Standard Guide for
Obtaining Data for Deterministic Fire Models[1]

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1. Scope

1.1 This guide describes data required as input for mathematical fire models.

1.2 Guidelines are presented on how the data can be obtained.

1.3 The emphasis in this guide is on compartment zone fire models.

1.4 The values stated in SI units are to be regarded as the standard.

1.5 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*

C 177 Test Method for Steady-State Heat Flux Measurements and Thermal Transmission Properties by Means of the Guarded-Hot-Plate Apparatus[2]

C 518 Test Method for Steady-State Heat Flux Measurements and Thermal Transmisson Properties by Means of the Heat Flow Meter Apparatus[2]

C 835 Test Method for Total Hemispherical Emittance of Surfaces from 20 to 1400°C[2]

D 2395 Test Methods for Specific Gravity of Wood and Wood-Base Materials[3]

D 3286 Test Method for Gross Calorific Value of Coal and Coke by the Isoperibol Bomb Calorimeter[4]

D 3417 Test Method for Heats of Fusion and Crystallization of Polymers by Thermal Analysis[5]

E 176 Terminology of Fire Standards[6]

E 408 Test Methods for Total Normal Emittance of Surfaces Using Inspection-Meter Techniques[7]

E 472 Practice for Reporting Thermoanalytical Data[8]

E 473 Terminology Relating to Thermal Analysis[9]

E 537 Test Method for Assessing the Thermal Stability of Chemicals by Methods of Differential Thermal Analysis[9]

E 603 Guide for Room Fire Experiments[6]

E 793 Test Method for Heats of Fusion and Crystallization by Differential Scanning Calorimetry[9]

E 906 Test Method for Heat and Visible Smoke Release Rates for Materials and Products[6]

E 967 Practice for Temperature Calibration of Differential Scanning Calorimeters and Differential Thermal Analyzers[9]

E 968 Practice for Heat Flow Calibration of Differential Scanning Calorimeters[9]

E 1142 Terminology Relating to Thermophysical Properties[9]

E 1321 Test Method for Determining Material Ignition and Flame Spread Properties[6]

E 1354 Test Method for Heat and Visible Smoke Release Rates for Materials and Products Using an Oxygen Consumption Calorimeter[6]

E 1623 Test Method for Determination of Fire and Thermal Parameters of Materials, Products, and Systems Using an Intermediate Scale Calorimeter (ICAL)[6]

3. Terminology

3.1 *Definitions*—For definitions of terms appearing in this guide, refer to Terminology E 176.

4. Significance and Use

4.1 This guide is intended primarily for users and developers of mathematical fire models. It is also useful for people conducting fire tests, making them aware of some important applications and uses for small-scale fire test results. The guide thus contributes to increased accuracy in fire model calculations, which depend greatly on the quality of the input data.

4.2 The emphasis of this guide is on zone models of compartment fires. However, other types of mathematical fire models need many of the same input variables.

NOTE 1—Mathematical fire models in this guide are referred to by their acronyms (see 5.4).

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[2] *Annual Book of ASTM Standards*, Vol 04.06.

[3] *Annual Book of ASTM Standards*, Vol 04.10.

[4] *Annual Book of ASTM Standards*, Vol 05.05.

[5] *Annual Book of ASTM Standards*, Vol 08.02.

[6] *Annual Book of ASTM Standards*, Vol 04.07.

[7] *Annual Book of ASTM Standards*, Vol 15.03.

[8] Discontinued; see *1995 Annual Book of ASTM Standards*, Vol 14.02.

[9] *Annual Book of ASTM Standards*, Vol 14.02.

5. Summary of Guide

5.1 This guide provides a compilation of material properties and other data that are needed as input for mathematical fire models. For every input variable, the guide includes a detailed description and information on how it can be obtained.

5.2 The following input variables are discussed: 6.1, air/fuel ratio; 6.2, combustion efficiency; 6.3, convective heat transfer coefficient; 6.4, density; 6.5, emissivity; 6.6, entrainment coefficient; 6.7, flame extinction coefficient; 6.8, flame spread parameter; 6.9, heat of combustion; 6.10, heat of gasification; 6.11, heat of pyrolysis; 6.12, rate of heat release; 6.13, ignition temperature; 6.14, mass loss rate; 6.15, production rate of species; 6.16, pyrolysis temperature; 6.17, specific heat; 6.18, thermal conductivity; and 6.19, thermal inertia.

5.3 Some guidance is also provided on where to find values for the various input variables.

5.4 A general commentary on zone models for compartment fires and a list of acronyms and data requirements for some models are included in Appendix X1.

6. Data for Zone Fire Models

6.1 *Air/Fuel Ratio*:

6.1.1 *Introduction*:

6.1.1.1 Flames can be characterized as being either premixed or diffusion. Premixed flames can be defined as those flames that result from the ignition of intimately mixed fuels and oxidizers. Diffusion flames can be defined as those flames that result from the ignition of the fuel within the region in which the originally separate fuel and oxidizer meet and mix. Diffusion flames are by far the more common type of flame to be encountered in hostile fire situations. A burning upholstered furniture item is an example of diffusion flame burning.

6.1.1.2 The source of the oxidizer in most fires is the oxygen contained in normal air. If a flame receives insufficient oxygen to burn all of the fuel vapors present completely, the flame is considered to be "oxygen limited" or "oxygen starved." Stoichiometric burning refers to conditions in which the amount of oxygen available in the combustion region exactly equals the amount required for complete combustion. A fuel-limited flame is one for which the amount of oxygen available is greater than that required for complete combustion of the available fuel vapors. Fuel-limited flame is sometimes also referred to as "free burn fire."

6.1.1.3 The air/fuel ratio, γ, of a fuel is a measure of the mass of air required per unit mass of fuel being burned. The effective air/fuel ratio required in some mathematical fire models is greater than or equal to the stoichiometric air/fuel ratio since it reflects the excessive air entrainment associated with free burning fires.

6.1.1.4 The air/fuel ratio is used in the fire models to calculate mass burning rates and hence heat release rate. The air/fuel ratio is unique to each fuel and is dimensionless [that is, mass/mass].

6.1.2 *Procedures to Obtain Air/Fuel Ratios*:

6.1.2.1 As mentioned above, the stoichiometric air/fuel ratio is derived easily from the chemical balance equation describing the complete combustion of the fuel in normal air. For example, consider the burning of propane (C_3H_8) gas in air.

Here, air is described simply as containing oxygen and nitrogen.

$$C_3H_8 + \underset{\text{reactants}}{5(O_2 + 3.76N_2)} \rightarrow \underset{\text{products}}{3\,CO_2 + 4H_2O + 18.8N_2} \tag{1}$$

The mass ratio of air to fuel is found to be 686.4/44 = 15.6. Thus, the stoichiometric air to fuel ratio, γ_s, for propane is found to be 15.6.

6.1.2.2 Some models use an "effective" air/fuel ratio; for example, see Ref (**1**).[10] The main purpose of using an effective ratio different from the stoichiometric ratio is to prevent full utilization of oxygen entrained from the lower layer. However, this ad hoc approach is not generally accepted and validated. A physically correct method of preventing full utilization of the entrained oxygen requires the inclusion of an oxygen mass balance in the set of model conservation equations. Only the stoichiometric air/fuel ratio is needed in this case, while the combustion submodel accounts for the effects of vitiation and oxygen starvation.

6.1.3 *Apparatus to Be Used*—There is no direct need for an apparatus to determine the stoichiometric air/fuel ratio. The ratio can be calculated from the stoichiometry of the combustion reactions, but this is often not possible since the elemental composition of the fuel is seldom known. The most common way of determining the stoichiometric air/fuel ratio in actual fires or experiments is by calculating the ratio between the amount of energy released by combustion per mass unit of air fully depleted of its oxygen and the heat of combustion. The former is nearly identical for a wide range of materials and equal to 3 MJ/kg of air ± 5 %. Methods of determining the latter are discussed in 6.9.

6.2 *Combustion Efficiency*:

6.2.1 *Introduction*—The effective heat of combustion in fires is smaller than the net heat of combustion because of the incomplete combustion of fuel vapors. The combustion efficiency, χ, accounts for incomplete combustion.

6.2.2 *Procedures to Obtain Combustion Efficiency*—The ratio between the effective heat of combustion and net heat of combustion is the combustion efficiency. Thus,

$$\chi = \frac{\Delta h_{c,eff}}{\Delta h_{net}} \tag{2}$$

where:
$\Delta h_{c,eff}$ = effective heat of combustion, kJ/kg, and
$\Delta h_{c,net}$ = net heat of combustion, kJ/kg.

The combustion efficiency for most hydrocarbons ranges from 0.4 to 0.9.

6.2.3 *Apparatus to Be Used*:

6.2.3.1 *Test Method D 3286* for $\Delta h_{c,net}$ (with adjustment for water vapor; see 6.9); and

6.2.3.2 *Cone Calorimeter* (Test Method E 1354), *ICAL Apparatus* (Test Method E 1623), or the *Factory Mutual Small Scale Flammability Apparatus* (**2**) for $\Delta h_{c,eff}$ (see 6.9).

6.3 *Convective Heat Transfer Coefficient*:

6.3.1 *Introduction*:

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[10] The boldface numbers in parentheses refer to the list of references at the end of this standard.

6.3.1.1 Convective heat transfer refers to the movement of heat (energy) between a solid surface and a contacting fluid due to a temperature difference between the two. The modeling of convective heat transfer requires the use of a convective heat transfer coefficient, commonly referred to as *h*, which can be defined as follows:

$$h \equiv \frac{\ddot{q}''}{\Delta T} \qquad (3)$$

where:
$\ddot{q}''$ = energy transferred per unit area, W/m^2, and
ΔT = temperature difference between the surface and moving fluid, K.

6.3.1.2 The convective heat transfer coefficient commonly has SI units of W/m^2·K; it is a function of the fluid properties (thermal conductivity, density, and viscosity), nature of the fluid flow (velocity and turbulence), and geometry of the solid surface.

6.3.2 *Procedures to Obtain the Convective Heat Transfer Coefficient*:

6.3.2.1 *General Method*:

(1) The selection of a proper heat transfer coefficient can be difficult due to the extremely large number of variables that must be included in its derivation, even for the relatively small number of practical situations encountered in mathematical fire modeling.

(2) One wishing to obtain values for heat transfer coefficients generally searches compilations of previously derived values for those that best apply to a problem or situation. Examples of these sources include heat transfer texts (for example, see Ref (3)). The situation can be further simplified when the fluid is air, which of course is the situation generally encountered in fire modeling. Most fire models assume that smoke behaves like and has physical characteristics similar to those of air.

(3) For example, the convective heat transfer coefficient for exchange between a turbulent air flow and a vertical plane can be approximated as follows:

$$h = 0.95(\Delta T)^{1/3} \qquad (4)$$

where:
h = W/m^2·K, and
ΔT = temperature difference between the vertical surface and the air, K.

6.3.2.2 *Default Values in Some Existing Fire Models*:

(1) Some models currently have fixed heat transfer coefficients. Regardless of the conditions within the hot layer, the coefficient is set at a constant value of approximately 10 W/m^2·K.

(2) Other models, such as CFC V (4) and FIRST (5) use a slightly more complex approach wherein the heat transfer coefficient is expressed as a function of the hot layer temperature. A lower limit of 5 W/m^2·K and an upper limit of 50 W/m^2·K were selected in this approach. The expression for calculating *h* in this method is as follows:

$$h = \text{minimum of } 50 \text{ W/m}^2\text{K and } 5 + 0.45(T_1 - T_w) \qquad (5)$$

where:
T_1 = layer temperature, K, and

T_w = wall temperature, K.

(3) Finally, some models (6,7) use an even more complex approach in which the heat transfer coefficient is calculated from the Nusselt Number (Nu), which is a function of the Grashof Number (Gr) and the Prandtl number (Pr) in the familiar form:

$$Nu \equiv \frac{hl}{k} = C_1 (\text{GrPr})^y \qquad (6)$$

where:
h = convective heat transfer coefficient, W/m^2·K,
l = characteristic length of surface, m,
k = thermal conductivity of the fluid, W/m·K,
C_1 = a constant, and
y = a constant.

(4) The equation implies that heat transfer is dominated by natural convection. This is not always true and not everywhere the case in room fires. For example, plume and vent flows generate significant velocities that drive heat transfer. Since the velocity is generated external to the heat transfer process, the convection heat transfer between walls or objects and these flows is forced rather than natural. For forced convection, the following equation for the Nusselt Number as a function of the Reynolds Number (Re) and the Prandtl number shall be used:

$$Nu \equiv \frac{hl}{k} = C_2 \text{Re}^x \text{Pr}^y \qquad (7)$$

where:
C_2 = a constant, and
x = a constant.

6.3.3 *Apparatus to Be Used*—Unless there is a need (and availability) of a heat transfer coefficient for a specific situation, sufficient accuracy should be provided by selecting a value (or deriving one) judiciously from tabular data (and formulas). If experimental data are desired, the apparatus required may vary depending on the problem being explored.

6.4 *Density*:

6.4.1 *Introduction*:

6.4.1.1 The density of a material is the mass of material per unit volume. In fire models, density is usually expressed as kg/m^3.

6.4.1.2 There are two reasons for density to change as a material is heated: volatile (flammable or nonflammable, or both) may be lost and dimensional changes (expansion or contraction) may occur. Although corrections for temperature dependence can be made (8), many models use constant (room) temperature values.

6.4.2 *Procedures to Obtain Density*:

6.4.2.1 The density of a material is determined by measuring the mass and physical dimensions (volume) of a sample of the material. There are detailed ASTM guidelines for certain types of building materials, for example, Test Methods D 2395 for wood and wood-base materials.

6.4.2.2 When the temperature dependence of density is sought, changes in mass with temperature can be determined using thermogravimetric analysis and changes in dimensions with temperature using dilatometric analysis (8,9).

6.4.3 *Apparatus to Be Used*:

6.4.3.1 *Mass Balance* (or equivalent).

6.4.3.2 *Caliper, Ruler* (or equivalent).

6.4.3.3 *Dilatometric Apparatus.*

6.4.3.4 *Thermogravimetric Analyzer.*

6.5 *Emissivity*:

6.5.1 *Introduction*—The emissivity of a material is the ratio of the power per unit area radiated from its surface to that radiated from a black body at the same temperature. A material's emissivity represents its thermal radiative behavior integrated over all wavelengths. Emissivity is a dimensionless quantity with an upper limit of unity for a black body.

6.5.2 *Procedures to Obtain Emissivity*— Several standard test methods have been developed to measure the emissivity of materials. A specimen of the material is usually placed in an evacuated chamber and heated (often with an electric current) to the temperature of interest. The power dissipated by the material is determined and equated to the radiative heat transfer to the surroundings. The emissivity of the material is computed using this power and the Stefan-Boltzman equation.

6.5.3 *Apparatus to Be Used*:

6.5.3.1 *Vacuum Emittance Test Apparatus* (Test Method C 835).

6.5.3.2 *Inspection Meter* (Test Methods E 408).

6.6 *Entrainment Coefficient*:

6.6.1 *Introduction*—Mass flow rates in flames and plumes are typically calculated in compartment zone fire models via empirical equations that are derived from entrainment theory. The latter is based on the assumption that the amount of air entrained into the flame or plume at a certain height is proportional to its (center-line) velocity at that height. The entrainment coefficient is defined as the constant of proportionality between both velocities or flow rates. The coefficient is dimensionless.

6.6.2 *Procedures to Obtain Entrainment Coefficient*:

6.6.2.1 For models that predict flame and plume flows via empirical equations, the entrainment coefficient is embedded into these equations. The equations are based on correlations of experimental data, and they are often hard-wired into the model code so that the user cannot change them. Some models account for a reduction in entrainment for flames and plumes against a wall or in a corner of walls. This is usually done automatically on the basis of the location of the fire, and the user is not allowed to change the entrainment coefficient explicitly.

6.6.2.2 Some models, such as the OSU room fire model (10), do not use empirical flame and plume equations. Alternatively, they include a numerical solution of the conservation equations in the flame and plume region. The entrainment coefficient shows up explicitly in the conservation equations, and the user is allowed to specify its value. The selection of a value for the coefficient is guided by experience and fine-tuned to optimize agreement between model predictions and experimental data.

6.6.3 *Apparatus to Be Used*—A standardized apparatus to measure the entrainment coefficient is not available. However, numerous experimental arrangements have been used to analyze diffusion flames and plumes. One approach to determine entrainment consists of detailed velocity, temperature, and composition mapping of the flame or plume (11,12). However, such measurements are very tedious and time-consuming, and the flow rates that are obtained from integration of the measured profiles are prone to errors. The only practical method of measuring entrainment and hence the entrainment constant is the layer method used by Beyler, Zukoski, and others (13,14).

6.7 *Flame Extinction Coefficient*:

6.7.1 *Introduction*—The flame extinction coefficient inter-relates average radiation parameters such as emissivity, flame intensity, and temperature over the entire spectrum of wavelengths. It is used in the following equation to calculate the emissive power of a flame:

$$\dot{E} = A\sigma_f^A \left(1 - e^{-kl}\right) \qquad (8)$$

where:

E = emissive power of the flame, W,
A = enveloping area of the flame, m^2,
σ = Boltzman constant, $5.67 \cdot 10^{-8}$ $W/m^2 \cdot K^4$,
T_f = flame temperature, K,
k = flame extinction coefficient, m^{-1}, and
l = path length, m.

k is also called the absorption coefficient, absorption-emission coefficient, or effective emission coefficient.

6.7.2 *Procedures to Obtain Flame Extinction Coefficient*—The coefficient k can be estimated from measurement of the emissivity ϵ and path length l, assuming emissivity can be expressed as $\epsilon = 1 - e^{-kl}$.

6.7.3 *Apparatus to Be Used*—There is no apparatus for measuring the flame extinction coefficient. The extinction coefficient can be determined by measuring all flame parameters in the equation for E except k. Fire models include many of such empirical equations, but the documentation usually does not specify what the parameters mean and how they are to be determined. It must be stressed that the equation for E is highly empirical. This makes it essential that the flame area, flame temperature, and extinction coefficient be determined in a self-consistent manner.

6.8 *Flame Spread Parameter*:

6.8.1 *Introduction*:

6.8.1.1 The opposed-flow (against the direction of the surrounding flow or against gravity) flame spread rate over a surface can be predicted via the equation originally developed by deRis (15):

$$V_p = \frac{\phi}{k\rho c(T_{ig} - T_s)^2} \qquad (9)$$

where:

V_p = flame travel rate, m/s,
ϕ = flame spread parameter, W^2/m^3,
k = thermal conductivity, $W/m \cdot K$,
ρ = density, kg/m^3,
c = heat capacity, $J/kg \cdot K$,
T_{ig} = surface temperature at ignition, K, and

T_s = surface temperature just prior to arrival of the flame front, K.

6.8.1.2 The flame spread parameter, ϕ, for specific orientations and in standard air environments is a characteristic for the heat transfer from the flame to the fuel ahead of the flame front in the vicinity of the flame foot. It is a material property expressed in W^2/m^3.

6.8.2 *Procedures to Obtain the Flame Spread Parameter*— The flame spread parameter can be obtained from a correlation of opposed-flow flame spread data, that is, flame spread rate over a range of irradiance levels (or surface temperatures). The test method described in Test Method E 1321 was developed specifically to measure the flame spread parameter. It must be stressed that the equation for V_p is highly empirical. This makes it essential that V_p, $k\rho\ c$, and T_{ig} be determined in a self-consistent manner. Further details on consistent methods to determine T_{ig} and $k\rho c$ can be found in 6.13 and 6.19, respectively.

6.8.3 *Apparatus to Be Used*:

6.8.3.1 *LIFT Apparatus* (Test Method E 1321).

6.9 *Heat of Combustion*:

6.9.1 *Introduction*—All combustion reactions generate energy, which may be expressed as heat. The heat of combustion is defined as the amount of heat generated when a unit quantity of fuel is oxidized completely. SI units for heat of combustion, Δh_c, is kJ/kg.

6.9.2 *Procedures to Obtain Heat of Combustion*:

6.9.2.1 Heats of combustion are measured by combustion bomb calorimetry. A known mass of fuel is burned completely in an adiabatic apparatus containing pure oxygen. This method yields the gross heat of combustion. The net heat of combustion can be determined by subtracting the latent heat of evaporation (2.26 kJ/kg of water) from the gross heat of combustion.

6.9.2.2 An effective heat of combustion can also be obtained from other tests that use oxygen calorimetry. For example, the cone calorimeter (Test Method E 1354) measures the mass loss rate and heat release rate. Incomplete combustion may occur in this environment. The effective heat of combustion, $\Delta h_{c,eff}$, is the ratio between heat release rate and mass loss rate.

$$\Delta h_{c,eff} = \frac{\dot{q}}{\dot{m}} \qquad (10)$$

where:
$\dot{q}$ = heat release rate, kW, and
$\dot{m}$ = mass loss rate of the sample, kg/s.

6.9.3 *Apparatus to Be Used*:

6.9.3.1 *Oxygen Bomb Calorimetry* (Test Method D 3286).

6.9.3.2 *Cone Calorimeter* (Test Method E 1354).

6.9.3.3 *ICAL Apparatus* (Test Method E 1623).

6.9.3.4 *Furniture calorimeter*.

6.10 *Heat of Gasification*:

6.10.1 *Introduction*—The heat of gasification of a material is equal to the net amount of heat that must be supplied through its exposed surface to convert a mass unit to gaseous volatiles.

$$\Delta h_g = \frac{\dot{q}''_{net}}{\dot{m}''} \qquad (11)$$

where:
$\dot{q}''_{net}$ = net heat flux into the material, kW/m^2, and
$\dot{m}''$ = mass loss rate of the material, $kg/m^2 \cdot s$.

The unit of Δh_g is kJ/kg.

6.10.2 *Procedures to Obtain Heat of Gasification*:

6.10.2.1 For a flaming sample, the net heat flux conducted into the material is equal to the sum of radiation and convection from the flame and the external heat flux (from the radiant heater in a small-scale test), minus the (radiant) heat losses from the surface. The flame flux and heat losses depend on the surface temperature, which is very difficult to measure. The cone calorimeter (Test Method E 1354) has been used, in conjunction with surface temperature measurements, to determine Δh_g for wood products and PMMA.

6.10.2.2 For some materials, the surface temperature is reasonably constant and independent of exposure conditions. A plot of (mean or peak) mass loss rates as a function of external irradiance yields a fairly linear relationship for such materials. Values of Δh_g can then be estimated from the inverse of the slope of the regression line through the data points. Tewarson and Petrella have used this technique to obtain Δh_g values for a wide range of plastics [2,16].

6.10.2.3 Unfortunately, surface temperatures are not constant for many materials, in particular charring materials and materials with a high smoke yield. The method by Tewarson and Petrella can still be used, but it yields results that have little physical meaning. Various investigators have used the version of the equation for Δh_g and have obtained a time-dependent heat of gasification curve instead of a single value [17,19]

6.10.3 *Apparatus to Be Used*:

6.10.3.1 *Cone Calorimeter* (Test Method E 1354).

6.10.3.2 *ICAL Apparatus* (Test Method E 1623).

6.10.3.3 *Factory Mutual Small Scale Flammability Apparatus* [2].

6.11 *Heat of Pyrolysis (Heat of Reaction)*:

6.11.1 *Introduction*:

6.11.1.1 Chemical reactions generally involve the generation or absorption of energy. The heat of pyrolysis is the energy emitted or lost during the pyrolysis or thermal degradation of material. It is also defined as the difference between the enthalpy of the virgin material and the enthalpy of the products. In calculation of the heat of reaction, the products are assumed to be at the pyrolysis temperature, and the virgin material is assumed to be at the ambient temperature. SI units of the heat of pyrolysis are J/kg. It is sometimes expressed in J/m^3 or $J/s \cdot m^3$ in models.

6.11.1.2 Bench scale tests generally measure the heat of pyrolysis of a small sample exposed to well-prescribed thermal conditions. Heat of pyrolysis or the corresponding change in enthalpy is usually an input parameter in the energy balance equation for a solid material undergoing thermal degradation.

6.11.1.3 The heat of pyrolysis is generally found in models that calculate the temperature profile within a solid material as it is being heated. The internal energy generation term can be represented in several different ways depending on model. One common way is to multiply the heat of pyrolysis Q (in kJ/kg) by the local rate of decomposition (in $kg/m^3 \cdot s$) to obtain the energy generation term. An alternative is simply to use an

energy generation term dE/dt (in kW/m^3). An alternative for Q is to input the specific heat capacities and enthalpies of formation and have the computer program calculate the enthalpies and corresponding heat of pyrolysis Q. Some models will not have a heat of pyrolysis term since the net energy change is assumed to be zero. The energy generation term may also include sensible energy as well as energy change due to pyrolysis.

6.11.2 *Procedures to Obtain Heat of Pyrolysis*:

6.11.2.1 The most common experimental procedure to measure the heat of pyrolysis is differential scanning calorimetry (DSC). A small quantity (a few mg) of sample is placed in the apparatus. Thermal degradation is obtained using a specified time-temperature exposure. Heat is added to the sample and an inert reference compound so the two materials are maintained at identical temperatures. The added heat is recorded and is assumed to equal the energy lost or gained as a result of the endothermic or exothermic reaction. The sample environment is purged with nitrogen or another inert gas when oxidation reactions are not to be considered. DSC results are affected by such factors as particle size and heating rate. Because of these factors, it can be argued that the DSC results for such small samples are not representative of the behavior of the material in practice. DSC procedures are also used to measure the enthalpy gain or loss associated with physical processes such as vaporization and desorption, as well as the specific heat capacity of a material.

6.11.2.2 The heat of pyrolysis (Δh_p) is generally considered negative for exothermic reactions and positive for endothermic reactions. DSC results are usually presented as a curve, with the energy input on the ordinate with upward deflection reflecting an exothermic reaction and time or temperature on the abscissa increasing from left to right. Standard practices for reporting thermoanalytical data are given in Practice E 472.

6.11.2.3 An alternative thermal analysis is differential thermal analysis (DTA). The temperature difference between the sample and the reference material is measured in DTA as a function of temperature. Quantitative results for the heat of pyrolysis can be calculated from DTA results. Thermogravimetry (TGA) can be used to measure the mass loss as a function of temperature.

6.11.2.4 Estimates for heat of pyrolysis have also been calculated from other measurements. One alternative to measuring the heat of reaction is to add the enthalpies of the products and subtract them from the enthalpy of the virgin material. Another procedure that has been used is to develop a transient heat balance model that has the heat of pyrolysis as the unknown. The energy balance equation is solved for the heat of pyrolysis based on experimentally obtained temperature profile data.

6.11.2.5 The methods mentioned above are not suitable for layered composite materials.

6.11.3 *Apparatus to Be Used*:

6.11.3.1 Several commercial instruments are available and are generally designed to perform other types of thermal analysis as well as DSC. The basic components of the DSC are the sample containers, heating unit, programmable temperature controller, inert reference material, and measuring and recording devices.

6.11.3.2 DSC procedures and apparatuses are discussed in Test Methods D 3417, E 537, and E 793. Power-compensation DSC and heat-flux DSC are two types of apparatuses. Calibration of DSC equipment is discussed in Practices E 967 and E 968.

6.12 *Rate of Heat Release*:

6.12.1 *Introduction*—A realistic calculation of the effects of fire requires knowledge of the burning rate. The burning rate can be expressed as the mass generation rate of fuel volatile or as a rate of heat release, $\dot{q}$. The units of heat release rate are W or kW.

6.12.2 *Procedures to Obtain Rate of Heat Release*:

6.12.2.1 The rate of heat release cannot be predicted from basic measurements of material properties; it is a function of the thermal environment, fuel volatilization, and efficiency of volatile combustion. The heat release rate and mass loss rate are related by the following equation:

$$\dot{q} = \dot{m}\chi\Delta h_{c,net} \tag{12}$$

where:
$\Delta h_{c,net}$ = net heat of combustion of the volatile, kJ/kg,
χ = combustion efficiency, and
$\dot{m}$ = mass loss rate of fuel, kg/s.

6.12.2.2 The heat release rate can also be estimated by assuming that heat is generated by a reaction in which only H_2O, CO_2, and CO are produced, and O_2 is depleted (**20**, chapter 3). The heat release rate, $\dot{q}$, can be calculated from the following equations (**21**):

$$\dot{q}'' = k_{O_2}\dot{D}''_{O_2} \tag{13}$$

and

$$\dot{q}'' = \frac{\Delta h_{c,net}}{k_{CO_2}}\dot{G}''_{CO_2} + \frac{\Delta h_{c,net} - \Delta h_{CO}}{k_{CO}}\dot{G}''_{CO} \tag{14}$$

where:
$\dot{q}''$ = heat release rate per unit area, kW/m^2,
$\Delta h_{c,net}$ = net heat of complete combustion of the material, kJ/kg,
Δh_{CO} = heat of combustion of CO, kJ/kg,
$\dot{D}''_{O_2}$ = depletion rate of oxygen per unit surface area, $kg/m^2 \cdot s$,
k_{O_2} = mass oxygen-to-fuel stoichiometric ratio, kg/kg,
k_{CO_2} = maximum possible yield of CO_2, kg/kg,
k_{CO} = maximum possible yield of CO, kg/kg,
$\dot{G}''_{CO_2}$ = generation rate of CO_2, $kg/m^2 \cdot s$, and
$\dot{G}''_{CO}$ = generation rate of CO, $kg/m^2 \cdot s$.

6.12.3 *Apparatus to Be Used*:

6.12.3.1 The heat release rate can be estimated by measuring the sensible enthalpy of the fire gas outflow. The Ohio State University apparatus (Test Method E 906) applies this principle, but it has proven difficult and generally inaccurate. Most heat release rate measurement devices currently use the oxygen calorimetry principle (**22**) as implemented in the cone calorimeter (Test Method E 1354). One can use the following for small-scale measurements:

(1) Ohio State University Calorimeter (Test Method E 906), preferably modified for oxygen consumption **(23,25)**.

(2) Cone Calorimeter (Test Method E 1354).

(3) Factory Mutual Small Scale Flammability Apparatus **(2)**.

6.12.3.2 Large-scale measurements can be obtained with the following:

(1) ICAL Apparatus (Test Method E 1623).

(2) Furniture Calorimeter **(26)**.

(3) Factory Mutual Fire Products Collection Calorimeter **(27)**.

(4) ASTM Proposed Room/Corner Test **(28)**.

6.12.3.3 These large-scale tests are usually overventilated. Ventilation limits and thermal feedback from the upper smoke layer and walls may have to be accounted for when applying the data to room fire models.

6.13 *Ignition Temperature*:

6.13.1 *Introduction*:

6.13.1.1 Ignition of a solid fuel is defined as the initiation of flaming combustion in the gas phase. When a solid material is exposed to external heat, at some point it will begin to pyrolyze. The fuel vapors mix with air in the boundary layer. Shortly thereafter, the pyrolysis rate may be sufficient for the lower flammability limit to be reached. This mixture will ignite under certain conditions.

6.13.1.2 A distinction should be made between two types of ignition:

(1) Piloted Ignition—Flaming combustion of the gas mixture initiates at a small pilot present in the gas phase. This pilot may be a gas flame, an electric spark, or a glowing wire. Temperature is high enough locally around the pilot for the combustion reactions to start, provided the mixture is flammable.

(2) Unpiloted Ignition—If there is no pilot, the surface of the solid must reach a sufficiently high temperature to trigger the combustion reactions.

6.13.1.3 The prediction of when a solid fuel ignites if exposed to a certain heat flux is a very difficult problem. It includes consideration of heat and mass transfer, in both the solid and gas phases, and fluid flow and mixing in the gas phase. Many investigators have assumed a critical surface temperature criterion for ignition in order to simplify the problem while maintain an acceptable degree of accuracy. This critical temperature is the ignition temperature. It is higher for unpiloted ignition than for piloted ignition. For each of the ignition modes, however, ignition temperature is a characteristic of the material and does not vary with heat flux. SI units are degrees Celsius or Kelvins.

6.13.1.4 Some investigators have actually measured surface temperature at ignition and showed that it is a reasonable criterion for engineering analyses **(29,30)**.

6.13.2 *Procedures to Obtain Ignition Temperature*:

6.13.2.1 Ignition temperatures may be obtained in two ways. The first is by actually measuring surface temperature in ignition tests. Various investigators have attached very fine thermocouples (5 mil or less) to the surface of the specimen **(29,30)**. This method is very tedious as it is difficult to handle fine thermocouples and to ensure good contact with the surface. A more practical technique for monitoring surface

temperature is via a narrow angle infrared pyrometer aimed at a small spot on the surface. However, a pyrometer measures thermal radiation rather than surface temperature. This radiation is partly emission, but also reflection, from the surface. Since surface characteristics (emissivity, absorptivity, and reflectivity) change during exposure and are usually known only roughly, the calculation of surface temperature from pyrometer readings is not trivial.

6.13.2.2 The other way of obtaining surface temperature is through the application of some ignition theory to a set of ignition test results. The results are a series of times to (piloted or unpiloted) ignition at various heat flux levels. Such data can be obtained in any apparatus that is capable of exposing specimens over a range of heat flux levels such as Test Methods E 906, E 1321, or E 1354.

6.13.2.3 A comprehensive theory for interpreting piloted ignition data obtained in the LIFT apparatus (Test Method E 1321) was developed by Quintiere, et al. **(31)**. The critical heat flux, that is, the irradiance level below which piloted ignition no longer occurs, is found experimentally. Ignition temperature then follows from a heat balance equation at the specimen surface at the critical irradiance and for very large times (steady state).

6.13.3 *Apparatus to Be Used*:

6.13.3.1 As mentioned in the previous section, any apparatus that is capable of exposing a specimen over a range of irradiance levels is suitable. In addition to the ASTM test methods mentioned above, there are quite a large number of other apparatuses such as the ISO 5657 ignitability test and the FM small-scale flammability apparatus.

6.13.3.2 There is no standard way of measuring surface temperature, either by thermocouples or by an infrared pyrometer.

6.14 *Mass Loss Rate*:

6.14.1 *Introduction*:

6.14.1.1 Most fuels involved in fires burn in the gas phase. The mass loss rate of such a fuel equals the rate at which the gasification of the fuel occurs. SI units of mass loss rate are kg/s. Mass loss rate is sometimes expressed per unit area in $kg/m^2 \cdot s$.

6.14.1.2 Bench-scale tests measure the mass loss rate of a sample exposed to well-prescribed thermal conditions. Mathematical room fire models can predict the thermal environment at discrete points. Given this exposure and bench-scale test data, models then determine the mass loss rate of the material involved.

6.14.2 *Procedures to Obtain Mass Loss Rate*:

(1) A distinction should be made between the burning of large surfaces and the burning of an item. Mathematical models can predict the mass loss rate of a large surface only, if flame spread over the surface is calculated correctly. A common procedure is to subdivide the surface into small segments so the heat flux to each segment can be considered uniform. Flame spread algorithms (both wind-aided and opposed flow) in the model determine when a segment becomes involved (ignites). Once involved, the model uses bench-scale mass loss data obtained over a range of irradiance levels. The model can

also use full-scale mass loss data obtained in a furniture calorimeter in the case of an item burning.

(2) Mathematical models must also account for the orientation of the fuel. This is accomplished via the exposure as orientation mainly influences feedback from the flame to the fuel and consequently exposure at the solid/gas interface.

6.14.2.1 *Large Surfaces*:

(1) The procedures used by models are based on bench-scale mass loss data obtained in a calorimeter over a range of irradiance levels. The mass loss rate of a segment or sample of a material can be expressed as follows:

$$\dot{m}'' = \frac{\dot{q}_e'' + \dot{q}_f'' - \dot{q}_l''}{\Delta h_g} \qquad (15)$$

where:
$\dot{m}''$ = mass loss rate per unit area, kg/s·m^2,
$\dot{q}_e''$ = external irradiance or exposure, kW/m^2,
$\dot{q}_f''$ = heat flux from the flame, kW/m^2,
$\dot{q}_l''$ = heat losses from the surface, kW/m^2, and
Δh_g = heat of gasification, kJ/kg.

(2) The burning behavior is more or less that of a liquid fuel (for example, PMMA) for some non-charring materials. The surface temperature of the burning material is constant, and steady $\dot{m}''$ can be obtained under constant $\dot{q}_e''$ if the material is sufficiently thick. For such materials, a number of tests can be run in a bench-scale calorimeter over a range of irradiance levels. The constants $\dot{q}_f'' - \dot{q}_l''$ and Δh_g can be obtained from the intercept and slope in a graph of $\dot{m}''$ versus $\dot{q}_e''$ (see 6.10.2). Many materials do not behave like this, but an approximation of $\dot{m}''$ with average values for $\dot{q}_f'' - \dot{q}_l''$ and Δh_g can still be acceptable.

(3) Tewarson, et al. (2) used this technique extensively, and they also explored the effect of O$_2$ concentration on burning rate. It was found that flame radiation is a linear function of O$_2$ concentration. Thus, it was possible to separate $\dot{q}_f''$ from $\dot{q}_l''$ by correlating the mass loss data obtained over a range of irradiance levels and O$_2$ concentrations.

(4) Charring materials such as wood do not have constant $\dot{q}_f'' - \dot{q}_l''$ and Δh_g values, even if $\dot{q}_e''$ is constant. In this case, $\dot{m}''$ can be calculated by a model on the basis of the exposure and exposure history by interpolation in a set of mass loss rate graphs obtained at constant $\dot{q}_e''$ in a bench-scale calorimeter. The time axis also must be scaled, for example, by using total mass loss.

6.14.2.2 *Items*—Models can use mass loss rate curves obtained in a furniture calorimeter (28) directly, provided that they take the ventilation limit and feedback from the upper layer and extended ceiling into account. Items can be treated as a collection of surfaces if such curves are not available. Other techniques are sometimes available for estimating the mass loss rate of a burning item on the basis of bench-scale data.

6.14.3 *Apparatus to Be Used*:

6.14.3.1 *Bench-Scale Data for Large Surfaces*:

(1) *Cone Calorimeter* (Test Method E 1354).

(2) *Factory Mutual Small-Scale Flammability Apparatus* (2).

6.14.3.2 *Full-Scale Data for Items*:

(1) *ICAL Apparatus* (Test Method E 1623).

(2) *Furniture Calorimeter* (26).

(3) *Proposed ASTM Room/Corner Test*, with additional instrumentation (28).

6.15 *Production Rate of Species*:

6.15.1 *Introduction*—The word species is used to refer to the chemical species, that is, the products of combustion, produced by the burning process. In some cases, species is also used to refer to the fire products related to the tenability of the smoke layer. Because of the complex chemistry involved in fire, it is not possible to predict the production rate of species from first principles. We must therefore rely on experimental data to predict the species production rate. SI units of the production rate of species are the same as the mass loss rate, kg/s. It can be expressed in kg/m^2·s in some cases.

6.15.2 *Procedures to Obtain Species Generation Rate*:

6.15.2.1 Some of the experimental apparatuses record the production of various species. The cone calorimeter, furniture calorimeter, and several full-room experiments measure several species using specific gas meters. The gas concentrations recorded in these fire experiments often include oxygen, carbon dioxide, carbon monoxide, and hydrocarbons.

6.15.2.2 Using the experimental measurements and the assumption that the species production rate is directly proportional the fuel mass loss rate, a proportionality constant can be obtained for each of the individual species measured using the following relationship:

$$Y_j = \frac{\int_0^t \dot{G}_j'' \, dt}{\int_0^t \dot{G}_f'' \, dt} \qquad (16)$$

where:
Y_j = yield of species, j, kg/kg,
$\dot{G}_f''(t)$ = mass production rate of fuel vapor per unit surface area, kg/m^2·s (Note: equal to fuel mass loss rate, $\dot{m}''$), and
$G_j''(t)$ = mass production rate of species j per unit surface area, kg/m^2·s.

6.15.2.3 Having obtained the species yield, Y_j, Y_j is now used experimentally in modeling to predict species generation using:

$$\dot{G}_j''(t) = Y_j \dot{G}_f''(t) = Y_j \dot{m}'' \qquad (17)$$

6.15.2.4 The value for Y_j can change over time depending on the combustion conditions. In this case, it is necessary to define Y_j as a function of time and not the time average value as given above. In this case, the instantaneous value for Y_j at time t^* is as follows:

$$Y_j(t^*) = \frac{\dot{G}_j''(t^*)}{\dot{G}_f''(t^*)} \qquad (18)$$

6.15.2.5 The above treatment oversimplies the problem of predicting the species production rates from fires. Close attention must be paid to the experimental methods used to obtain the data. Some of the variables that affect the species production rate include the type of fuel, geometry of the fuel, and radiation feedback to the fuel surface. The species production rate is also a strong function of the ventilation within the fire compartment and can vary by as much as an order of magnitude between under-ventilated and over-ventilated conditions.

6.15.3 *Apparatus to Be Used*:

6.15.3.1 *Bench-Scale Test*:

(*1*) *Cone Calorimeter* (Test Method E 1354).

(*2*) *Factory Mutual Small-Scale Flammability Apparatus* **(2)**.

6.15.3.2 *Full-Scale Tests*:

(*1*) *ICAL Apparatus* (Test Method E 1623).

(*2*) *Furniture Calorimeter* **(26)**.

(*3*) *Proposed ASTM Room/Corner Test* **(28)**.

6.15.3.3 Specific gas analyzers are required in each case for measuring each of the different species.

6.16 *Pyrolysis Temperature*:

6.16.1 *Introduction*:

6.16.1.1 When a solid material is exposed to external heat, at some point it will begin to pyrolyze. Pyrolysis is defined as thermal degradation in the absence of oxygen. Certain types of plastics (for example, PMMA) burn more or less like a liquid. Phase changes (solid to gas) occur at the surface, and there is no solid residue. Other materials, such as wood, do not vaporize completely but also produce a carboneous char. The char layer becomes thicker with time, and pyrolysis occurs at increasing depth below the surface.

6.16.1.2 For both types of materials, pyrolysis is usually modeled as a combination of Arrhenius-type chemical reactions for all components of the fuel:

$$\frac{\partial \rho}{\partial t} = \sum_{i=1}^{i=j} A_i (\rho_i - \rho_{ic})^{n_i} \exp\left(-\frac{E_i}{RT}\right) \qquad (19)$$

where:

ρ = density, kg/m3,
t = time, s,
ρ_i = density of component i, kg/m^3,
ρ_{ic} = final (char) density of component i, kg/m^3,
n_i = order of the reaction for component i,
A_i = pre-exponential factor for component i,
E_i = activation energy for component i, J/mole,
R = universal gas constant, J/mole·K, and
T = absolute temperature, K.

6.16.1.3 Modeling pyrolysis via equations of the Arrhenius form is not trivial even if the fuel is approximated as consisting of only one component. This is because it is rather difficult to find the kinetic parameters A, n, and E while the Arrhenius form is only an approximation to begin with.

6.16.1.4 When heated at rates typical for fire conditions, many building materials start pyrolyzing at a certain temperature below which pyrolysis is negligible. This temperature is controlled by the activation energy. Pyrolysis is completed within a relatively narrow temperature range. This is because, after the start of pyrolysis, the rate increases very steeply for a temperature increase of only a few degrees. At the same time, the fuel is depleted and the density term approaches zero rapidly.

6.16.1.5 In an attempt to avoid the complications associated with the Arrhenius equation, many investigators have assumed that pyrolysis occurs abruptly once a material-dependent temperature is reached. This temperature, T_p, is the pyrolysis temperature. SI units are degrees Celsius or Kelvins.

6.16.2 *Procedures to Obtain Pyrolysis Temperature*:

6.16.2.1 T_p is reported in the literature for some materials. A common value is 288°C for wood, as given by Schaffer **(32)**.

6.16.2.2 T_p may be obtained from thermogravimetric data if there is no guidance in the literature. Thermogravimetric analysis consists of measuring the mass loss rate of a small amount of material (or of one of its individual components when heated at a steady rate). Arrhenius equations are used to correlate the data. As explained above, pyrolysis is usually completed within a small temperature range. T_p may be estimated as the mean of this range or perhaps some other representative value. T_p is different from T_{ig} for piloted ignition, but the two are quite close for some materials, and T_{ig} may be used as an estimate for T_p.

6.16.3 *Apparatus to Be Used*—There is no standard fire test to measure pyrolysis temperature. T_p may be estimated from TGA data as outlined above. It may possibly also be determined by fitting output from a simplified pyrolysis model to the mass loss rate or heat release rate data from a calorimeter such as Test Method E 1354.

6.17 *Specific Heat*:

6.17.1 *Introduction*:

6.17.1.1 The specific heat of a material is the amount of heat required to raise the temperature of a 1 kg mass of material by 1 K. For materials that undergo a physico-chemical change (or reaction) at some temperature, their apparent specific heat can be defined as the sum of the sensible and latent (reaction) heats required to raise the temperature of 1 kg of the material by 1 K.

6.17.1.2 The thermal response of a material subject to physico-chemical changes is characterized in some fire models by its specific heat and relevant latent heats separately; in other models, in terms of the lumped quantity, the apparent specific heat. Great care should be exercised in determining in which form the specific heat is required for a model.

6.17.1.3 Where models for early fire growth require data for the specific heat of room lining materials, room temperature values are often used. On the other hand, models predicting the fire resistance of building elements usually require temperature-dependent data for the specific heat.

6.17.2 *Procedures to Obtain Specific Heat*:

6.17.2.1 Specific heats are generally measured over large temperature ranges using differential scanning calorimetry. This method involves heating a sample and a reference material at a constant rate (K/s) by using separately controlled resistance heaters. The differential heat flow into or out of the sample compared with the reference material is measured in units of W/g. Either the apparent specific heat or the specific heat plus any latent heats can be determined from this measurement and the predetermined rate of heating.

6.17.2.2 Several differential scanning calorimeters are available commercially.

6.17.3 *Apparatus to Be Used*:

6.17.3.1 *Differential Scanning Calorimeter*.

6.18 *Thermal Conductivity*:

6.18.1 *Introduction*:

6.18.1.1 Conductive heat transfer refers to the movement of heat (energy) through a material in response to a temperature gradient. The modeling of conductive heat transfer (in transient or steady-state phenomena) requires knowledge of the thermal

conductivity of a material. Commonly denoted by k, the thermal conductivity has units of W/m·K and is defined as follows:

$$k = \frac{-\dot{q}''}{\left(\dfrac{dT}{dx}\right)} \qquad (20)$$

where:
$\dot{q}''$ = rate of conductive heat (energy) transfer in the x-direction per unit area, W/m², and
dT/dx = temperature gradient in the x-direction.

6.18.1.2 Thermal conductivity depends on the moisture content, temperature, porosity, density, and microstructure of the material. Some models ignore such dependencies and instead use constant values for thermal conductivity.

6.18.2 *Procedures to Obtain Thermal Conductivity*:

6.18.2.1 There are two methods for measuring the thermal conductivity of a solid: the steady-state method and the transient method.

6.18.2.2 The steady-state technique uses heat sources to maintain a stable temperature gradient across a sample (**8**). The thermal conductivity measured is quoted at the mean of the hot and cold face temperatures. This technique is slow, often requiring days to determine the thermal conductivity at a few temperatures.

6.18.2.3 Transient methods for determination of the thermal conductivity of a solid are generally referred to as "hot wire" methods (**33**). In the test, the rate of temperature rise of an electrically heated wire surrounded by the specimen at the temperature of interest is measured and related to the thermal conductivity of the specimen. The technique is much faster than steady-state methods.

6.18.2.4 Several steady-state and transient thermal conductivity meters are available commercially.

6.18.3 *Apparatus to Be Used*:

6.18.3.1 *Guarded Hot Plate Apparatus* (Test Method C 177).

6.18.3.2 *Heat Flow Meter* (Test Method C 518).

6.19 *Thermal Inertia*:

6.19.1 *Introduction*:

6.19.1.1 The thermal inertia of a material, $k\rho c$, is the product of its thermal conductivity, k, density, ρ, and specific heat, c. The units of thermal inertia are J²/s-m⁴-K².

6.19.1.2 The thermal inertia appears in models involving the transient heating of solids. The higher the thermal inertia of a solid, the longer it takes to approach the temperature of a fluid stream in which it is placed (**34**).

6.19.2 *Procedures to Obtain Thermal Inertia*:

6.19.2.1 The thermal inertia is determined for most applications as the product of thermal conductivity, density, and specific heat as measured using the methodologies outlined in 6.4, 6.17 and 6.18 of this guide.

6.19.2.2 In modelling some classes of problems, particularly where the solid undergoes rapid thermal degradation such as that which occurs when flames spread across its surface, it is useful to introduce an effective thermal inertia. This effective thermal inertia can be determined by the analysis of piloted-ignition data generated under radiant heat exposures (Test Method E 1321).

6.19.3 *Apparatus to be Used*:

6.19.3.1 *Ohio State University Calorimeter* (Test Method E 906).

6.19.3.2 *LIFT Apparatus* (Test Method E 1321).

6.19.3.3 *Cone Calorimeter* (Test Method E 1354).

6.19.3.4 *ICAL Apparatus* (Test Method E 1623).
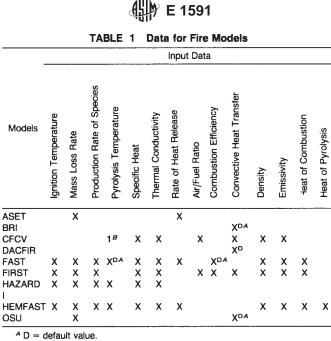
7. Sources of Data

7.1 In some models for early fire growth and fire resistance of building elements, the values for the input variables discussed in Section 6 are incorporated through either default values or material property files. More extensive data can be found in textbooks on heat transfer, thermodynamics, and combustion; in engineering handbooks (for example, Ref (**35**)); and in some of the references listed at the end of this guide. Data for specific materials or conditions may also be found in the literature (for example, Ref (**36**)).

8. Use of Parameters by Various Models

8.1 Table 1 is a cross-reference between some of the models listed in Table X1.1 and the model parameters discussed in Section 6 of this guide. This table gives some idea of the extent to which the model parameters discussed in this guide are actually being used.

9. Keywords

9.1 air/fuel ratio; combustion efficiency; convective heat transfer coefficient; data for fire models; density; emissivity; entrainment coefficient; fire model; flame extinction coefficient; flame spread parameter; heat of combustion; heat of gasification; heat of pyrolysis; rate of heat release; ignition temperature; mass loss rate; material properties; production rate of species; pyrolysis temperature; specific heat; thermal conductivity; and thermal inertia

TABLE 1 Data for Fire Models

Models	Ignition Temperature	Mass Loss Rate	Production Rate of Species	Pyrolysis Temperature	Specific Heat	Thermal Conductivity	Rate of Heat Release	Air/Fuel Ratio	Combustion Efficiency	Convective Heat Transfer	Density	Emissivity	Heat of Combustion	Heat of Pyrolysis
ASET		X					X							
BRI										X[DA]				
CFCV				1[B]	X	X			X	X	X	X		
DACFIR										X[D]				
FAST	X	X	X	X[DA]	X	X	X		X[DA]		X	X	X	
FIRST	X	X	X		X	X		X	X	X	X	X	X	
HAZARD I	X	X	X	X	X	X								
HEMFAST	X	X	X	X	X	X	X				X	X	X	X
OSU		X								X[DA]				

[A] D = default value.
[B] 1 = most versions.

APPENDIX

(Nonmandatory Information)

X1. COMMENTS ON ZONE MODELING OF COMPARTMENT FIRES

TABLE X1.1 List of Major Pre-Flashover Zone Models

Model	Authors	Year	References
CFC III	Emmons, Mitler, and Trefethen	1978	(1,37)
CALTECH	Zukoski and Kubota	1980	(38)
NBS	Quintiere and McCaffrey	1980	(39)
RFIRES	Pape and Waterman	1981	(40)
CFC V	Emmons and Mitler	1981	(4,41,42)
DACFIR	MacArthur	1982	(43)
ASET	Cooper, Stroup, and Walton	1982	(44-46)
OSU	Smith, Satija, Sauer, and Green	1983	(10,47,48)
BRI	Tanaka	1983	(6,49)
CSTB	Curtat	1983	(50)
CFC VI	Gahm, Rockett, and Morita	1983	(51-53)
HYSLAV	Hägglund	1983	(54,55)
FAST	Jones	1985	(7,56-58)
COMPBRN	Ho, Siu, Apostolakis, and Flanagan	1986	(59)
HEMFAST	Dietenberger	1987	(60,61)
FIRST	Mitler and Rockett	1987	(5)
LAVENT	Davis and Cooper	1989	(62)
WPI	Barnett	1989	(63)
CCFM	Forney, Cooper, and Moss	1990	(64)
CFAST	Jones and Forney	1990	(65)
SP	Wickström and Göransson	1990	(66)
LUND	Magnusson and Karlsson	1990	(67)
FFM	Dietenberger	1991	()
FIRM	Birk	1991	(69)

X1.1 Zone models subdivide the gas volume in the fire room (and adjacent compartments in the case of fire or smoke movement models) into a small number of zones, such as a lower gas layer, an upper gas layer, the fire plume, etc. Properties describing the thermodynamic state and composition of each zone are assumed to be uniform or varying according to a predetermined and experimentally verified function of the space coordinates and time. Zone models solve the conservation equations for each of the zones. Many pre-flashover zone fire models have been developed since the mid-1970s for various applications at different levels of complexity. Some pre-flashover zone models are listed in Table X1.1.

X1.2 The history of zone fire models is addressed in references such as Refs (20) and (69-71) .

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