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An American National Standard

Standard Guide for Assessment of Measurement Uncertainty in Fire Tests[1]

This standard is issued under the fixed designation E2536; 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.

INTRODUCTION

The objective of a measurement is to determine the value of the measurand, that is, the physical quantity that needs to be measured. Every measurement is subject to error, no matter how carefully it is conducted. The (absolute) error of a measurement is defined in Eq 1.

All terms in Eq 1 have the units of the physical quantity that is measured. This equation cannot be used to determine the error of a measurement because the true value is unknown, otherwise a measurement would not be needed. In fact, the true value of a measurand is unknowable because it cannot be measured without error. However, it is possible to estimate, with some confidence, the expected limits of error. This estimate is referred to as the uncertainty of the measurement and provides a quantitative indication of its quality.

Errors of measurement have two components, a random component and a systematic component. The former is due to a number of sources that affect a measurement in a random and uncontrolled manner. Random errors cannot be eliminated, but their effect on uncertainty is reduced by increasing the number of repeat measurements and by applying a statistical analysis to the results. Systematic errors remain unchanged when a measurement is repeated under the same conditions. Their effect on uncertainty cannot be completely eliminated either, but is reduced by applying corrections to account for the error contribution due to recognized systematic effects. The residual systematic error is unknown and shall be treated as a random error for the purpose of this standard.

General principles for evaluating and reporting measurement uncertainties are described in the Guide on Uncertainty of Measurements (GUM). Application of the GUM to fire test data presents some unique challenges. This standard shows how these challenges can be overcome. An example to illustrate application of the guidelines provided in this standard can be found in Appendix X1.

$$\varepsilon \equiv y - Y \quad (1)$$

where:

ε = measurement error;
y = measured value of the measurand; and
Y = true value of the measurand.

1. Scope

1.1 This guide covers the evaluation and expression of uncertainty of measurements of fire test methods developed and maintained by ASTM International, based on the approach presented in the GUM. The use in this process of precision data obtained from a round robin is also discussed.

1.2 The guidelines presented in this standard can also be applied to evaluate and express the uncertainty associated with fire test results. However, it may not be possible to quantify the uncertainty of fire test results if some sources of uncertainty cannot be accounted for. This problem is discussed in more detail in Appendix X2.

1.3 Application of this guide is limited to tests that provide quantitative results in engineering units. This includes, for

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[1] This guide is under the jurisdiction of ASTM Committee E05 on Fire Standards and is the direct responsibility of Subcommittee E05.31 on Terminology and Services / Functions.

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example, methods for measuring the heat release rate of burning specimens based on oxygen consumption calorimetry, such as Test Method E1354.

1.4 This guide does not apply to tests that provide results in the form of indices or binary results (for example, pass/fail). For example, the uncertainty of the Flame Spread Index obtained according to Test Method E84 cannot be determined.

1.5 In some cases additional guidance is required to supplement this standard. For example, the expression of uncertainty of heat release rate measurements at low levels requires additional guidance and uncertainties associated with sampling are not explicitly addressed.

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

1.7 The values stated in SI units are to be regarded as standard. No other units of measurement are included in this standard.

2. Referenced Documents

2.1 *ASTM Standards:*[2]

E84 Test Method for Surface Burning Characteristics of Building Materials
E119 Test Methods for Fire Tests of Building Construction and Materials
E176 Terminology of Fire Standards
E230 Specification and Temperature-Electromotive Force (EMF) Tables for Standardized Thermocouples
E691 Practice for Conducting an Interlaboratory Study to Determine the Precision of a Test Method
E1354 Test Method for Heat and Visible Smoke Release Rates for Materials and Products Using an Oxygen Consumption Calorimeter

2.2 *ISO Standards:*[3]

ISO/IEC 17025 General requirements for the competence of testing and calibration laboratories
GUM Guide to the expression of uncertainty in measurement

2.3 *CEN Standard:*[4]

EN 13823 Reaction to fire tests for building products – Building products excluding floorings exposed to the thermal attack by a single burning item

3. Terminology

3.1 *Definitions:* For definitions of terms used in this guide and associated with fire issues, refer to the terminology contained in Terminology E176. For definitions of terms used in this guide and associated with precision issues, refer to the terminology contained in Practice E691.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *accuracy of measurement, n*—closeness of the agreement between the result of a measurement and the true value of the measurand.

3.2.2 *combined standard uncertainty, n*—standard uncertainty of the result of a measurement when that result is obtained from the values of a number of other quantities, equal to the positive square root of a sum of terms, the terms being the variances or covariances of these other quantities weighted according to how the measurement result varies with changes in these quantities.

3.2.3 *coverage factor, n*—numerical factor used as a multiplier of the combined standard uncertainty in order to obtain an expanded uncertainty.

3.2.4 *error (of measurement), n*—result of a measurement minus the true value of the measurand; error consists of two components: random error and systematic error.

3.2.5 *expanded uncertainty, n*—quantity defining an interval about the result of a measurement that may be expected to encompass a large fraction of the distribution of values that could reasonably be attributed to the measurand.

3.2.6 *measurand, n*—quantity subject to measurement.

3.2.7 *precision, n*—variability of test result measurements around reported test result value.

3.2.8 *random error, n*—result of a measurement minus the mean that would result from an infinite number of measurements of the same measurand carried out under repeatability conditions.

3.2.9 *repeatability (of results of measurements), n*—closeness of the agreement between the results of successive independent measurements of the same measurand carried out under repeatability conditions.

3.2.10 *repeatability conditions, n*—on identical test material using the same measurement procedure, observer(s), and measuring instrument(s) and performed in the same laboratory during a short period of time.

3.2.11 *reproducibility (of results of measurements), n*—closeness of the agreement between the results of measurements of the same measurand carried out under reproducibility conditions.

3.2.12 *reproducibility conditions, n*—on identical test material using the same measurement procedure, but different observer(s) and measuring instrument(s) in different laboratories performed during a short period of time.

3.2.13 *standard deviation, n*—a quantity characterizing the dispersion of the results of a series of measurements of the same measurand; the standard deviation is proportional to the square root of the sum of the squared deviations of the measured values from the mean of all measurements.

3.2.14 *standard uncertainty, n*—uncertainty of the result of a measurement expressed as a standard deviation.

3.2.15 *systematic error (or bias), n*—mean that would result from an infinite number of measurements of the same measurand carried out under repeatability conditions minus the true value of the measurand.

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[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] Available from International Organization for Standardization, P.O. Box 56, CH-1211, Geneva 20, Switzerland.

[4] Available from European Committee for Standardization (CEN), Avenue Marnix 17, B-1000, Brussels, Belgium, http://www.cen.eu.

3.2.16 *type A evaluation (of uncertainty), n*—method of evaluation of uncertainty by the statistical analysis of series of observations.

3.2.17 *type B evaluation (of uncertainty), n*—method of evaluation of uncertainty by means other than the statistical analysis of series of observations.

3.2.18 *uncertainty of measurement, n*—parameter, associated with the result of a measurement, that characterizes the dispersion of the values that could reasonably be attributed to the measurand.

4. Summary of Guide

4.1 This guide provides concepts and calculation methods to assess the uncertainty of measurements obtained from fire tests.

4.2 Appendix X1 of this guide contains an example to illustrate application of this guide by assessing the uncertainty of heat release rate measured in the Cone Calorimeter (Test Method E1354).

5. Significance and Use

5.1 Users of fire test data often need a quantitative indication of the quality of the data presented in a test report. This quantitative indication is referred to as the "measurement uncertainty". There are two primary reasons for estimating the uncertainty of fire test results.

5.1.1 ISO/IEC 17025 requires that competent testing and calibration laboratories include uncertainty estimates for the results that are presented in a report.

5.1.2 Fire safety engineers need to know the quality of the input data used in an analysis to determine the uncertainty of the outcome of the analysis.

6. Evaluating Standard Uncertainty

6.1 A quantitative result of a fire test Y is generally not obtained from a direct measurement, but is determined as a function f from N input quantities $X_1, \ldots, X_N$:

$$Y = f(X_1, X_2, \ldots, X_N) \qquad (2)$$

where:

Y = measurand;
f = functional relationship between the measurand and the input quantities; and
X_i = input quantities ($i = 1 \ldots N$).

6.1.1 The input quantities are categorized as:

6.1.1.1 quantities whose values and uncertainties are directly determined from single observation, repeated observation or judgment based on experience, or

6.1.1.2 quantities whose values and uncertainties are brought into the measurement from external sources such as reference data obtained from handbooks.

6.1.2 An estimate of the output, y, is obtained from Eq 2 using input estimates $x_1, x_2, \ldots, x_N$ for the values of the N input quantities:

$$y = f(x_1, x_2, \ldots, x_N) \qquad (3)$$

Substituting Eq 2 and 3 into Eq 1 leads to:

$$y = Y + \varepsilon = Y + \varepsilon_1 + \varepsilon_2 + \ldots + \varepsilon_N \qquad (4)$$

where:

ε_1 = contribution to the total measurement error from the error associated with x_i.

6.2 A possible approach to determine the uncertainty of y involves a large number (n) of repeat measurements. The mean value of the resulting distribution ($\bar{y}$) is the best estimate of the measurand. The experimental standard deviation of the mean is the best estimate of the standard uncertainty of y, denoted by $u(y)$:

$$u(y) \approx \sqrt{s^2(\bar{y})} = \sqrt{\frac{s^2(y)}{n}} = \sqrt{\frac{\sum_{k=1}^{n}(y_k - \bar{y})^2}{n(n-1)}} \qquad (5)$$

where:

u = standard uncertainty,
s = experimental standard deviation,
n = number of observations;
y_k = kth measured value, and
$\bar{y}$ = mean of n measurements.

The number of observations n shall be large enough to ensure that $\bar{y}$ provides a reliable estimate of the expectation μ_y of the random variable y, and that $s^2(\bar{y})$ provides a reliable estimate of the variance $\sigma^2(\bar{y}) = \sigma(y)/n$. If the probability distribution of y is normal, then standard deviation of $s(\bar{y})$ relative to $\sigma(\bar{y})$ is approximately $[2(n\text{-}1)]–^{1/2}$. Thus, for $n = 10$ the relative uncertainty of $s(\bar{y})$ is 24 %t, while for $n = 50$ it is 10 %. Additional values are given in Table E.1 in annex E of the GUM.

6.3 Unfortunately it is often not feasible or even possible to perform a sufficiently large number of repeat measurements. In those cases, the uncertainty of the measurement can be determined by combining the standard uncertainties of the input estimates. The standard uncertainty of an input estimate x_i is obtained from the distribution of possible values of the input quantity X_i. There are two types of evaluations depending on how the distribution of possible values is obtained.

6.3.1 *Type A evaluation of standard uncertainty*—A type A evaluation of standard uncertainty of x_i is based on the frequency distribution, which is estimated from a series of n repeated observations $x_{i,k}$ ($k = 1 \ldots n$). The resulting equation is similar to Eq 5:

$$u(x_i) \approx \sqrt{s^2(\bar{x}_i)} = \sqrt{\frac{s^2(x_i)}{n}} = \sqrt{\frac{\sum_{k=1}^{n}(x_{i,k} - \bar{x}_i)^2}{n(n-1)}} \qquad (6)$$

where:

$x_{i,k}$ = kth measured value; and
$\bar{x}_i$ = mean of n measurements.

6.3.2 *Type B evaluation of standard uncertainty:*

6.3.2.1 A type B evaluation of standard uncertainty of x_i is not based on repeated measurements but on an a priori frequency distribution. In this case the uncertainty is determined from previous measurements data, experience or general knowledge, manufacturer's specifications, data provided in calibration certificates, uncertainties assigned to reference data taken from handbooks, etc.

6.3.2.2 If the quoted uncertainty from a manufacturer specification, handbook or other source is stated to be a particular multiple of a standard deviation, the standard uncertainty $u_c(x_i)$ is simply the quoted value divided by the multiplier. For example, the quoted uncertainty is often at the 95 % level of confidence. Assuming a normal distribution this corresponds to a multiplier of two, that is, the standard uncertainty is half the quoted value.

6.3.2.3 Often the uncertainty is expressed in the form of upper and lower limits. Usually there is no specific knowledge about the possible values of X_i within the interval and one can only assume that it is equally probable for X_i to lie anywhere in it. Fig. 1 shows the most common example where the corresponding rectangular distribution is symmetric with respect to its best estimate x_i. The standard uncertainty in this case is given by:

$$u(x_i) = \frac{\Delta X_i}{\sqrt{3}} \tag{7}$$

where:

ΔX_i = half-width of the interval.

If some information is known about the distribution of the possible values of X_i within the interval, that knowledge is used to better estimate the standard deviation.

6.3.3 *Accounting for multiple sources of error*—The uncertainty of an input quantity is sometimes due to multiple sources error. In this case, the standard uncertainty associated with each source of error has to be estimated separately and the standard uncertainty of the input quantity is then determined according to the following equation:

$$u(x_i) = \sqrt{\sum_{j=1}^{m} [u_j(x_i)]^2} \tag{8}$$

where:

m = number of sources of error affecting the uncertainty of x_i; and
u_j, = standard uncertainty due to jth source of error.

7. Determining Combined Standard Uncertainty

7.1 The standard uncertainty of y is obtained by appropriately combining the standard uncertainties of the input estimates $x_1, x_2, \ldots, x_N$. If all input quantities are independent, the combined standard uncertainty of y is given by:

$$u_c(y) = \sqrt{\sum_{i=l}^{N}\left[\frac{\partial f}{\partial X_i}\Big|_{xi}\right]^2 u^2(x_i)} \equiv \sqrt{\sum_{i=l}^{N}[c_i u(x_i)]^2} \tag{9}$$

where:

u_c = combined standard uncertainty, and
$c_{i,}$ = sensitivity coefficients.

Eq 9 is referred to as the *law of propagation of uncertainty* and based on a first-order Taylor series approximation of $Y = f(X_1, X_2, \ldots, X_N)$. When the nonlinearity of f is significant, higher-order terms must be included (see clause 5.1.2 in the GUM for details).

7.2 When the input quantities are correlated, Eq 9 must be revised to include the covariance terms. The combined standard uncertainty of y is then calculated from:

$$u_c(y) = \sqrt{\sum_{i=l}^{N}[c_i u(x_i)]^2 + 2\sum_{i=l}^{N-1}\sum_{j=i+l}^{N} c_i c_j u(x_i) u(x_j) r(x_i, x_j)} \tag{10}$$

where:

$r(x_i, x_j)$ = estimated *correlation coefficient* between X_i and X_j.

Since the true values of the input quantities are not known, the correlation coefficient is estimated on the basis of the measured values of the input quantities.

8. Determining Expanded Uncertainty

8.1 It is often necessary to give a measure of uncertainty that defines an interval about the measurement result that may be expected to encompass a large fraction of the distribution of values that could reasonably be attributed to the measurand. This measure is termed expanded uncertainty and is denoted by U. The expanded uncertainty is obtained by multiplying the combined standard uncertainty by a coverage factor k:

$$U(y) = k u_c(y) \tag{11}$$

where:

U = expanded uncertainty, and
k = coverage factor.

8.1.1 The value of the coverage factor k is chosen on the basis of the level of confidence required of the interval $y - U$ to $y + U$. In general, k will be in the range 2 to 3. Because of the Central Limit Theorem, k can usually be determined from:

$$k = t(\nu_{eff}) \tag{12}$$

where:

t = t-distribution statistic for the specified confidence level and degrees of freedom, and
ν_{eff} = effective degrees of freedom.

Table 1 gives values of the t-distribution statistic for different levels of confidence and degrees of freedom. A more complete table can be found in Annex G of the GUM.

8.1.2 The effective degrees of freedom can be computed from the Welch-Satterthwaite formula:

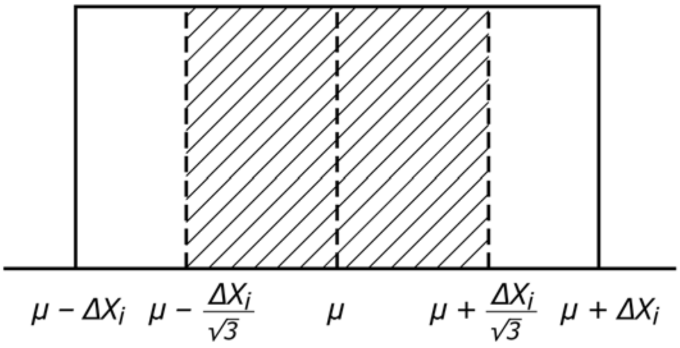

FIG. 1 Rectangular Distribution

TABLE 1 Selected Values of the *t*-distribution Statistic

Degrees of Freedom	Confidence Level		Degrees of Freedom	Confidence Level		Degrees of Freedom	Confidence Level	
	95%	99%		95%	99%		95%	99%
1	12.71	63.66	6	2.45	3.71	20	2.09	2.85
2	4.30	9.92	7	2.36	3.50	30	2.04	2.75
3	3.18	5.84	8	2.31	3.36	40	2.02	2.70
4	2.78	4.60	9	2.26	3.25	50	2.01	2.68
5	2.57	4.03	10	2.23	3.17	∞	1.96	2.58

$$\nu_{eff} = \frac{[u_c(y)]^4}{\sum_{i=l}^{N} \frac{[u(x_i)]^4}{\nu_i}} \tag{13}$$

where:

ν_i = degrees of freedom assigned to the standard uncertainty of input estimate x_i.

8.1.3 The degrees of freedom ν_i is equal to $n - 1$ if x_i is estimated as the arithmetic mean of n independent observations (type A standard uncertainty evaluation). If $u(x_i)$ is obtained from a type B evaluation and it can be treated as exactly known, which is often the case in practice, $\nu_i \rightarrow \infty$. If $u(x_i)$ is not exactly known, ν_i can be estimated from:

$$\nu_i \approx \frac{1}{2}\frac{[u_c(x_i)]^2}{[\sigma(u(x_i))]^2} \approx \frac{1}{2}\left(\frac{\Delta u(x_i)}{u(x_i)}\right)^{-2} \tag{14}$$

The quantity in large brackets in Eq 14 is the relative uncertainty of $u(x_i)$, which is a subjective quantity whose value is obtained by scientific judgement based on the pool of available information.

8.2 The probability distribution of $u_c(y)$ is often approximately normal and the effective degrees of freedom of $u_c(y)$ is of significant size. When this is the case, one can assume that taking $k = 2$ produces an interval having a level of confidence of approximately 95.5 %, and that taking $k = 3$ produces an interval having a level of confidence of approximately 99.7 %.

9. Reporting Uncertainty

9.1 The result of a measurement and the corresponding uncertainty shall be reported in the form of $Y = y \pm U$ followed by the units of y and U. Alternatively, the relative expanded uncertainty $U/|y|$ in percent can be specified instead of the absolute expanded uncertainty. In either case the report shall describe how the measurand Y is defined, specify the approximate confidence level and explain how the corresponding coverage factor was determined. The former can be done by reference to the appropriate fire test standard.

9.2 The report shall also include a discussion of sources of uncertainty that are not addressed by the analysis.

10. Summary of Procedure For Evaluating and Expressing Uncertainty

10.1 The procedure for evaluating and expressing uncertainty of fire test results involves the following steps:

10.1.1 Express mathematically the relationship between the measurand Y and the input quantities X_i upon which Y depends: $Y = f(X_1, X_2, \ldots, X_N)$.

10.1.2 Determine x_i, the estimated value for each input quantity X_i.

10.1.3 Identify all sources of error for each input quantity and evaluate the standard uncertainty $u(x_i)$ for each input estimate x_i.

10.1.4 Evaluate the correlation coefficient for estimates of input quantities that are dependent.

10.1.5 Calculate the result of the measurement, that is, the estimate y of the measurand Y from the functional relationship f using the estimates x_i of the input quantities X_i obtained in 10.1.2.

10.1.6 Determine the combined standard uncertainty $u_c(y)$ of the measurement result y from the standard uncertainties and correlation coefficients associated with the input estimates as described in Section 7.

10.1.7 Select a coverage factor k on the basis of the desired level of confidence as described in Section 8 and multiply $u_c(y)$ by this value to obtain the expanded uncertainty U.

10.1.8 Report the result of the measurement y together with its expanded uncertainty U as discussed in Section 9.

11. Keywords

11.1 fire test; fire test laboratory; measurand; measurement uncertainty; quality

APPENDIXES

(Nonmandatory Information)

X1. ILLUSTRATIVE EXAMPLE

X1.1 Introduction:

X1.1.1 Heat release rate measured in the Cone Calorimeter according to Test Method E1354 is used here to illustrate the application of the guidelines provided in this guide.

X1.2 Express the relationship between the measurand *Y* and the input quantities X_i.

X1.2.1 The heat release rate is calculated according to Eq 4 in Test Method E1354:

$$\dot{Q} = \left[\frac{\Delta h_c}{r_o}\right] 1.10C \sqrt{\frac{\Delta P}{T_e}} \left[\frac{X^o_{O_2} - X_{O_2}}{1.105 - 1.5X_{O_2}}\right] \qquad (X1.1)$$

where:

$\dot{Q}$ = heat release rate (kW),
Δh_c = net heat of combustion (kJ/kg),
r_o = stoichiometric oxygen to fuel ratio (kg/kg),
C = orifice coefficient ($m^{1/2} \cdot kg^{1/2} \cdot K^{1/2}$),
ΔP = pressure drop across the orifice plate (Pa),
T_e = exhaust stack temperature at the orifice plate flow meter (K),
$X_{O_2}{}^o$ = ambient oxygen mole fraction in dry air (0,2095), and
X_{O_2} = measured oxygen mole fraction in the exhaust duct.

The ratio of Δh_c to r_o is referred to as "Thornton's constant". The average value of this constant is 13,100 kJ/kg O_2, which is accurate to within ±5 % for a large number of organic materials (**1**).[5]

X1.2.2 Eq X1.1 is based on the assumption that the standard volume of the gaseous products of combustion is 50 % larger than the volume of oxygen consumed in combustion. This is correct for complete combustion of methane. However, for pure carbon there is no increase in volume because one mole of CO_2 is generated per mole of O_2 consumed. For pure hydrogen the volume doubles as two moles of water vapor are generated per mole O_2 consumed. A more accurate form of Eq X1.1 that takes the volume increase into account is as follows: (**2**)

$$\dot{Q} = \left[\frac{\Delta h_c}{r_o}\right] 1.10C \sqrt{\frac{\Delta P}{T_e}} \left[\frac{X^o_{O_2} - X_{O_2}}{1 + (\beta - 1)X^o_{O_2} - \beta X_{O_2}}\right] \qquad (X1.2)$$

where:

β = moles of gaseous combustion products generated per mole of O_2 consumed.

This is the equation that is used to estimate the uncertainty of heat release rate measurements in the Cone Calorimeter. Hence, the output and input quantities are as follows:

$$Y \equiv \dot{Q},\ X_1 \equiv \frac{\Delta h_c}{r_o},\ X_2 = C,\ X_3 \equiv \Delta P,\ X_4 = T_e,\ X_5 = X_{O_2},\ X_6 = \beta \qquad (X1.3)$$

Note that in a test $\dot{Q}$ is calculated as a function of time based on the input quantities measured at discrete time intervals Δt.

X1.3 Determine x_i, the estimated value of X_i for each input quantity.

X1.3.1 For the purpose of this example a 19 mm thick slab of western red cedar was tested at a heat flux of 50 kW/m^2. The test was conducted in the horizontal orientation with the retainer frame. The spark igniter was used and the test was terminated after 15 min.

X1.3.2 The corresponding measured values of ΔP (X_3), T_e (X_4) and X_{O_2} (X_5) are shown as a function of time in Figs. X1.1-X1.3, respectively. Note that the latter is shifted over the delay time of the oxygen analyzer to synchronize X_5 with the other two measured input quantities.

X1.3.3 The first input quantity is estimated as $X_1 = \Delta h_c / r_o \approx$ 13 100 kJ/kg $= x_1$, which is based on the average for a large number of organic materials (**1**). The orifice constant was obtained from a methane gas burner calibration as described in section 13.2 of Test Method E1354 and is equal to $X_2 = C \approx$ 0.04430 $m^{1/2} g^{1/2} K^{1/2} = x_2$. Finally, the mid value of 1.5 is used to estimate the expansion factor β.

X1.4 Identify all sources of error and evaluate the standard uncertainty for each X_i.

X1.4.1 Standard uncertainty of $\Delta h_c / r_o$- The average value of 13 100 kJ/kg is reported in the literature to be accurate to within ±5 % for a large number of organic materials (**1**). The probability distribution is assumed to be rectangular, which, according to Eq 7 leads to:

$$u(x_1) \approx \frac{\Delta x_1}{\sqrt{3}} = \frac{0.05 \times 13{,}100}{\sqrt{3}} = 378\ \frac{kJ}{kg} \qquad (X1.4)$$

X1.4.2 Standard uncertainty of *C*:

X1.4.2.1 The orifice constant was obtained from a methane gas burner calibration. The burner was supplied with 99.99 % pure methane at a flow corresponding to a heat release rate of approximately 5 kW. The value of *C* was calculated according to Eq 2 in Test Method E1354:

$$C = \frac{\dot{Q}b}{12\,540 \times 1.10} \sqrt{\frac{T_e}{\Delta P}} \left[\frac{1.105 - 1.5X_{O_2}}{X^o_{O_2} - X_{O_2}}\right] \qquad (X1.5)$$

where:

$\dot{Q}b$ = burner heat release rate (kW).

Note that Eq 2 in Test Method E1354 assumes that $\dot{Q}b$ is exactly 5 kW. Eq X1.5 is preferred because the burner heat release rate is never exactly 5 kW.

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

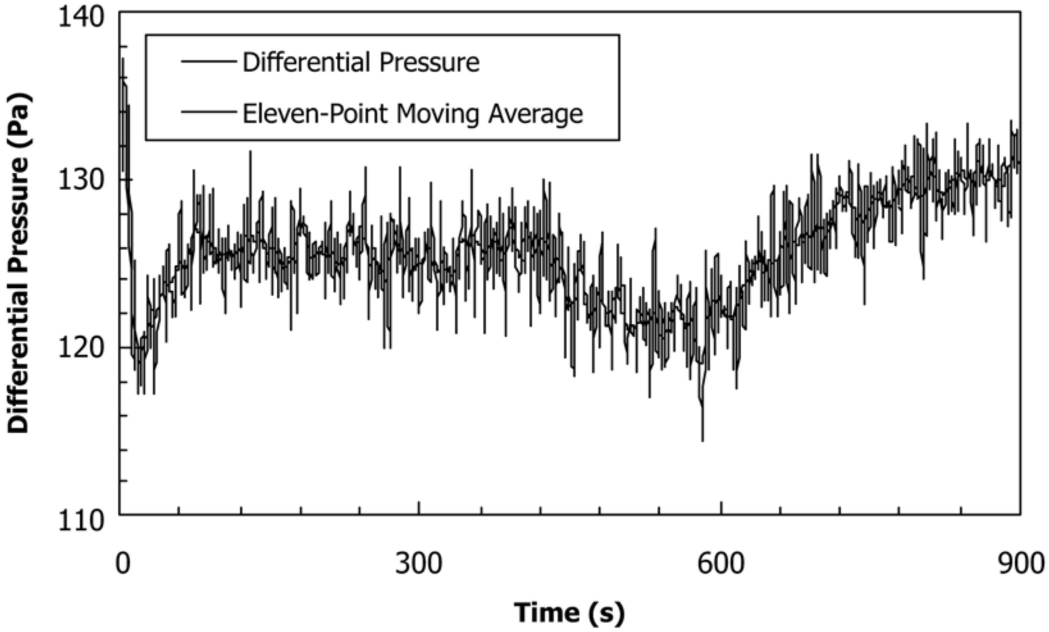

FIG. X1.1 Differential Pressure Measurements

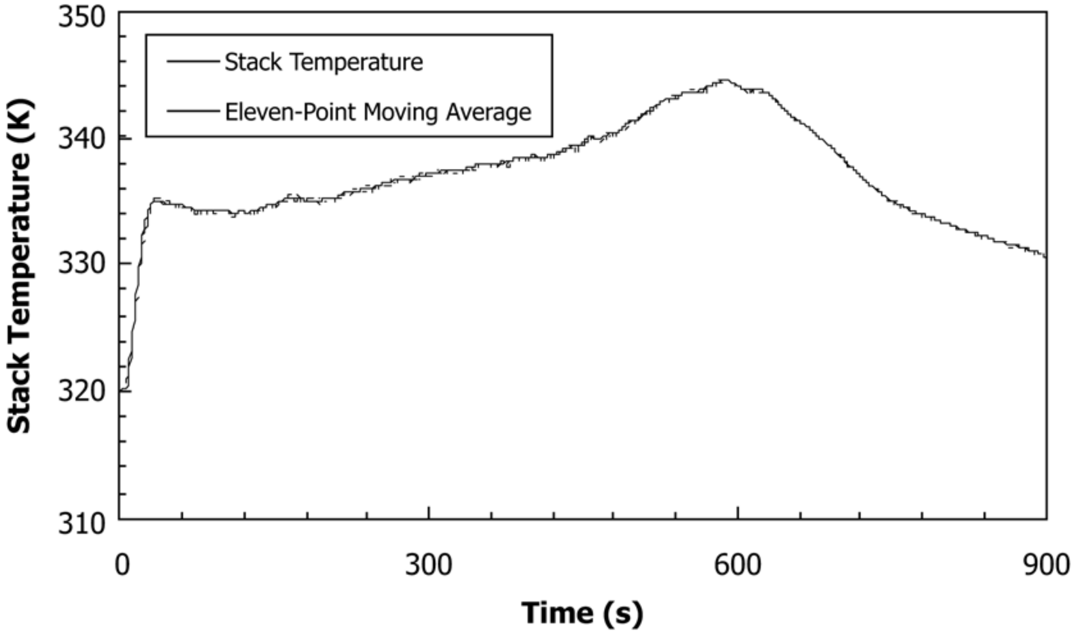

FIG. X1.2 Stack Temperature Measurements

X1.4.2.2 After a 2-min baseline period, the methane supply valve was opened and the gas burner was ignited. For the next 5 min the burner was supplied with methane at a flow rate corresponding to a heat release rate of approximately 5 kW. The methane supply valve was then closed and the calibration was terminated 2 min later. During the entire nine minutes data were collected at 1-s intervals.

X1.4.2.3 The orifice constant was estimated as 0.04430 $m^{1/2}g^{1/2}K^{1/2}$ on the basis of the average of 180 values calculated every second according to Eq X1.5 during the final 3 min of the burn. The uncertainty due to the variations of *C* during this 3-min period can be calculated according to Eq 5 and is equal to ±0.00007 $m^{1/2}\cdot kg^{1/2}\cdot K^{1/2}$.

X1.4.2.4 Some uncertainty is associated with the fact that C is not a true constant, but varies slightly as a function of the heat release rate. To determine this component of the uncertainty methane gas burner calibrations were performed at heat release rate levels of nominally 1, 3, 5, 7, and 9 kW. The resulting *C* values are given in Table X1.1. The corresponding uncertainty can be estimated from the standard deviation and is equal to 0.00020 $m^{1/2}\cdot kg^{1/2}\cdot K^{1/2}$.

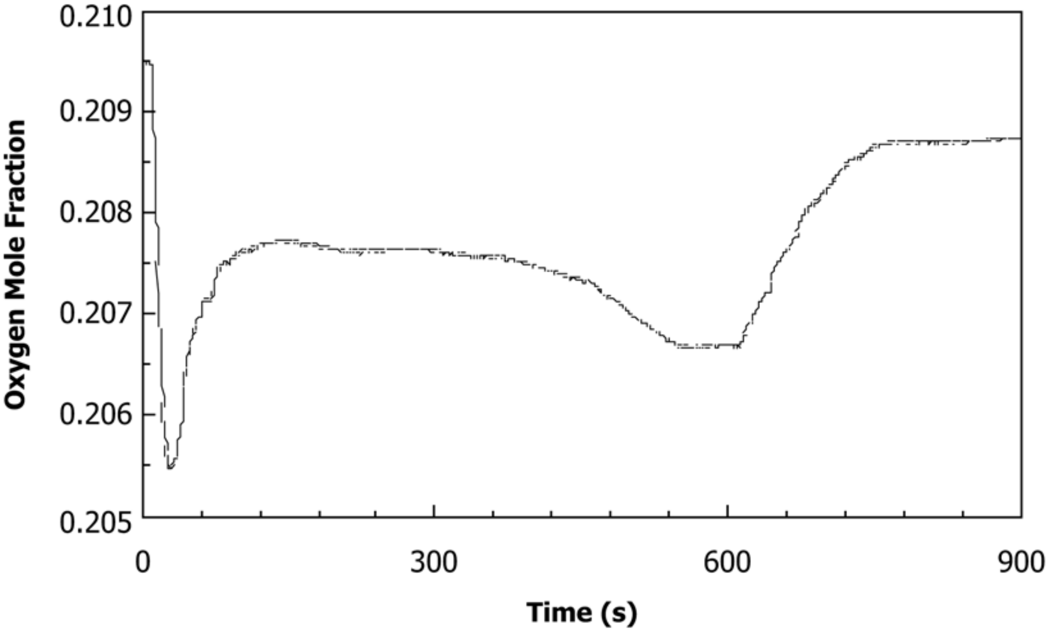

FIG. X1.3 Oxygen Mole Fraction Measurements

TABLE X1.1 Uncertainty of *C* Due to Non-linearity

Q$\dot{b}$ (kW)	*C* ($m^{1/2}$·$kg^{1/2}$· $K^{1/2}$)
1.03	0.04382
2.97	0.04406
4.92	0.04430
6.94	0.04408
8.82	0.44270
Mean	0.04411
Standard Deviation	0.00020

X1.4.2.5 The uncertainty of *C* is also partly due to errors in measuring $\dot{Q}b$,T_e, ΔP, and X_{O2}. These measurement errors consist of two components: the calibration error of the sensor and the measurement error of the data acquisition system. The former is determined from the sensor's calibration certificate or standard. The latter can be found on the manufacturer's data acquisition system specification sheet and is usually a function of the analog signal that is measured.

(1) For example, the stack thermocouple that was used for the measurements described in this appendix conforms to Specification E230, which specifies a limit of error for Type K thermocouples of ±2.2 K. Assuming a rectangular probability distribution, according to Eq 7 this corresponds to a standard uncertainty of ±1.27 K. The accuracy of Type K thermocouple measurements according to the data acquisition specification sheet based on a normal distribution and three standard deviations is equal to ±1 K, which leads to a standard uncertainty of ±0.33 K. The combined uncertainty based on Eq 8 is ±1.31 K.

(2) The standard uncertainties of the methane flow and differential pressure measurements are determined in a similar manner as for the stack temperature, except that the data acquisition measurement uncertainty component is determined based on the manufacturer's specifications as a function of the sensor signal in Volts. The standard uncertainty of the oxygen mole fraction measurement is also determined in a similar manner, except that the sensor calibration uncertainty component is based on the drift that is allowed by Test Method E1354. Section 6.11 of the standard specifies that the drift must not exceed 50 ppm over a 30-min period. Since the methane calibration was performed over less than 30 min, the corresponding standard uncertainty does not exceed ±50/√3 ppm ≈ ± 29 ppm.

(3) Note that the uncertainties due to noise of the $\dot{Q}b$, T_e, ΔP, and X_{O_2}measurements are not explicitly considered because they are accounted for by the uncertainty associated with the variations of *C* during the 3-min period over which the orifice constant is determined.

(4) The combined standard uncertainty of *C* due to measurement errors of the input quantities can now be determined from the law of propagation of uncertainty for independent input quantities, Eq 9. The sensitivity coefficients are given by:

$$\frac{\partial C}{\partial \dot{Q}b} = \frac{1}{12\,540 \times 1.10}\sqrt{\frac{T_e}{\Delta P}\left[\frac{1.105 - 1.5X_{O_2}}{X^o_{O_2} - X_{O_2}}\right]} \tag{X1.6}$$

$$\frac{\partial C}{\partial T_e} = \frac{1}{2}\frac{\dot{Q}b}{12\,540 \times 1.10}\sqrt{\frac{1}{T_e \Delta P}\left[\frac{1.105 - 1.5X^o_{O_2}}{X^o_{O_2} - X_{O_2}}\right]} \tag{X1.7}$$

$$\frac{\partial C}{\partial \Delta P} = -\frac{1}{2}\frac{\dot{Q}b}{12\,540 \times 1.10}\sqrt{\frac{T_e}{\Delta P^3}\left[\frac{1.105 - 1.5X_{O_2}}{X^o_{O_2} - X_{O_2}}\right]} \tag{X1.8}$$

$$\frac{\partial\ C}{\partial X_{O_2}} = \frac{\dot{Q}b}{12\,540 \times 1.10}\sqrt{\frac{T_e}{\Delta P}\left[\frac{1.105 - 1.5X^o_{O_2}}{\left(X^o_{O_2} - X_{O_2}\right)^2}\right]} \tag{X1.9}$$

The resulting combined uncertainty due to flow rate, temperature, pressure and oxygen mole fraction measurement error is 0.00019 $m^{1/2}$·$kg^{1/2}$·$K^{1/2}$.

(5) Finally, combination with the uncertainties due to noise and non-linearity leads to the following total combined uncertainty of *C*:

$$u(x_2) = \sqrt{0.00020^2 + 0.00007^2 + 0.00019^2} = 0.00028\ m^{1/2}\cdot kg^{1/2}\cdot K^{1/2} \tag{X1.10}$$

X1.4.3 *Standard Uncertainty of* Δ*P*—The standard uncertainty of Δ*P* consists of three components: the calibration error of the sensor, the measurement error of the data acquisition system, and uncertainty due to noise. The first two components are determined as discussed in the previous section. To estimate the third component, an 11-point moving average is calculated of Δ*P* versus time (see Fig. X1.1). The uncertainty due to noise is then determined as the standard deviation of the difference between the actual differential pressure measurement and the moving average over the entire test duration.

X1.4.4 *Standard Uncertainty of* T_e—The standard uncertainty of T_e consists of the same three components as Δ*P*. The three components are estimated as described in X1.4.3.

X1.4.5 *Standard Uncertainty of* X_{O_2}—The standard uncertainty of X_{O_2} also consists of the same three components. The uncertainty due to the noise in this case is estimated as ± 50 ppm, based on the fact that Section 6.11 of Test Standard E1354 specifies that the noise of the oxygen analyzer output based on the root-mean-square value must not exceed ±50 ppm over a 30-min period.

X1.4.6 *Standard Uncertainty of* β—The expansion factor ranges between 1 and 2. The probability distribution is assumed to be rectangular, which, according to Eq 7 leads to:

$$u(x_6) \approx \frac{\Delta x_6}{\sqrt{3}} = \frac{0.5}{\sqrt{3}} = 0.29 \qquad \text{(X1.11)}$$

X1.5 Evaluate the correlation coefficient for dependent input quantities.

X1.5.1 $\Delta h_c/r_o$, *C*, and β are constants and do not result in any covariance terms in Eq 10.

X1.5.2 The correlation coefficients for the measured input quantities are given in Table X1.2.

X1.6 Calculate *y* using the input estimates x_i obtained in X1.3.

X1.6.1 Fig. X1.4 shows the resulting heat release rate versus time calculated according to Eq X1.2 using the input estimates obtained in X1.3.

X1.7 Determine the combined standard uncertainty $u_c(y)$

X1.7.1 The combined standard uncertainty of the heat release rate at every time step can now be determined from the law of propagation of uncertainty, Eq 10. The sensitivity coefficients are given by:

$$\frac{\partial \dot{Q}}{\partial \left(\frac{\Delta h_c}{r_o}\right)} = 1.10C\sqrt{\frac{\Delta P}{T_e}}\left[\frac{X^o_{O_2} - X_{O_2}}{1+(\beta-1)X^o_{O_2} - \beta X_{O_2}}\right] \qquad \text{(X1.12)}$$

TABLE X1.2 Correlation Coefficients for Measured Input Quantities

	Δ*P*	T_e	X_{O_2}
Δ*P*	1.00	–0.57	0.76
T_e	–0.57	1.00	–0.64
X_{O_2}	0.76	–0.64	1.00

$$\frac{\partial \dot{Q}}{\partial C} = \left(\frac{\Delta h_c}{r_o}\right) 1.10\sqrt{\frac{\Delta P}{T_e}}\left[\frac{X^o_{O_{O_2}} - X_{O_2}}{1+(\beta-1)X^o_{O_2} - \beta X_{O_2}}\right] \qquad \text{(X1.13)}$$

$$\frac{\partial \dot{Q}}{\partial \Delta P} = \frac{1}{2}\left(\frac{\Delta hc}{r_o}\right) 1.10C\sqrt{\frac{1}{\Delta PT_e}}\left[\frac{X^o_{O_2} - X_{O_2}}{1+(\beta-1)X^o_{O_2} - \beta X_{O_2}}\right] \qquad \text{(X1.14)}$$

$$\frac{\partial \dot{Q}}{\partial T_e} = \frac{1}{2}\left(\frac{\Delta\ hc}{r_o}\right) 1.10C\sqrt{\frac{\Delta P}{T_e^3}}\left[\frac{X^o_{O_2} - X_{O_2}}{1+(\beta-1)X^o_{O_2} - \beta X_{O_2}}\right] \qquad \text{(X1.15)}$$

$$\frac{\partial \dot{Q}}{\partial X_{O_2}} = -\left(\frac{\Delta h_c}{r_o}\right) 1.10C\sqrt{\frac{\Delta\ P}{T_e}}\left[\frac{1 - X^o_{O_2}}{\left(1+(\beta-1)X^o_{O_2} - \beta X_{O_2}\right)^2}\right] \qquad \text{(X1.16)}$$

$$\frac{\partial \dot{Q}}{\partial \beta} = -\left(\frac{\Delta h_c}{r_o}\right) 1.10C\sqrt{\frac{\Delta P}{T_e}}\left[\frac{\left(X^o_{O_2} - X_{O_2}\right)^2}{\left(1+(\beta-1)X^o_{O_2} - \beta X_{O_2}\right)^2}\right] \qquad \text{(X1.17)}$$

X1.8 Select a coverage factor *k*.

X1.8.1 The coverage factor is estimated at *k* = 2 for a level of confidence of approximately 95 %, based on the assumption that the probability distribution of the combined standard uncertainty is approximately normal and the degrees of freedom is significant.

X1.9 Report the result of the measurement *y* together with its expanded uncertainty *U*.

X1.9.1 Fig. X1.5 shows the resulting heat release rate per unit specimen area versus time and the expanded uncertainty at a confidence level of 95 %. Table X1.3 gives the values and corresponding expanded uncertainty for some heat release rate parameters that must be reported as specified in clause 14 of Test Method E1354.

X1.10 *Sources of uncertainty not considered in the analysis:*

X1.10.1 The uncertainty calculations presented in this Appendix do not account for dynamic effects, that is, the fact that all sensors and the oxygen analyzer in particular do not respond instantaneously to variations of the measured quantity. Uncertainties due to dynamic errors can be significant but are difficult to estimate. A detailed discussion of uncertainties of heat release rate measurements due to dynamic errors can be found in Sette (**3**).

X1.10.2 The example presented in this appendix is based on a test conducted at a heat flux level of 50 kW/m². However, the heat flux meter that is used to calibrate the heater is subject to error. Section 6.13.1 of Test Method E1354 specifies that the accuracy of the heat flux meter must be within ±3 %. This implies that the actual heat flux in the test was between 48.5 and 51.5 kW/m². Moreover, the heat flux is not fully uniformly distributed over the specimen surface and varies slightly during the test. Uncertainties associated with heat flux setting and control are not considered in the analysis presented in this appendix.

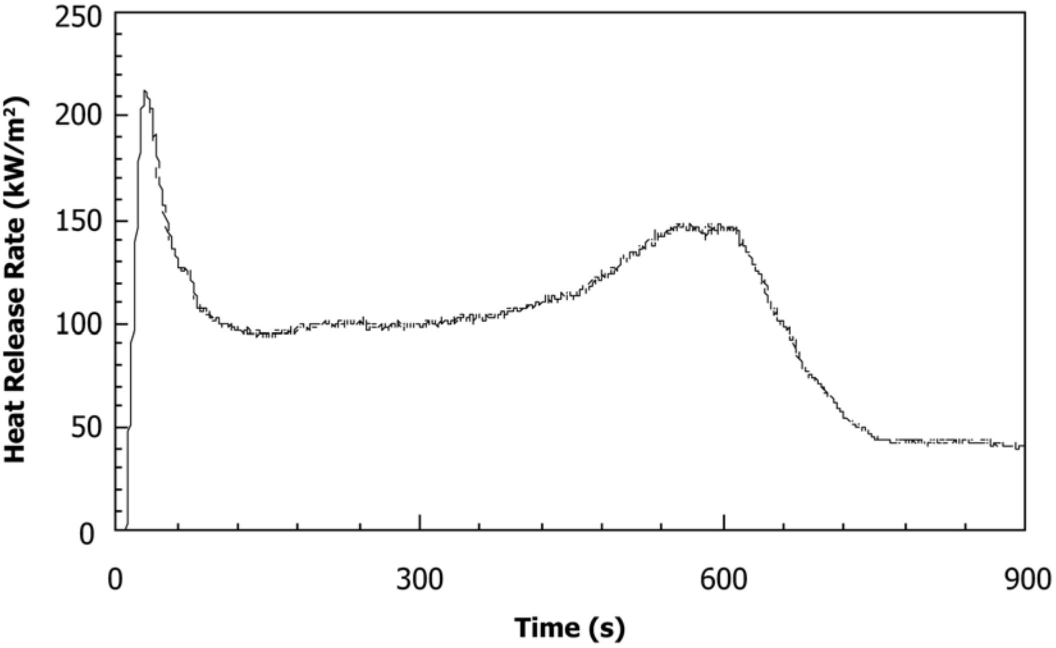

FIG. X1.4 Heat Release Rate versus Time

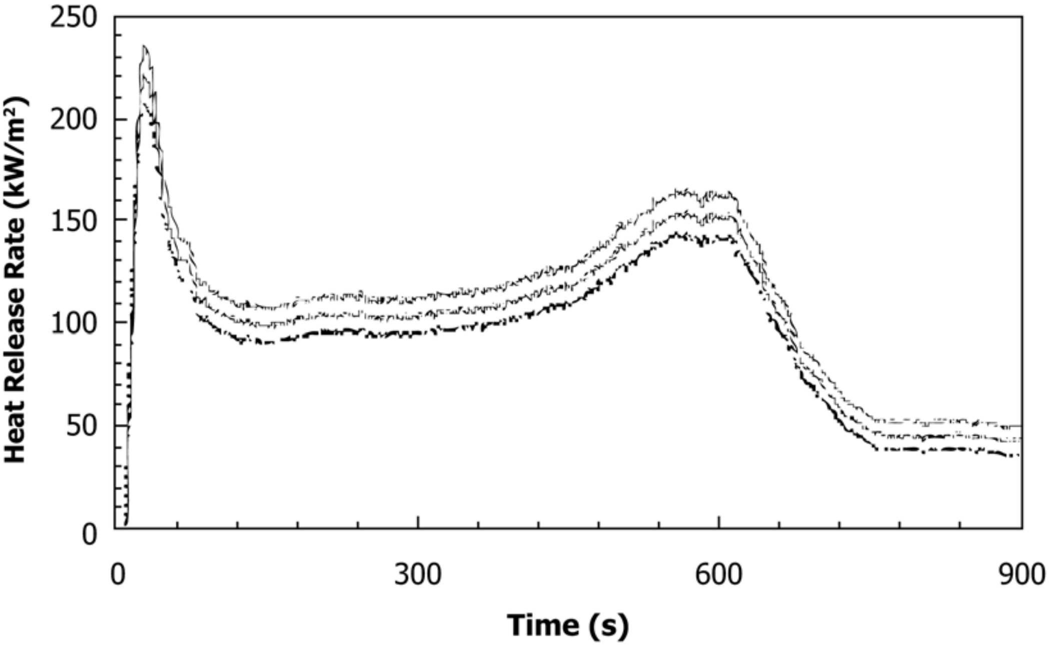

FIG. X1.5 Heat Release Rate with Expanded Uncertainty at the 95 % Confidence Level

TABLE X1.3 Expanded Uncertainty of Some Heat Release Parameters

	Value	*U*	*U*
Peak Heat Release Rate (kW/m^2)	222.4	14.4	6.5 %
One-Minute Average Heat Release Rate (kW/m^2)	156.1	11.1	7.1 %
Three-Minute Average Heat Release Rate (kW/m^2)	122.0	9.4	7.7 %
Five-Minute Average Heat Release Rate (kW/m^2)	115.4	9.1	7.9 %
Total Heat Release (MJ/m^2)	92.3	7.8	8.4 %

X2. UNCERTAINTY OF FIRE TEST RESULTS

X2.1 This standard provides guidance for evaluating the uncertainty of measurements in fire tests. The process of estimating the uncertainty of fire test results is more involved and needs to address the following three sources: uncertainties in the test conditions, uncertainties associated with the specimen being tested, and uncertainties in the measurements to quantify how the specimen responds in the test. Examples of the application of the concepts presented in this standard and additional guidance for the assessment of uncertainty in fire tests are provided in the literature (**2-28**).

X2.2 In some cases it is possible to determine how the uncertainties from these three sources affect the overall uncertainty of the final fire test result. Total heat release measured in the Cone Calorimeter (Test Method E1354) is an example of that.

X2.2.1 *Uncertainties in the Test Conditions*—The uncertainty of the total heat release associated with the test conditions is primarily due to errors in heat flux measurements. Test Method E1354 specifies that the accuracy of the heat flux meter shall be within ±3 %. The uncertainty associated with the heat flux measurements can therefore be accounted for.

X2.2.2 *Uncertainties Associated with the Specimen Being Tested*—The uncertainty of the heat release rate associated with the specimen being tested is primarily due to variations in the thickness and area of the specimen. The actual dimensions can be measured with great accuracy and since the total heat release is proportional to the volume of the specimen, corrections can be made to account for the uncertainty due to variations in specimen size.

X2.2.3 *Uncertainties in the Measurements to Quantify How the Specimen Responds in the Test*—The uncertainty of heat release measurements in the Cone Calorimeter is illustrated in Appendix X1 by means of an example. The contribution of this uncertainty to the overall uncertainty overwhelms the uncertainties in the test conditions and those associated with the specimen being tested.

X2.3 More often it is not possible to account for all sources contributing to the uncertainty of fire test results. The uncertainty of the fire resistance rating of a non-loadbearing wall assembly based on a furnace test according to Test Methods E119 is discussed here as an example.

X2.3.1 *Uncertainties in the Test Conditions*—The test specimen is exposed in a furnace to a standard fire, which is specified in the form of a time-temperature curve. The effect of permissible variations in furnace thermocouple location and response time, deviations within acceptable limits from the standard time-temperature curve and thermocouple measurement errors on the uncertainty of the fire resistance rating of the assembly cannot be determined. In addition, Test Methods E119 requires that wall assemblies with a fire resistance rating of 1 h or greater be subjected to a hose stream test. The uncertainties associated with the hose stream test cannot be quantified.

X2.3.2 *Uncertainties Associated with the Specimen Being Tested*—Test Methods E119 specifies that the test specimen shall be representative of the construction for which classification is desired. This implies that the materials, workmanship and details have to be the same as in the field. However, it is not possible to evaluate the uncertainty that results from any deviations. In addition, Test Methods E119 specifies a minimum specimen area, minimum width and minimum height. The uncertainty resulting from variations in wall dimensions within these acceptable limits cannot be quantified. Finally, the standard acknowledges the importance of providing a moisture condition within the specimen representative of that in similar construction in buildings but also recognizes the difficulty in achieving specific moisture conditions in practice.

X2.3.3 *Uncertainties in the Measurements to Quantify How the Specimen Responds in the Test*
The fire resistance rating of an unloaded wall assembly is determined by the time when the temperature rise on the unexposed side exceeds a specified limit or when flames or hot gases pass through the assembly, whichever occurs first. The temperature on the unexposed side is measured with nine thermocouples. Test Methods E119 describes the temperature sensor and method of attachment, but does not specify the exact location of four of the nine thermocouples. Although it may be feasible to determine the effect of the uncertainty of the unexposed surface temperature measurements on the uncertainty of the fire resistance rating of a wall assembly, it is not possible to assess the effect of variations in the location of four of the nine thermocouples. Passage of flame or hot gases is determined based on the ignition of a cotton pad. However, the pad and its application are not described in any detail and the resulting uncertainty can therefore not be quantified.

X2.3.4 It is obvious from X2.3.1 – X2.3.3 that it is not possible to quantify the effects from the three sources of error on the uncertainty of the fire resistance rating of a non-loadbearing wall assembly. The only way to determine the uncertainty of the fire resistance rating of such an assembly (or any other fire resistant construction) is on the basis of a statistical assessment of a series of repeat measurements. Unfortunately, the excessive cost of this approach prohibits its use on a routine basis.

X2.4 The sources of uncertainty that cannot be accounted for might in fact be the major contributors, in which case it is not feasible to develop a meaningful estimate of the overall uncertainty of a fire test result. The usefulness of this standard is then limited to evaluating and expressing the uncertainty of measurements that are made during the test.

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