



## Standard Guide for Obtaining Data for Fire Growth Models<sup>1</sup>

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 ( $\epsilon$ ) 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:<sup>2</sup>

**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Test Method for Enthalpies of Fusion and Crystallization of Polymers by Differential Scanning Calorimetry (DSC) (Withdrawn 2004)<sup>3</sup>

**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)<sup>3</sup>

**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)

<sup>1</sup> 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.

<sup>2</sup> For referenced ASTM standards, visit the ASTM website, [www.astm.org](http://www.astm.org), or contact ASTM Customer Service at [service@astm.org](mailto:service@astm.org). For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

<sup>3</sup> The last approved version of this historical standard is referenced on [www.astm.org](http://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,  $\chi$ , 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,

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

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/m<sup>3</sup>.

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**).<sup>4</sup>

##### 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:

<sup>4</sup> 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, m<sup>2</sup>,
- $\sigma$  = Boltzman constant,  $5.67 \cdot 10^{-8}$  W/m<sup>2</sup>·K<sup>4</sup>,
- $T_f$  = flame temperature, K,
- $k$  = flame extinction coefficient, m<sup>-1</sup>, 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  $\epsilon$  and path length  $l$ , assuming emissivity can be expressed as  $\epsilon = 1 - e^{-kl}$ .

**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,
- $\phi$  = flame spread parameter, W<sup>2</sup>/m<sup>3</sup>,
- $k$  = thermal conductivity, W/m·K,
- $\rho$  = density, kg/m<sup>3</sup>,
- $c$  = 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,  $\phi$ , 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<sup>2</sup>/m<sup>3</sup>.

**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,  $\Delta h_c$ , 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/m<sup>2</sup>, and
  - $\dot{m}$  = mass loss rate of the material, kg/m<sup>2</sup>·s.
- $\Delta h_g$  = 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