Designation: E2536 – 09

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.

$$\varepsilon \equiv y - Y \tag{1}$$

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

[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.

Current edition approved Oct. 1, 2009. Published November 2009. Originally approved in 2006. Last previous edition approved in 2006 as E2536-06. DOI: 10.1520/E2536-09.

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

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.

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.

[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.

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 $X_1, \ldots, X_N$:

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

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:

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

Substituting Eq 2 and 3 into Eq 1 leads to:

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

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 $u(y)$:

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

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 $[2(n-1)]^{-1/2}$. 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:

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

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 j[th] 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.

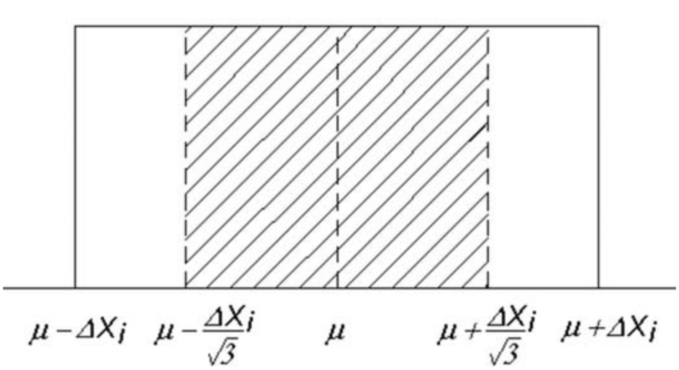

FIG. 1 Rectangular Distribution

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:

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

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

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

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:

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

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:

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

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).

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):

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

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:

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

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

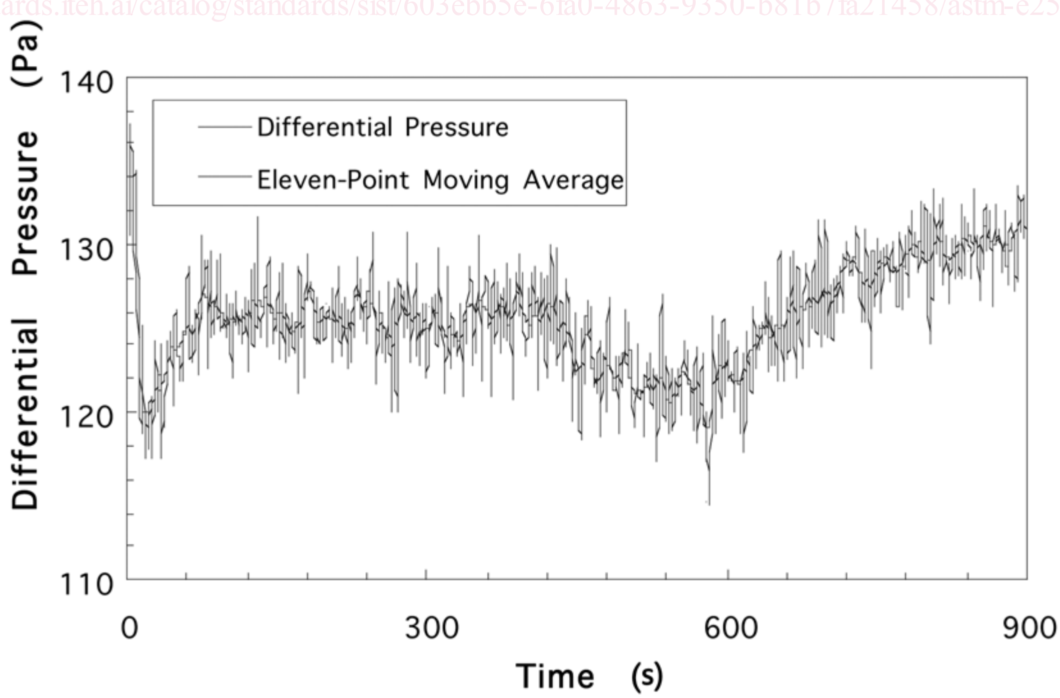

FIG. X1.1 Differential Pressure Measurements