + I \right] / L \quad (10)$$

where L , as before, is the heat of pyrolysis, \dot{q}_{cfw}'' is the convective heat feedback from the flame to fuel wall, \dot{q}_{rfw}'' is radiative feedback, and \dot{q}_{lwo}'' is the rate at which the fuel surface loses heat to the ambience.

Equation (10) may be applied to both instantaneous and time-averaged quantities. Thus, the heat-release rate is given by

$$\dot{q}_G'' \approx \frac{\Delta H_b}{L} \left[\dot{q}_{cfw}'' + \dot{q}_{rfw}'' - \dot{q}_{lwo}'' + I \right] \quad (11)$$

This simple equation is valuable in deducing very useful information from the heat-release rate data. For example, it suggests that a linear plot of \dot{q}_G'' versus I is a straight line (Figure 3) of slope $\Delta H_b/L$ and intercept $\dot{q}_G''(I=0) = (\Delta H_b/L) (\dot{q}_{cfw}'' + \dot{q}_{rfw}'' - \dot{q}_{lwo}'')$. We call the slope

$\Delta H_b/L$ "thermal sensitivity index" (TSI). Knowing its value and ΔH_b for a given material, one can calculate the latent heat of pyrolysis, an illusive property for most plastics. The TSI is, in fact, a primitive form of Spalding's mass transfer B number⁸⁻¹⁰ which holds great promise as a measure of relative flammability of materials. For wood and most polymers, TSI is of the order of unity; for low energy liquids, such as methanol, it is of the order of 10; and for high energy fuels, such as gasoline, it is of the order of 100. When multiplied by the stoichiometric fuel/oxygen mass ratio (computable from known molecular formula of the polymer) and oxygen mass fraction in the ambient air (≈ 0.21), TSI gives a satisfactory estimate for B. Note from Figure 3 that the material X, having a higher TSI than material Y, loses its relative desirability as quickly as the external irradiance increases. Thus, it is obvious that a knowledge of TSI allows better choice of materials in the design of fire-safe structures.

Turning once again to the Eq. (11), the heat-release rate is theoretically zero when I is equal to

$$I_{cr} = - \left[\dot{q}''_{cfw} + \dot{q}''_{rfw} - \dot{q}''_{lw\infty} \right] \quad (12)$$

This critical irradiance may be termed "limiting thermal index" (LTI). If the combined convective and radiative heat feedback is in excess of the total heat loss rate, then the LTI is negative and will result in a sustained fire even in the absence of external radiation. Material Y in Fig. 3 is an example for this. When $I = 0$, the heat-release rate for such a material is theoretically $\dot{q}''_G = (\Delta H_b/L) (\dot{q}''_{cfw} + \dot{q}''_{rfw} - \dot{q}''_{lw\infty}) = -\text{TSI} \times \text{LTI}$. (It is also imperative that for materials and geometries with negative LTIs, the self-feedback is given by $-\text{LTI}$). On the other hand, if the loss rate exceeds the feedback rate, LTI is positive, such as for material X in Fig. 3. When this happens, the fire on a material specimen cannot self-sustain without an external source of heat. (Note, the experimental LTI values are almost always larger than the theoretical values).

Two points of practical significance evolve from the concept of LTI. First, the higher the LTI for a given material assembly, the safer and more desirable it is. Then, to make the material burn continuously, either an increased amount of heat must be imposed or losses must be reduced. In this sense, LTI is somewhat analogous (and perhaps, even related) to the well-known limiting oxygen index (LOI). Both the LTI and the LOI are indirect measures of the energetic impotence of a flame, its vulnerability to suppression activities, and its ability to resist ignition.

Second, for a suppressible fire, \dot{q}''_G at $I = 0$ is negative, for then I is positive. This prescribes the amount of cooling (i.e., increase in $\dot{q}''_{lw\infty}$) needed to achieve successful extinguishment.

$$\dot{q}''_{lw\infty} \geq \dot{q}''_{cfw} + \dot{q}''_{rfw} \quad (13)$$

Conventional practices for accomplishing this extinguishment condition include: augmentation of $\dot{q}''_{l,wc}$ by the use of heat sink agents such as water; and reduction of the combustion temperature (and hence, the feed-back rates) by the introduction of agents which chemically intrude and alter the reaction mechanism.

SMOKE PRODUCTION

If one measures the attenuation of a light beam (of length, l) in the flue gas flow (of volumetric flow rate, \dot{v}), which is constant for an isothermal calorimeter, the optical density, D ($= \sigma l / 2.303$, where σ is attenuation coefficient), may be determined as in the conventional smoke chamber. The attenuation coefficient is approximately proportional to the smoke particle cross section πr_p^2 (r_p being the average particle radius) and to the particulate number concentration n_p''' which varies with time. Then, with κ_2 as proportionality constant,

$$D(t) = l \kappa_2 \pi r_p^2 n_p'''(t) / 2.303 \quad (14)$$

If $m_p'''(t)$ is the particulate mass concentration, and ρ_p is the particulate material density, the number concentration may be rewritten as $n_p''' = m_p''' / (4\pi r_p^3 \rho_p / 3)$. But the mass concentration is related to particulate mass flow rate, \dot{m}_p , and the total volumetric flow rate, \dot{v} , as $m_p''' = \dot{m}_p / \dot{v}$. Therefore,

$$D(t) = \frac{l \kappa_2}{2.303} \cdot \pi r_p^2 \cdot \frac{\dot{m}_p(t)}{\frac{4}{3} \pi r_p^3 \rho_p \dot{v}(t)} \quad (15)$$

If we assume that a fraction Y_p of the mass lost by the specimen appears as particulates, $Y_p \equiv \dot{m}_p / \dot{m} = \dot{m}_p / \dot{m}'' A$, where A is the specimen surface area, then

$$D(t) = \left(\frac{\kappa_2}{2.303} \cdot \frac{3}{4} \cdot \frac{1}{r_p \rho_p} \right) \cdot Y_p \cdot \left(\frac{\dot{m}'' A l}{\dot{v}} \right) \quad (16)$$

This equation is more useful if we define a modified optical density $D'(t)$.

$$D'_f(t) \equiv \frac{D(t) \dot{v}(t)}{\dot{m}''(t) A l} = \left(\frac{\kappa_2}{2.303} \cdot \frac{3}{4} \cdot \frac{1}{r_p \rho_p} \right) \cdot Y_p \quad (17)$$

The first bracketed term on the right hand side is a function of the properties of the average smoke particle resulting from a given polymer burning under the given conditions. Y_p is a property of this burning process as well. Note, whereas D is dimensionless, D' has the dimensions of m^2/g . Recalling the definition of heat of burning, \dot{m}'' can be rewritten as $\dot{q}''_G / \Delta H_b$ so that $D'(t) = D(t) \dot{v}(t) \Delta H_b / \dot{q}''_G(t) A l$. If in a particular experiment D is measured with two sets of light sources and receivers with two different values of l , the slope of D versus l , with known \dot{v} , ΔH_b , \dot{q}''_G , and A , results in the determination of the right hand

side of Eq. (17). From these values, determined under various conditions, some fundamental conclusions may be drawn about the nature of the smoke particles and their yield.

How can the smoke measurements made in the flow system of a heat-release rate calorimeter be correlated with, compared with, or converted to the conventional smoke chamber information? To answer this question, consider the NBS or XP-2 chamber of volume v . The number concentration of smoke particles, n'' , may then be written as $m_p / [(4\pi r_p^3 \rho_p / 3)v]$. Assuming further that the particulate mass, m_p , is a fraction, Y_p , of the total mass lost Δm by the sample, we obtain

$$D = \left(\frac{\kappa_2}{2.303} \cdot \frac{3}{4} \cdot \frac{1}{r_p \rho_p} \right) \cdot Y_p \cdot \left(\frac{\Delta m \ell}{v} \right) \quad (18)$$

which may be rewritten as¹¹

$$D'_c(t) \equiv \frac{D(t)v}{\Delta m(t)\ell} = \left(\frac{\kappa_2}{2.303} \cdot \frac{3}{4} \cdot \frac{1}{r_p \rho_p} \right) \cdot Y_p \quad (19)$$

Note the apparent equivalence of the definitions of the modified optical densities D'_f and D'_c so that

$$D'_f \equiv \frac{D_f \dot{v}}{m'' A \ell} = \frac{D_c v}{\Delta m \ell} \equiv D'_c \quad (20)$$

Through this relation the extensively available smoke chamber data could be correlated with the heat-release rate calorimeter data. This equivalence also facilitates separation of Y_p from the particle properties, leading to classification of materials with respect to their "smoke content."

In a manner analogous to the smoke measurement, the toxic species emanated from the combustion could be determined by an analysis of the effluent stream. If the i th species mass concentration measured in the flow is m_i'' (kg of i/m^3), then it is related to the production rate \dot{m}_i (kg of i/s), volume flow \dot{v} (m^3/s), specimen mass loss rate \dot{m} and heat-release rate according to

$$\begin{aligned} \dot{m}_i &= m_i'' \dot{v} \\ Y_i &\equiv \dot{m}_i / \dot{m} = m_i'' \dot{v} / \dot{m} = m_i'' \dot{v} \Delta H_b / \dot{q}''_G A \end{aligned} \quad (21)$$

CONCLUSION

Above, only a partial thumbnail sketch has been presented of the sort of applied and fundamental variables that can be measured by the heat-release rate calorimeter and that can be defended by quantitatively meaningful combustion arguments to relate them to fire safety. Some of these variables, arguments, concepts, and relationships are presented in the detail required to enunciate the avenues of exploring the full

potential of heat-release rate calorimeter before it becomes a rigid conceptually unchangeable standard test. The concepts explored here can be treated with more rigor as required to delineate to interacting processes of the fire and to deduce properties of materials and their applications in a sensible manner.

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NOMENCLATURE

\bar{a}	Flame spread constant (m/s)
A	Specimen area (m ²)
\bar{b}	Flame spread constant (m ⁵ /sW ²)
C	Specific heat (J/g K)
D	Optical density
D'	Modified optical density (m ² /kg)
g	Acceleration due to gravity (m/s ²)
h	Heat transfer coefficient (W/m ² K)
H	Height of the specimen panel (m)
H'	Height of the specimen panel covered by flame(m)
ΔH_b	Heat of burning (J/kg)
I	Imposed radiant flux (W/m ²)
K	Thermal conductivity (W/mK)
l	Specimen thickness, optical path length (m)
L	Latent heat of pyrolysis (J/kg)
Δm	Total mass lost by the specimen (kg)
\dot{m}	Mass loss rate (kg/s)
\dot{m}''	Mass loss rate per unit area (kg/m ² s)
\dot{m}_i	Rate of production of ith product (kg/s)
m_i'''	Mass concentration of ith product (kg/m ³)
n_p'''	Number concentration of smoke particles (1/m ³)
q''	Heat-release rate (W/m ²)
q''^G	Heat flux (W/m ²)
r_p	Smoke particle radius (m)
t	Time (s)
T	Temperature (K)
u	Velocity (m/s)
\dot{v}	Volumetric flow rate of flue gases (m ³ /s)
V	Flame spread velocity (m/s)
W	Width of the specimen panel (m)
W'	Width of the specimen panel covered by flames (m)
x	Depth beneath the exposed surface (m)
Y_i	Yield, mass fraction of ith specie in the test material
α	Thermal diffusivity (m ² /s)
ρ	Density (kg/m ³)
δ	Forward radiation distance (m)
ν	Kinematic viscosity (m ² /s)
K_1, K_2	Constants of proportionality
ω, Q	Constant coefficients

Subscripts:

a,b	space stations a and b
b	burning
B	bottom ignition
c	chamber
cfw	convective (from flame to fuel wall)
cr	critical
e	endurance
f	flow, flame
g	gas-phase
i	initial
lw_{∞}	loss (fuel wall to ambience)
p	particle, pyrolysis
r fw	radiative (from flame to fuel wall)
s	solid, specimen
T	top ignition
1,2	time instants 1 and 2
∞	ambient

Superscript * for ignition threshold conditions.

REFERENCES

1. H. S. Carslaw and J. C. Jaeger, "Conduction of Heat in Solids," Clarendon Press, London (1959)
2. D. L. Simms, "On the Pilot Ignition of Wood by Radiation," Combustion and Flame, Vol. 7, pp. 253-261, (1963).
3. N. J. Alvares, P. L. Blackshear, Jr., and A. M. Kanury, "The Influence of Free Convection on the Ignition of Vertical Cellulosic Panels by Thermal Radiation," Combustion Science and Technology, Vol. 1, pp. 407-413, (1970).
4. K. Akita, "Studies on the Mechanism of Ignition of Wood." Report of the Fire Research Institute of Japan, Vol. 9, Nos. 1 and 2. pp. 1-44, 51-54, 77-83 and 95-96. (1959).
5. E. E. Smith, "Heat Release Rate of Building Materials," pp. 119-134 in ASTM Special Technical Publication #502. Ignition, Heat Release and Noncombustibility of Materials. American Society for Testing and Materials, (1972).
6. A. J. Amaro, A. M. Kanury, A. E. Lipska, and S. B. Martin, "Thermal Indices from Heat-Release Rate Calorimetry," WSS/CI 74-37. Paper presented at the Fall 1974 meeting of the Western States Section of the Combustion Institute, Northridge, California, (October 1974).
7. J. N. deRis, "Spread of a Laminar Diffusion Flame," pp. 241-252, Twelfth Symposium (International) on Combustion, The Combustion Institute, Pittsburgh, Pa., (1969).
8. D. B. Spalding, "Some Fundamentals of Combustion," Butterworths, London, (1955).

9. A. M. Kanury, "Modeling of Pool Fires with a Variety of Polymers," pp. 193-202. Fifteenth Symposium (International) on Combustion, The Combustion Institute, Pittsburg, Pa., (1975).
10. D. J. Holve, and R. F. Sawyer, "Diffusion-Controlled Combustion of Polymers," pp. 351-361, Fifteenth Symposium (International) on Combustion, The Combustion Institute, Pittsburgh, Pa., (1975).
11. J. D. Seader, and W. P. Chien, "Mass Optical Density as a Correlating Parameter for the NBS Smoke Density Chamber," J. of Fire and Flammability, 5 pp. 151-163, (1974).

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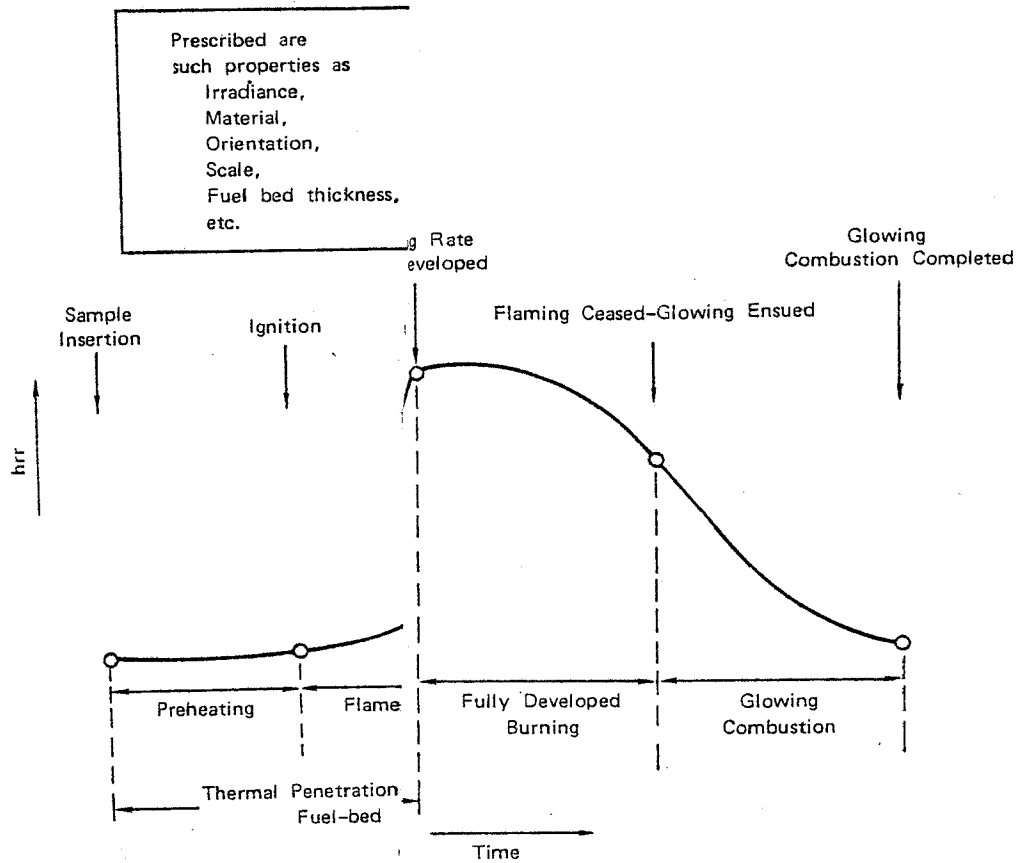


FIGURE 1 A HYPOTHETIC LEASE RATE VERSUS TIME OUTPUT CURVE

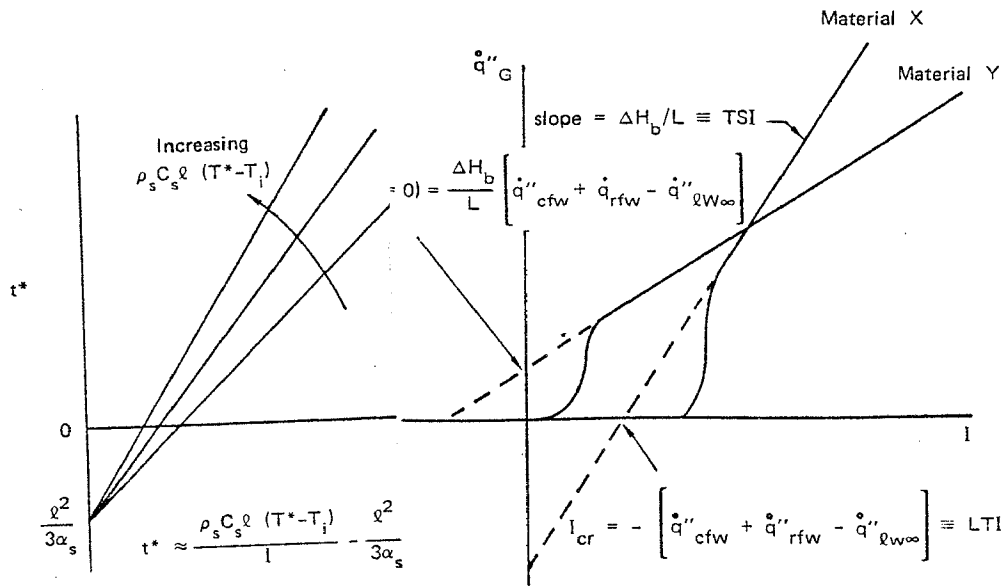


FIGURE 2 IGNITION TIME FIGURE 3 ILLUSTRATION OF TSI AND LTI