



Standard Guide for Obtaining Data for Fire Growth Models¹

This standard is issued under the fixed designation E1591; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ϵ) indicates an editorial change since the last revision or reapproval.

1. Scope

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

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

1.3 The emphasis in this guide is on ignition, pyrolysis and flame spread models for solid materials.

1.4 The values stated in SI units are to be regarded as standard. No other units of measurement are included in this 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, health, and environmental practices and determine the applicability of regulatory limitations prior to use.*

1.6 This fire standard cannot be used to provide quantitative measures.

1.7 *This international standard was developed in accordance with internationally recognized principles on standardization established in the Decision on Principles for the Development of International Standards, Guides and Recommendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.*

2. Referenced Documents

2.1 ASTM Standards:²

C177 Test Method for Steady-State Heat Flux Measurements and Thermal Transmission Properties by Means of the Guarded-Hot-Plate Apparatus

C518 Test Method for Steady-State Thermal Transmission Properties by Means of the Heat Flow Meter Apparatus

C835 Test Method for Total Hemispherical Emittance of Surfaces up to 1400°C

C1371 Test Method for Determination of Emittance of Materials Near Room Temperature Using Portable Emis-someters

D2395 Test Methods for Density and Specific Gravity (Relative Density) of Wood and Wood-Based Materials

D3417 Test Method for Enthalpies of Fusion and Crystallization of Polymers by Differential Scanning Calorimetry (DSC) (Withdrawn 2004)³

D5865 Test Method for Gross Calorific Value of Coal and Coke

D7309 Test Method for Determining Flammability Characteristics of Plastics and Other Solid Materials Using Microscale Combustion Calorimetry

E176 Terminology of Fire Standards

E408 Test Methods for Total Normal Emittance of Surfaces Using Inspection-Meter Techniques

E472 Practice for Reporting Thermoanalytical Data (Withdrawn 1995)³

E537 Test Method for Thermal Stability of Chemicals by Differential Scanning Calorimetry

E793 Test Method for Enthalpies of Fusion and Crystallization by Differential Scanning Calorimetry

E906 Test Method for Heat and Visible Smoke Release Rates for Materials and Products Using a Thermopile Method

E967 Test Method for Temperature Calibration of Differential Scanning Calorimeters and Differential Thermal Analyzers

E968 Practice for Heat Flow Calibration of Differential Scanning Calorimeters

E1321 Test Method for Determining Material Ignition and Flame Spread Properties

E1354 Test Method for Heat and Visible Smoke Release Rates for Materials and Products Using an Oxygen Consumption Calorimeter

E1537 Test Method for Fire Testing of Upholstered Furniture

E1623 Test Method for Determination of Fire and Thermal Parameters of Materials, Products, and Systems Using an Intermediate Scale Calorimeter (ICAL)

¹ This guide is under the jurisdiction of ASTM Committee E05 on Fire Standards and is the direct responsibility of Subcommittee E05.33 on Fire Safety Engineering. Current edition approved April 1, 2020. Published May 2020. Originally approved in 1994. Last previous edition approved in 2013 as E1591–13. DOI: 10.1520/E1591-20.

² For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

³ The last approved version of this historical standard is referenced on www.astm.org.

E2058 Test Methods for Measurement of Material Flammability Using a Fire Propagation Apparatus (FPA)

E2257 Test Method for Room Fire Test of Wall and Ceiling Materials and Assemblies

3. Terminology

3.1 *Definitions*—For definitions of terms appearing in this guide, refer to Terminology **E176**.

4. Significance and Use

4.1 This guide is intended primarily for users and developers of mathematical fire growth 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 growth model calculations, which depend greatly on the quality of the input data.

4.2 The emphasis of this guide is on ignition, pyrolysis and flame spread models for solid materials.

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 growth models. For every input parameter, the guide includes a detailed description and information on how it can be obtained.

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

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

6. Data for Fire Growth Models

6.1 Combustion Efficiency:

6.1.1 *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.

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

$$\chi = \frac{\Delta h_{c,eff}}{\Delta h_{c,net}} \quad (1)$$

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.

6.1.3 Apparatus to Be Used:

6.1.3.1 *Test Method D5865* for $\Delta h_{c,net}$ (with adjustment for water vapor; see **6.6**); and

6.1.3.2 *Cone Calorimeter* (Test Method **E1354**), *ICAL Apparatus* (Test Method **E1623**), or the *Fire Propagation Apparatus* (Test Method **E2058**) for $\Delta h_{c,eff}$ (see **6.6**).

6.2 Density:

6.2.1 Introduction:

6.2.1.1 The density of a material is the mass of material per unit volume. In fire models, density is usually expressed as kg/m³.

6.2.1.2 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 (**1**), many models use constant (room) temperature values.

6.2.2 Procedures to Obtain Density:

6.2.2.1 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 **D2395** for wood and wood-base materials.

6.2.2.2 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 (**1, 2**).⁴

6.2.3 Apparatus to Be Used:

6.2.3.1 *Mass Balance* (or equivalent).

6.2.3.2 *Caliper, Ruler* (or equivalent).

6.2.3.3 *Dilatometric Apparatus*.

6.2.3.4 *Thermogravimetric Analyzer*.

6.3 Emissivity:

6.3.1 *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.

6.3.2 *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.

6.3.3 Apparatus to Be Used:

6.3.3.1 *Vacuum Emittance Test Apparatus* (Test Method **C835**).

6.3.3.2 *Portable Emittance Meter* (Test Methods **C1371**).

6.3.3.3 *Inspection Meter* (Test Methods **E408**).

6.4 Flame Extinction Coefficient:

6.4.1 *Introduction*—The flame extinction coefficient interrelates 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:

⁴ The boldface numbers in parentheses refer to a list of references at the end of this standard.

$$\dot{E} = A\sigma T_f^4 (1 - e^{-kl}) \quad (2)$$

where:

- E = emissive power of the flame, W,
- A = enveloping area of the flame, m²,
- σ = Boltzman constant, 5.67·10⁻⁸ W/m²·K⁴,
- 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.

6.4.2 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 $\varepsilon = 1 - e^{-kl}$.

6.4.3 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 \dot{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 \dot{E} is highly empirical. This makes it essential that the flame area, flame temperature, and extinction coefficient be determined in a self-consistent manner.

6.5 Flame Spread Parameter:

6.5.1 Introduction:

6.5.1.1 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 (3):

$$V_p = \frac{\phi}{k\rho c(T_{ig} - T_s)^2} \quad (3)$$

where:

- V_p = flame travel rate, m/s,
- ϕ = flame spread parameter, W²/m³,
- k = thermal conductivity, W/m·K,
- ρ = density, kg/m³,
- c = heat capacity, J/kg·K,
- T_{ig} = surface temperature at ignition, K, and
- T_s = surface temperature just prior to arrival of the flame front, K.

6.5.1.2 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 W²/m³.

6.5.2 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 E1321 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 6.10 and 6.16, respectively.

6.5.3 Apparatus to Be Used:

6.5.3.1 LIFT Apparatus (Test Method E1321).

6.6 Heat of Combustion:

6.6.1 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.

6.6.2 Procedures to Obtain Heat of Combustion:

6.6.2.1 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.

6.6.2.2 An effective heat of combustion can be obtained from other tests that use oxygen calorimetry. For example, the cone calorimeter (Test Method E1354) 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.

$$\Delta h_{c,eff} = \frac{\dot{q}}{\dot{m}} \quad (4)$$

where:

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

6.6.3 Apparatus to Be Used:

6.6.3.1 Oxygen Bomb Calorimetry (Test Method D5865).

6.6.3.2 Cone Calorimeter (Test Method E1354).

6.6.3.3 ICAL Apparatus (Test Method E1623).

6.6.3.4 Furniture Calorimeter (Test Method E1537).

6.6.3.5 Microscale Combustion Calorimeter (Test Method D7309).

6.7 Heat of Gasification:

6.7.1 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.

$$\Delta h_g = \frac{\dot{q}_{net}''}{\dot{m}''} \quad (5)$$

where:

- \dot{q}_{net}'' = net heat flux into the material, kW/m², and
- \dot{m}'' = mass loss rate of the material, kg/m²·s.
- Δh_g = heat of gasification, kJ/kg.

6.7.2 Procedures to Obtain Heat of Gasification:

6.7.2.1 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 E1354) has been used, in

conjunction with surface temperature measurements, to determine Δh_g for wood products and PMMA.

6.7.2.2 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 (4, 5).

6.7.2.3 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 (6-8)

6.7.3 Apparatus to Be Used:

6.7.3.1 Cone Calorimeter (Test Method E1354).

6.7.3.2 ICAL Apparatus (Test Method E1623).

6.7.3.3 Fire Propagation Apparatus (Test Method E2058).

6.8 Heat of Pyrolysis (Heat of Reaction):

6.8.1 Introduction:

6.8.1.1 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 pyrolysis products. In the 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 kJ/kg. It is sometimes expressed in kJ/m³ in models.

6.8.1.2 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.

6.8.1.3 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/m³·s) to obtain the energy generation term. An alternative is simply to use an energy generation term dE/dt (in kW/m³). 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.

6.8.2 Procedures to Obtain Heat of Pyrolysis:

6.8.2.1 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.

6.8.2.2 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 E472.

6.8.2.3 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.

6.8.2.4 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 pyrolysis 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.

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

6.8.3 Apparatus to Be Used:

6.8.3.1 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.

6.8.3.2 DSC procedures and apparatuses are discussed in Test Methods D3417, E537, and E793. Power-compensation DSC and heat-flux DSC are two types of apparatuses. Calibration of DSC equipment is discussed in Practices E967 and E968.

6.9 Heat Release Rate:

6.9.1 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.

6.9.2 Procedures to Obtain Heat Release Rate: