



BSI Standards Publication

Estimation of uncertainty in the single burning item test

National foreword

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TECHNICAL REPORT

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Estimation of uncertainty in the single burning item test

Messunsicherheit - Thermische Beanspruchung durch
einen einzelnen brennenden Gegenstand (SBI)

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European foreword

This document (CEN/TR 16988:2016) has been prepared by Technical Committee CEN/TC 127 “Fire Safety in Buildings”, the secretariat of which is held by BSI.

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This document has been prepared under a mandate given to CEN by the European Commission and the European Free Trade Association.

1 Scope

1.1 General

The measuring technique of the SBI (single burning item) test instrument is based on the observation that, in general, the heats of combustion per unit mass of oxygen consumed are approximately the same for most fuels commonly encountered in fires [Huggett [12]]. The mass flow, together with the oxygen concentration in the extraction system, suffices to continuously calculate the amount of heat released. Some corrections can be introduced if CO₂, CO and/or H₂O are additionally measured.

1.2 Calculation procedure

1.2.1 Introduction

The main calculation procedures for obtaining the HRR and its derived parameters are summarized here for convenience. The formulas will be used in the following clauses and especially in the clause on uncertainty.

The calculations and procedures can be found in full detail in the SBI standard [1].

1.2.2 Synchronization of data

The measured data are synchronized making use of the dips and peaks that occur in the data due to the switch from 'primary' to 'main' burner around $t = 300$ s, i.e. at the start of the thermal attack to the test specimen. Synchronization is necessary due to the delayed response of the oxygen and carbon dioxide analysers. The filters, long transport lines, the cooler, etc. in between the gas sample probe and the analyser unit, cause this shift in time.

After synchronization, all data are shifted so that the 'main' burner ignites – by definition – at time $t = 300$ s.

1.2.3 Heat output

1.2.3.1 Average heat release rate of the specimen (HRR_{30s})

A first step in the calculation of the HRR contribution of the specimen is the calculation of the global HRR. The global HRR is constituted of the HRR contribution of both the specimen and the burner and is defined as

$$\text{HRR}_{\text{total}}(t) = E' \dot{V}_{D298}(t) x_{a,O_2} \left(\frac{\phi(t)}{1 + 0,105\phi(t)} \right) \quad (1)$$

where

$\text{HRR}_{\text{total}}(t)$ is the total heat release rate of the specimen and burner (kW);

E' is the heat release per unit volume of oxygen consumed at 298 K, = 17 200 (kJ/m³);

$\dot{V}_{D298}(t)$ is the volume flow rate of the exhaust system, normalized at 298 K (m³/s);

x_{a,O_2} is the mole fraction of oxygen in the ambient air including water vapour;

$\phi(t)$ is the oxygen depletion factor.

The last two terms x_{a,O_2} and $\left(\frac{\phi(t)}{1 + 0,105\phi(t)} \right)$ express the amount of moles of oxygen, per unit volume, that have chemically reacted into some combustion gases. Multiplication with the volume flow gives the

amount of moles of oxygen that have reacted away. Finally this value is multiplied with the 'Huggett' factor. Huggett stated that regardless of the fuel burnt roughly a same amount of heat is released.

The volume flow of the exhaust system, normalized at 298 K, $V_{D298}(t)$ is given by

$$V_{D298}(t) = cA \frac{k_t}{k_\rho} \sqrt{\frac{\Delta p(t)}{T_{ms}(t)}} \quad (2)$$

where

$$c = \sqrt{(2T_0 / \rho_0)} = 22,4 \text{ [K}^{0,5} \cdot \text{m}^{1,5} \cdot \text{kg}^{-0,5} \text{]}$$

A is the area of the exhaust duct at the general measurement section (m²);

k_t is the flow profile correction factor; converts the velocity at the height of the bi-directional probe in the axis of the duct to the mean velocity over the cross section of the duct;

k_ρ is the Reynolds number correction for the bidirectional probe, taken as 1,08;

$\Delta p(t)$ is the pressure difference over the bi-directional probe (Pa);

$T_{ms}(t)$ is the temperature in the measurement section (K).

The oxygen depletion factor $\phi(t)$ is defined as

$$\phi(t) = \frac{\bar{x}O_2(30s...90s)\{1 - xCO_2(t)\} - xO_2(t)\{1 - \bar{x}CO_2(30s...90s)\}}{\bar{x}O_2(30s...90s)\{1 - xCO_2(t) - xO_2(t)\}} \quad (3)$$

where

$xO_2(t)$ is the oxygen concentration in mole fraction;

$xCO_2(t)$ is the carbon dioxide concentration in mole fraction;

Ys...Zs mean taken over interval Y s to Z s.

The mole fraction of oxygen in ambient air, taking into account the moisture content, is given by

$$x_{a,O_2} = \bar{x}O_2(30s...90s) \left[1 - \frac{H}{100p} \exp \left\{ 23,2 - \frac{3816}{T_{ms}(30s...90s) - 46} \right\} \right] \quad (4)$$

where

$xO_2(t)$ is the oxygen concentration in mole fraction;

H is the relative humidity (%);

p is the ambient pressure (Pa);

$T_{ms}(t)$ is the temperature in the general measurement section (K).

Since we are interested in the HRR contribution of the specimen only, the HRR contribution of the burner should be subtracted. An estimate of the burner contribution $HRR_{burner}(t)$ is taken as the $HRR_{total}(t)$ during the base line period preceding the thermal attack to the specimen. A mass flow controller ensures an identical HRR through the burners before and after switching from primary to the main burner. The average HRR of the burner is calculated as the average $HRR_{total}(t)$ during the base line period with the primary burner on ($210 \text{ s} \leq t \leq 270 \text{ s}$):

$$\text{HRR}_{\text{av_burner}} = \overline{\text{HRR}}_{\text{total}}(210\text{ s} \dots 270\text{ s}) \quad (5)$$

where

HRR_{av_burner} is the average heat release rate of the burner (kW);

HRR_{total}(t) is the total heat release rate of specimen and burner (kW).

HRR of the specimen

In general, the HRR of the specimen is taken as the global HRR, $\text{HRR}_{\text{total}}(t)$, minus the average HRR of the burner, $\text{HRR}_{\text{av_burner}}$:

For $t > 312$ s:

$$\text{HRR}(t) = \text{HRR}_{\text{total}}(t) - \text{HRR}_{\text{av_burner}} \quad (6)$$

where:

HRR(t) is the heat release rate of the specimen (kW);

HRR_{total}(t) is the global heat release rate of specimen and burner (kW);

HRR_{av_burner} is the average heat release rate of the burner (kW).

During the switch from the primary to the main burner at the start of the exposure period, the total heat output of the two burners is less than $\text{HRR}_{\text{av_burner}}$ (it takes some time for the gas to be directed from one burner to the other). Formula (24) gives negative values for $\text{HRR}(t)$ for at most 12 s (burner switch response time). Such negative values and the value for $t = 300$ s are set to zero, as follows:

For $t = 300$ s:

$$\text{HRR}(300) = 0 \text{ kW} \quad (7)$$

For $300 \text{ s} < t \leq 312 \text{ s}$:

$$\text{HRR}(t) = \max \{ 0 \text{ kW}, \text{HRR}_{\text{total}}(t) - \text{HRR}_{\text{av_burner}} \} \quad (8)$$

where

max.[a, b] is the maximum of two values a and b.

Calculation of $\text{HRR}_{30\text{s}}$

In view of the calculation of the FIGRA index, the HRR data are smoothened with a 'flat' 30 s running average filter using 11 consecutive measurements:

$$\text{HRR}_{30\text{s}}(t) = \frac{0,5\text{HRR}(t-15) + \text{HRR}(t-12) + \dots + \text{HRR}(t+12) + 0,5\text{HRR}(t+15)}{10} \quad (9)$$

where

$\text{HRR}_{30\text{s}}(t)$ is the average of $\text{HRR}(t)$ over 30 s (kW);

$\text{HRR}(t)$ is the heat release rate at time t (kW).

1.2.3.2 Calculation of THR(t) and THR_{600s}

The total heat release of the specimen $\text{THR}(t)$ and the total heat release of the specimen in the first 600 s of the exposure period ($300 \text{ s} \leq t \leq 900 \text{ s}$), $\text{THR}_{600\text{s}}$, are calculated as follows:

$$\text{THR}(t_a) = \frac{1}{1000} \sum_{300s}^{t_a} \text{HRR}(t) \times 3 \quad (10)$$

$$\text{THR}_{600s} = \frac{1}{1000} \sum_{300s}^{900s} \text{HRR}(t) \times 3 \quad (11)$$

whereby the factor 1 000 is introduced to convert the result from kJ into MJ and the factor 3 stands for the time interval in-between 2 consecutive measurements,

and where

$\text{THR}(t_a)$ is the total heat release of the specimen during the period $300 \text{ s} \leq t \leq t_a$ (MJ);

$\text{HRR}(t)$ is the heat release rate of the specimen (kW);

THR_{600s} is the total heat release of the specimen during the period $300 \text{ s} \leq t \leq 900 \text{ s}$ (MJ); (equal to $\text{THR}(900)$).

1.2.3.3 Calculation of FIGRA_{0,2MJ} and FIGRA_{0,4MJ} (Fire growth rate indices)

The FIGRA is defined as the maximum of the ratio $\text{HRR}_{\text{av}}(t)/(t - 300)$, multiplied by 1 000. The ratio is calculated only for that part of the exposure period in which the threshold levels for HRR_{av} and THR have been exceeded. If one or both threshold values are not exceeded during the exposure period, FIGRA is equal to zero. Two combinations of threshold values are used, resulting in FIGRA_{0,2MJ} and FIGRA_{0,4MJ}.

- a) The average of HRR, HRR_{av} , used to calculate the FIGRA is equal to HRR_{30s} , with the exception of the first 12 s of the exposure period. For data points in the first 12 s, the average is taken only over the widest possible symmetrical range of data points within the exposure period:

$$\text{For } t = 300 \text{ s: } \text{HRR}_{\text{av}}(300 \text{ s}) = 0 \quad (12)$$

$$\text{For } t = 303 \text{ s: } \text{HRR}_{\text{av}}(303 \text{ s}) = \overline{\text{HRR}}(300 \text{ s} \dots 306 \text{ s}) \quad (13)$$

$$\text{For } t = 306 \text{ s: } \text{HRR}_{\text{av}}(306 \text{ s}) = \overline{\text{HRR}}(300 \text{ s} \dots 312 \text{ s}) \quad (14)$$

$$\text{For } t = 309 \text{ s: } \text{HRR}_{\text{av}}(309 \text{ s}) = \overline{\text{HRR}}(300 \text{ s} \dots 318 \text{ s}) \quad (15)$$

$$\text{For } t = 312 \text{ s: } \text{HRR}_{\text{av}}(312 \text{ s}) = \overline{\text{HRR}}(300 \text{ s} \dots 324 \text{ s}) \quad (16)$$

$$\text{For } t \geq 315 \text{ s: } \text{HRR}_{\text{av}}(t) = \text{HRR}_{30s}(t) \quad (17)$$

- b) Calculate FIGRA_{0,2MJ} for all t where:

$$(\text{HRR}_{\text{av}}(t) > 3 \text{ kW}) \text{ and } (\text{THR}(t) > 0,2 \text{ MJ}) \text{ and } (300 \text{ s} < t \leq 1\,500 \text{ s});$$

and calculate FIGRA_{0,4MJ} for all t where:

$$(\text{HRR}_{\text{av}}(t) > 3 \text{ kW}) \text{ and } (\text{THR}(t) > 0,4 \text{ MJ}) \text{ and } (300 \text{ s} < t \leq 1\,500 \text{ s});$$

both using:

$$\text{FIGRA} = 1000 \times \max \left(\frac{\text{HRR}_{\text{av}}(t)}{t - 300} \right) \quad (18)$$

where:

FIGRA is the fire growth rate index

HRR_{av}(t) is the average of HRR(t) as specified in a) (kW);

As a consequence, specimens with a HRR_{av} not exceeding 3 kW during the total test have FIGRA values FIGRA_{0,2MJ} and FIGRA_{0,4MJ} equal to zero. Specimens with a THR not exceeding 0,2 MJ over the total test period have a FIGRA_{0,2MJ} equal to zero and specimen with a THR not exceeding 0,4 MJ over the total test period have a FIGRA_{0,4MJ} equal to zero.

2 Uncertainty

2.1 Introduction

According to EN ISO/IEC 17025 [3], which sets out the general requirements for the competence of testing and calibration laboratories, and EN ISO 10012 [7], which sets out the requirements for assuring the quality of measuring equipment, uncertainties shall be reported in both testing and calibration reports.

The general principles for evaluating and reporting uncertainties are given in the ISO Guide to the Expression of Uncertainty in Measurement (GUM) [6], but need to be applied to the specific case of fire testing. Due to the harmonization of fire testing in the European Community (EUROCLASSES; EN 13501-1 [21]) and the pressure on testing laboratories to operate under accreditation, this is becoming even more important.

It is of common knowledge that measurement results are never perfectly accurate. In practice the sources of systematic and random errors which can affect the results of measurement are numerous, even for the most careful operators. To describe this lack of perfection, the term 'uncertainty' is used. Although the concept of uncertainty may be related to a 'doubt', in the real sense the knowledge of uncertainty implies increased confidence in the validity of results.

The qualitative concept of accuracy is quantified by the uncertainty which varies inversely 'proportioned' to it. Accuracy consists of both trueness and precision as shown in Figure 1. A numerical measure for precision is the standard deviation, while trueness is expressed numerically by the systematic error or the bias.

It is considered good practice to eliminate any systematic errors. However, if the value of a systematic error is unknown it may be regarded as a random error. Random errors result in a spread of the values and can usually be reduced by increasing the number of observations. Its expectation or expected value is zero.

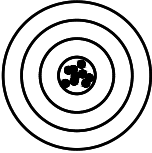
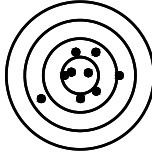
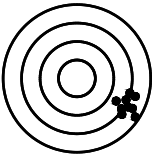
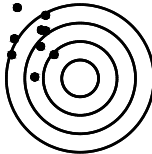
	high precision	low precision
high trueness	 (high accuracy)	
low trueness		

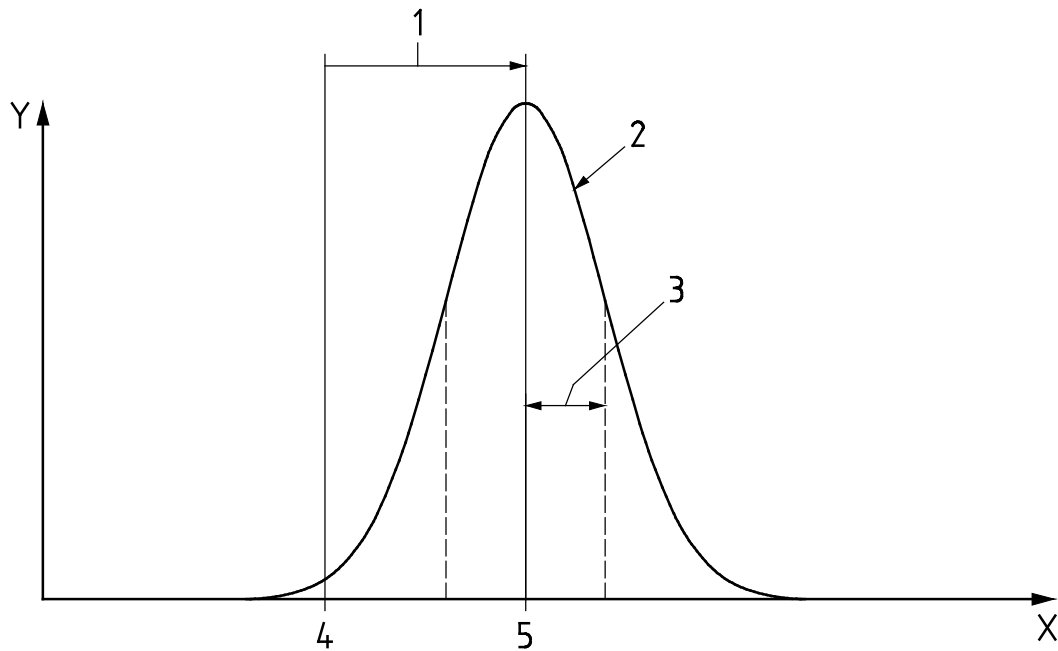
Figure 1 — Concepts of accuracy (uncertainty), precision (standard deviation) and trueness (bias)

In general, the result of a measurement is only an approximation or estimate of the value of the specific quantity subject to measurement, that is, the measurand, and so the result is complete only when accompanied by a quantitative statement of its uncertainty.

Without knowledge of the accuracy (trueness and precision) of measurement methods and/or the uncertainty of measurement results, it can appear very easy to make decisions. But, in practice, these decisions might be incorrect and sometimes lead to serious consequences, if the measurement uncertainty is not taken into account.

For example, in fire testing, when rejecting instead of accepting a good product during a certification process or, conversely, when accepting a bad product by error. So, it is vital to quantify the reliability of the measurement results to greatly reduce any disputes and adverse consequences of legal proceedings. This is of particular importance if the growing number of cases of litigation in Europe and the liability problems of manufacturers in case of accidents are considered.

The difference between error and uncertainty should always be borne in mind. For example, the result of a measurement after correction can unknowably be very close to the unknown value of the measurand, and thus have negligible error, even though it might have a large uncertainty.



Key

- X value
- Y frequency
- 1 bias
- 2 repeated measurements would give values with this frequency curve
- 3 standard deviation (σ)
- 4 true value
- 5 expected value

Figure 2 — Concepts of accuracy (uncertainty), precision (standard deviation) and trueness (bias)

2.2 Elaboration of terms and concepts

2.2.1 Mean and variance

A population with a 'normal' probability density function is characterized by its mean value μ and its variance σ^2 : $N(\mu, \sigma^2)$. When both μ and σ^2 are unknown, they can be estimated by taking a number n of samples and by calculating the estimated mean \bar{x} , the estimated variance s^2 and the estimated standard deviation s .

$$\bar{x} = \frac{1}{n} \sum_{i=1}^n x_i \tag{19}$$

$$s^2 = \frac{1}{n-1} \sum_{i=1}^n (x_i - \bar{x})^2 \tag{20}$$

If a covariance exists between two variables x and y , it is given by

$$s_{ij}^2 = \frac{1}{n-1} \sum_{i=1}^n (x_i - \bar{x})(y_i - \bar{y}) \tag{21}$$

2.2.2 Estimation of the confidence interval for the population mean

Often the standard deviation σ is unknown. To evaluate the confidence interval, some estimate of σ shall be made. The most obvious candidate is the sample standard deviation s . But the use of s introduces an additional source of unreliability, especially if the sample is small. To retain the confidence interval, the interval shall therefore be widened. This is done by using the t distribution instead of the standard normal distribution. For a sample size larger than 100, the t -distribution approaches the normal distribution. For a 95 % (two tails of 2,5 %) confidence interval – which we strive for – the uncertainty is estimated by

$$t_{0,025} \frac{s}{\sqrt{n}} \quad (22)$$

The value $t_{0,025}$ depends on the amount of information used in calculating s^2 , i.e. on the degrees of freedom. For large sample sizes, $t_{0,025}$ approaches 1,96 which is the value for a normal distribution. For a normal distribution, a coverage factor 2 (1,96) corresponds to a 95 % confidence interval (see 2.2.6).

2.2.3 Sources of uncertainty

According to GUM [6] any detailed report of the uncertainty should consist of a complete list of the components, specifying for each the method used to obtain its numerical value. The components may be grouped into two categories based on their method of evaluation:

Type A **The components in category A are characterized by the estimated variances s_i^2 or by the estimated standard deviation s_i derived from data by statistical methods. Where appropriate the covariance s_{ij}^2 should be given.**

For such a component, the standard uncertainty is $u_i = s_i$.

Type B **The standard uncertainty of a Type B evaluation is approximated based on specifications, calibrations, handbooks, experience, judgements etc. and is represented by a quantity u_j . It is obtained from an assumed probability distribution based on all the available information.**

Where appropriate the covariance should be given and should be treated in a similar way.

The 'type' classification does not indicate any difference in the nature of the components resulting from the two types of evaluation. Both are based on probability distributions, and the uncertainty components resulting from either type are quantified by standard deviations. It should be recognized that a Type B evaluation of standard uncertainty can be as reliable as a Type A evaluation.

The standard deviation of a Type B evaluation is based on the shape of the distribution. Distributions used in this document are the rectangular, the triangular, the trapezoidal and the normal distribution. For the rectangular and triangular also asymmetric distributions are discussed.

2.2.4 Standard uncertainties for different distributions

Normal distribution

Often calibration certificates, handbooks, manufacturer's specifications, etc. state a particular multiple of a standard deviation. In this case, a normal distribution is assumed to obtain the standard uncertainty.

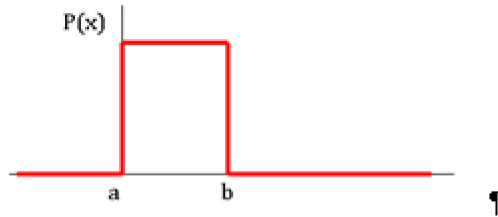
Rectangular distribution

In other cases the probability that the value of X_i lies within the interval a^- to a^+ for all practical purposes is equal to one and the probability that X_i lies outside this interval is essentially zero. If there is no specific knowledge about the possible values of X_i within the interval, a uniform or rectangular

distribution of values is assumed. The associated standard deviation is function of the width of the distribution as:

$$u_{rect} = \frac{a}{\sqrt{3}} \quad (23)$$

Indeed, for a rectangular distribution, the variance is obtained as in 24. Given the probability function of the rectangular distribution



$$P(x) = \begin{cases} 0 & x < a \\ \frac{1}{b-a} & a < x < b \\ 0 & x > b \end{cases} \quad (24)$$

This can be written in terms of the Heaviside step function $H(x)$ as

$$P(x) = \frac{H(x-a) - H(x-b)}{b-a} \quad (25)$$

This makes that the variance σ^2 with population mean μ for an asymmetric distribution becomes

$$\mu = \int_{-\infty}^{\infty} P(x)x dx = \int_a^b \frac{x}{(b-a)} dx = \frac{b+a}{2} \quad (26)$$

$$\sigma^2 = \int_{-\infty}^{\infty} P(x)(x-\mu)^2 dx \quad (27)$$

$$\sigma^2 = \int_{-\infty}^{\infty} \frac{H(x-a) - H(x-b)}{b-a} (x - \frac{a+b}{2})^2 dx \quad (28)$$

$$\sigma^2 = \int_a^b \frac{(x - \frac{a+b}{2})^2}{b-a} dx = \frac{(a+b)^2}{12} \quad (29)$$

So for a symmetric rectangular interval $a-$ to $a+$, the variance reduces to

$$\sigma^2 = \frac{a^2}{3}. \quad (30)$$

The sample estimate of the standard deviation thus is:

$$u_{rect} = \frac{a}{\sqrt{3}}. \quad (31)$$

The rectangular distribution is a reasonable default model in the absence of any other information. But if it is known that values of the quantity in question near the centre of the limits are more likely than values close to the limits, a triangular or a normal distribution might be a better model.

Triangular and trapezoidal distribution

In many cases it is more realistic to expect that values near the bounds are less likely than those near the midpoint. It is then reasonable to replace the symmetric rectangular distribution by a symmetric trapezoidal distribution having equal sloping sides, a base of width $2a$ and a top of width $2a\beta$ where $0 \leq \beta \leq 1$. Similar as for a rectangular distribution, for a trapezoidal distribution the standard deviation becomes:

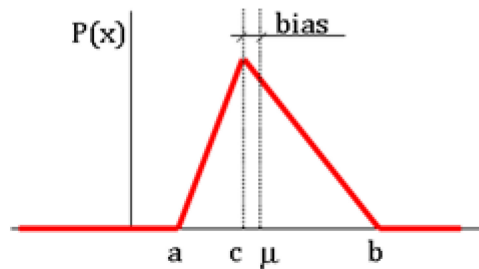
$$u_{trap} = \frac{a\sqrt{(1+\beta^2)}}{\sqrt{6}} \quad (32)$$

As β goes to 1 this trapezoidal distribution approaches the rectangular distribution while for $\beta = 0$ it is a triangular distribution.

$$u_{trian} = \frac{a}{\sqrt{6}} \quad (33)$$

Asymmetric distributions

For an asymmetric triangular distribution the mean value and standard deviation become



$$\mu = \frac{1}{3}(a + b + c) \quad (34)$$

$$u_{asymmetric_triangular} = \sqrt{\frac{1}{18}(a^2 + b^2 + c^2 - ab - ac - bc)} \quad (35)$$

For the limit case of a 'one sided triangular distribution ($a = c = 0$; $b = b$) this reduces to

$$\mu = \frac{b}{3} \quad (36)$$

$$u_{asymmetric_triangular} = \frac{b}{3\sqrt{2}} \quad (37)$$

The limit case of a 'one sided rectangular distribution ($a = 0$; $b = b$) reduces to

$$\mu = \frac{b}{2} \quad (38)$$

$$u_{\text{asymmetric_rectangular}} = \frac{b}{\sqrt{12}} \quad (39)$$

For asymmetric distributions the difference between the mean value μ and c will be considered as a bias and, as recommended by the GUM [6], it will be corrected for.

2.2.5 Combined uncertainty

2.2.5.1 Uncorrelated input quantities

The standard uncertainty of y , where y is the estimate of the measurand Y and thus the measurement, is obtained by appropriately combining the standard uncertainties of the input estimates x_i . In case all input quantities are independent, this combined standard uncertainty $u_c(y)$ is the positive square root of the combined variance $u_c^2(y)$ and is given by

$$u_c = \sqrt{\sum_{i=1}^N [c_i u(x_i)]^2} \quad (40)$$

where the sensitivity coefficient is given by

$$c_i = \frac{\partial y}{\partial x_i} \quad (41)$$

2.2.5.2 Correlated input quantities

Formula (41) is only valid when the input quantities X_i are independent or uncorrelated. When the input quantities are correlated, the appropriate expression for the combined variance $u_c^2(y)$ associated with the result of the measurement is

$$u_c = \sqrt{\sum_{i=1}^N [c_i u(x_i)]^2 + 2 \sum_{i=1}^{N-1} \sum_{j=i+1}^N c_i c_j u(x_i) u(x_j) r(x_i, x_j)} \quad (42)$$

whereby the degree of correlation between x_i and x_j is characterized by the estimated correlation coefficient (Pearson)

$$r(x_i, x_j) = \frac{u(x_i, x_j)}{u(x_i) u(x_j)} \quad -1 \leq r(x_i, x_j) \leq +1 \quad (43)$$

If the estimates x_i and x_j are independent, $r(x_i, x_j) = 0$, and a change in one does not imply an expected change in the other. Pearson's coefficient reflects the degree of linear relationship between two data sets. Its value is between -1 and $+1$. A value of $+1$ means that there is a perfect positive linear relationship between the two data sets. A value of -1 means that there is a perfect negative linear relationship, and a value of 0 means there is no linear relationship at all between the data sets.

The measurands E' , p_{atm} , T_{room} , φ , α , c , A , k_t and k_p , are constant or can be considered constant throughout the test. They are treated as independent input quantities.

The oxygen concentration (XO_2), the carbon dioxide concentration (XCO_2), the exhaust gas temperature in the measurement section (T_{ms}) and the differential pressure over the velocity probe (Δp) are significantly correlated to each other and the correlation coefficients will be chosen as indicated in Table 1.

Table 1 — Assumed correlation coefficients between XO_2 , XCO_2 , T_{ms} and Δp

	O₂	CO₂	Δp	T_{ms}
--	----------------------	-----------------------	-----------	-----------------------

O₂	1	-1	-1	-1
CO₂	-1	1	1	1
Δp	-1	1	1	1
T_{ms}	-1	1	1	1

2.2.6 Expanded uncertainty

Although the combined standard uncertainty u_c is used to express the uncertainty of a wide variety of applications, what is often required is a measure of uncertainty that defines an interval about the measurement result y within which the value of the measurand Y can be confidently asserted to lie. The measure of uncertainty intended to meet this requirement is termed expanded uncertainty, U , and is obtained by multiplying $u_c(y)$ by a coverage factor k . So $U = k u_c(y)$ and it is confidently believed that Y is greater than or equal to $y - U$, and is less than or equal to $y + U$, which is commonly written as $Y = y \pm U$.

In general, the value of the coverage factor k is chosen on the basis of the desired level of confidence to be associated with the interval defined by $U = k u_c$. Typically, k is in the range 2 to 3. When the normal distribution applies and u_c is a reliable estimate of the standard deviation of y , $U = 2 u_c$ (i.e. $k = 2$) defines an interval having a level of confidence of approximately 95 % (95,44 %), and $U = 3 u_c$ (i.e. $k = 3$) defines an interval having a level of confidence greater than 99 % (99,73 %).

In this document, we will work with standard deviations to express the uncertainty of individual measurands and combined standard uncertainties, and with a coverage factor of 2 to express the confidence interval on the estimate of the overall uncertainty.

On occasion, a self-defined apparent standard deviation defined as the uncertainty for a 95 % interval divided by 1,96 will be used. This is useful when for example using t-distributions since for this distribution the expanded uncertainty $U(k = 1,96) \neq 1,96 * U(k = 1)$. Since we know that we finally want to end up with a 95 % confidence interval but we are working with standard deviations, t-distributions will be calculated based on a 95 % confidence interval divided by 1,96.

This allows us to work with standard deviations all the time and to, at the end, multiply with the coverage factor of $k = 1,96$.

$$U_{95\%}(x) = 1,96 \sqrt{\left(c_{x1} \frac{U(x_1)}{1,96} \right)^2 + \left(c_{x2} \frac{U(x_2)}{1,96} \right)^2 + \dots} \quad (44)$$

2.2.7 Uncorrected bias

Although it is recommended (and strongly preferred) practice of correcting for all known bias effects, in view of backwards compatibility of test results for example, an increased uncertainty interval may be the preferred option.

Unfortunately, the GUM [6] does not deal directly with the situation where a known measurement bias is present but is uncorrected.

Several proposed methods of treating uncorrected bias are available. We propose to follow the guidelines of Phillips et al. [14] because of its conservative approach. This method algebraically sums the signed bias δ with the expanded uncertainty, unless the bias is larger:

$$Y = y_{-U}^{+U+} \quad (45)$$

Where

$$U^+ = \begin{cases} ku_c - \delta & \text{if } ku_c - \delta > 0 \\ 0 & \text{if } ku_c - \delta \leq 0 \end{cases} \quad (46)$$

And

$$U^- = \begin{cases} ku_c + \delta & \text{if } ku_c + \delta > 0 \\ 0 & \text{if } ku_c + \delta \leq 0 \end{cases} \quad (47)$$

Note that the expanded uncertainty shall be re-computed if the coverage factor is changed, and in particular, that $U \pm (k = 2) \neq 2 * U \pm (k = 1)$.

The combined standard uncertainty u_c is calculated out of the standard uncertainty associated with the bias u_b and the standard uncertainty u that accounts for the combination of all other uncertainty sources not directly associated with the bias.

$$u_c = (u^2 + u_b^2)^{1/2} \quad (48)$$

The proposed approach can somewhat overestimate the uncertainty. In the case of a coverage factor $k = 2$, the method maintains the 95 % confidence interval until the ratio of the bias to the combined standard uncertainty becomes larger than the coverage factor. For such large bias values, the method produces uncertainty intervals that are slightly conservative.

Note that the sign of the sensitivity coefficient is important to know the effect on the global uncertainty. As an example, suppose x_1 and x_2 both have uncorrected bias and the expanded uncertainty is given by

$$x_{1-U^{1+}}^{+U^{1+}} \quad (49)$$

$$x_{2-U^{2-}}^{+U^{2+}} \quad (50)$$

The uncertainty interval on x defined as

$$x = \frac{x_1}{x_2} \quad (51)$$

then becomes

$$\frac{u(x)}{x} = \begin{cases} + \sqrt{\left(\frac{U^{1+}}{x_1}\right)^2 + \left(\frac{U^{2-}}{x_2}\right)^2} \\ - \sqrt{\left(\frac{U^{1-}}{x_1}\right)^2 + \left(\frac{U^{2+}}{x_2}\right)^2} \end{cases} \quad (52)$$

assuming $x_1 \neq 0$ and $x_2 \neq 0$.

An underestimation of x_1 leads to an underestimation of x , while an underestimation of x_2 leads to an overestimation of x .

2.3 Combined standard uncertainties

2.3.1 Combined standard uncertainty on sums

Since the discussion on the uncertainty of a data acquisition system often requires the standard uncertainty on the sum of N independent variables/measurements, a short review is as follows.

Assume the sum

$$y = a \sum_i^N x_i \quad (53)$$

Taking the partial derivative to the different components x_i results in the corresponding sensitivity coefficients $c_i = a$.

The standard uncertainty of y is obtained by appropriately combining the standard uncertainties of the input estimates x_i . This combined standard uncertainty $u_c(y)$ is the positive square root of the combined variance $u_c^2(y)$ and is given by

$$u_c(y) = \sqrt{\sum_{i=1}^N [c_i u(x_i)]^2} = a \sqrt{\sum_{i=1}^N u^2(x_i)} \quad (54)$$

Note that for correlated measurements this is no longer true as will be discussed in the next clause.

2.3.2 Combined standard uncertainty on averages

If x_i is a repetitive independent measurement of a measurand X , the uncertainty on the average is given by

$$u_c(x) = \frac{\sqrt{\sum_{i=1}^N u^2(x_i)}}{N} = \frac{\sqrt{N u^2(x_i)}}{N} = \frac{u(x_i)}{\sqrt{N}} \quad (55)$$

If however the uncertainty of a component is related to an effect with periodicity exceeding the weighing interval ($t_N - t_1 < T_{\text{effect}}$), the uncertainty on the average is more likely to be

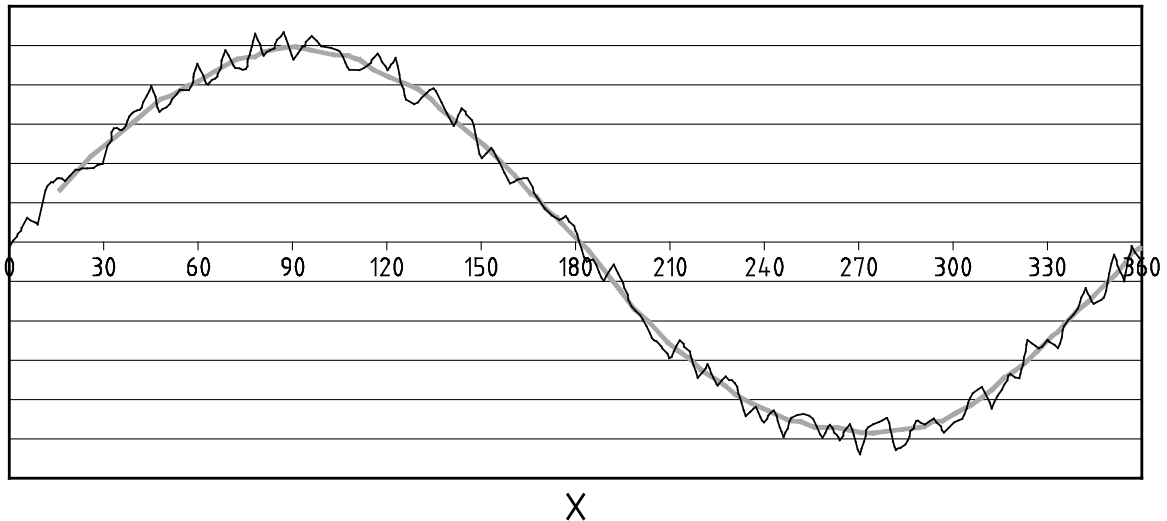
$$u_c(x) = \overline{u(x_i)} \quad (56)$$

One could say that the measurement results are highly correlated ($r = 1$) such that Formula (42) becomes ($c_i = 1/N$)

$$u_c = \sqrt{\sum_{i=1}^N [c_i u(x_i)]^2 + 2 \sum_{i=1}^{N-1} \sum_{j=i+1}^N c_i c_j u(x_i) u(x_j)} = \frac{\sum_{i=1}^N u(x_i)}{N} = \overline{u(x_i)} \quad (57)$$

When for example calculating the 30 s running average of the HRR (Formula (27) this should be kept in mind. The running average will reduce the uncertainty associated with noise, but will not, for example, eliminate the uncertainty related to daily cycle temperature variations.

Figure 3 illustrates this by way of example. Suppose a cyclic phenomenon with periodicity $t_s = 360$ s introduces an uncertainty of 500 ppm. Noise on the signal introduces an uncertainty estimated at 100 ppm.



Key

- X time (s)
- running average over 30 s
- signal with noise

Figure 3 — Effect of averaging on uncertainty (function of periodicity)

From this example it is clear that the running average over 10 samples (30 s) may reduce the uncertainty associated with noise with a factor $\sqrt{10}$, but does not affect the uncertainty related to longer term variations ($t_s \gg 30$ s).

A similar statement is true for the calculation of the total heat release in the first 10 min of a test (600 s). Suppose the measurements are perfectly correlated ($r = 1$) the uncertainty on the sum becomes ($c_i = 1$):

$$u_c = \sqrt{\sum_{i=1}^N [c_i u(x_i)]^2 + 2 \sum_{i=1}^{N-1} \sum_{j=i+1}^N c_i c_j u(x_i) u(x_j)} = \sum_{i=1}^N u(x_i) \quad (58)$$

which is higher than Formula (55). In this case, events with a periodicity of approximately 10 minutes or less will be dampened out while events with a longer periodicity will not be dampened out (r goes to 1).

For parameters like MARHE, which is also based on total heat release, the behaviour with respect to uncertainty will depend upon the integration time which is variable.

On the other hand however, uncertainties related to very slow processes ($\tau > 10$ times test run) hardly contribute to the uncertainty on the oxygen depletion since it is a relative measurement, i.e. the actual status is compared with the initial status at the start of the test.

This document therefore considers measurements as being independent, include the uncertainty related to slow processes ($\tau > 10$ times test run) in the zero calibration (= daily calibration of zero points), include the uncertainty related to drift over one test run in the uncertainty related to the actual measurement point.

2.3.3 Combined standard uncertainty of a product and a division

Throughout the document, often the uncertainty has to be calculated for a product and for a division.

Starting from the general form

$$y = ax_1x_2 \quad (59)$$

The partial derivative to the variables x_1 and x_2 is given by

$$\frac{\partial y}{\partial x_1} = ax_2 = \frac{y}{x_1} \quad (\text{if } x_1 \neq 0) \quad (60)$$

$$\frac{\partial y}{\partial x_2} = ax_1 = \frac{y}{x_2} \quad (\text{if } x_2 \neq 0) \quad (61)$$

Thus the combined standard uncertainty on y is estimated out of

$$\frac{u(y)}{y} = \sqrt{\left(\frac{u(x_1)}{x_1}\right)^2 + \left(\frac{u(x_2)}{x_2}\right)^2} \quad (\text{if } x_1 \neq 0 \text{ and } x_2 \neq 0) \quad (62)$$

This formula holds for a division. Indeed, taking the partial derivatives of the general form

$$y = a \frac{x_1}{x_2} \quad (63)$$

$$\frac{\partial y}{\partial x_1} = \frac{a}{x_2} = \frac{y}{x_1} \quad (\text{if } x_1 \neq 0) \quad (64)$$

$$\frac{\partial y}{\partial x_2} = -\frac{ax_1}{x_2^2} = -\frac{y}{x_2} \quad (\text{if } x_2 \neq 0) \quad (65)$$

NOTE The statement (if $x_i \neq 0$) will be omitted from now on if it can reasonably be assumed that x_i will always fulfil this requirement in a practical sense.

2.3.4 Combined standard uncertainty on the heat release rate (Q)

The heat release rate ($Q = \text{HRR}_{\text{total}}$) is given by Formula (19)

$$\dot{Q} = \frac{\phi}{\{1 + (\alpha - 1)\phi\}} E' X_{O_2}^{D^\circ} \dot{V}_{D298} \quad (66)$$

Substituting the volume flow \dot{V}_{D298} (2.3.7) this becomes

$$\dot{Q} = \frac{\phi}{\{1 + (\alpha - 1)\phi\}} E' X_{O_2}^{D^\circ} c_A \frac{k_t}{k_p} \sqrt{\frac{\Delta p(t)}{T_{\text{ms}}(t)}} \quad (67)$$

Taking the partial derivative of Q to the different components x_i results in the corresponding sensitivity coefficients c_i^Q :

$$c_\phi^Q \equiv \frac{\partial \dot{Q}}{\partial \phi} = \frac{E' X_{O_2}^{D^\circ} \dot{V}_{D298} - (\alpha - 1)\dot{Q}}{[1 + (\alpha - 1)\phi]} \quad (68)$$

$$c_{X_{O_2}^A}^Q = c_\phi^Q c_{X_{O_2}^A}^\phi \quad \text{see also 2.3.5} \quad (69)$$

$$c_{X_{CO_2}^A}^Q = c_\phi^Q c_{X_{CO_2}^A}^\phi \quad \text{see also 2.3.5} \quad (70)$$

$$c_{E'}^Q \equiv \frac{\partial Q}{\partial E'} = \frac{Q}{E'} \quad (71)$$

$$c_{\alpha}^Q \equiv \frac{\partial Q}{\partial \alpha} = Q \left[\frac{-\phi}{1 + (\alpha - 1)\phi} \right] \quad (72)$$

$$c_{X_{O_2}^{D^{\circ}}}^Q \equiv \frac{\partial Q}{\partial X_{O_2}^{D^{\circ}}} = \frac{Q}{X_{O_2}^{D^{\circ}}} \quad (73)$$

$$c_{V_D}^Q \equiv \frac{\partial Q}{\partial V_D} = \frac{Q}{V_D} \quad (74)$$

$$c_c^Q = c_{V_D}^Q c_c^{V_D} \quad \text{see also 2.3.7} \quad (75)$$

$$c_A^Q = c_{V_D}^Q c_A^{V_D} \quad \text{see also 2.3.7} \quad (76)$$

$$c_{k_t}^Q = c_{V_D}^Q c_{k_t}^{V_D} \quad \text{see also 2.3.7} \quad (77)$$

$$c_{k_p}^Q = c_{V_D}^Q c_{k_p}^{V_D} \quad \text{see also 2.3.7} \quad (78)$$

$$c_{\Delta p}^Q = c_{V_D}^Q c_{\Delta p}^{V_D} \quad \text{see also 2.3.7} \quad (79)$$

$$c_{T_{ms}}^Q = c_{V_D}^Q c_{T_{ms}}^{V_D} \quad \text{see also 2.3.7} \quad (80)$$

$$c_{X_{O_2}^{A^{\circ}}}^Q = c_{\phi}^Q c_{X_{O_2}^{A^{\circ}}}^{\phi} + c_{X_{O_2}^{D^{\circ}}}^Q c_{X_{O_2}^{A^{\circ}}}^{X_{O_2}^{D^{\circ}}} \quad \text{see also 2.3.5 and 2.3.6} \quad (81)$$

$$c_{X_{CO_2}^{A^{\circ}}}^Q = c_{\phi}^Q c_{X_{CO_2}^{A^{\circ}}}^{\phi} \quad \text{see also 2.3.5} \quad (82)$$

and to the combined standard uncertainty

$$u(Q) = \left[\begin{aligned} & \left(c_{XO_2^A}^Q u(XO_2^A) \right)^2 + \left(c_{XCO_2^A}^Q u(XCO_2^A) \right)^2 + \left(c_E^Q u(E) \right)^2 + \left(c_\alpha^Q u(\alpha) \right)^2 \\ & + \left(c_{XO_2^D}^Q u(XO_2^D) \right)^2 + \left(c_c^Q u(c) \right)^2 + \left(c_A^Q u(A) \right)^2 + \left(c_{k_t}^Q u(k_t) \right)^2 \\ & + \left(c_{k_p}^Q u(k_p) \right)^2 + \left(c_{\Delta p}^Q u(\Delta p) \right)^2 + \left(c_{T_{ms}}^Q u(T_{ms}) \right)^2 \\ & + \left(c_{XO_2^{A^\circ}}^Q u(XO_2^{A^\circ}) \right)^2 + \left(c_{XCO_2^{A^\circ}}^Q u(XCO_2^{A^\circ}) \right)^2 \\ & - 2c_{XO_2^A}^Q c_{XCO_2^A}^Q u(XO_2^A) u(XCO_2^A) \\ & - 2c_{XO_2^A}^Q c_{T_{ms}}^Q u(XO_2^A) u(T_{ms}) \\ & - 2c_{XO_2^A}^Q c_{\Delta p}^Q u(XO_2^A) u(\Delta p) \\ & + 2c_{XCO_2^A}^Q c_{T_{ms}}^Q u(XCO_2^A) u(T_{ms}) \\ & + 2c_{XCO_2^A}^Q c_{\Delta p}^Q u(XCO_2^A) u(\Delta p) \\ & + 2c_{T_{ms}}^Q c_{\Delta p}^Q u(T_{ms}) u(\Delta p) \end{aligned} \right]^{1/2} \quad (83)$$

2.3.5 Combined standard uncertainty on the depletion factor (ϕ)

The depletion factor in the exhaust duct is given by

$$\phi = \frac{X_{O_2}^{A^\circ} - X_{O_2}^A \frac{1 - X_{CO_2}^{A^\circ}}{(1 - X_{CO_2}^A)}}{X_{O_2}^{A^\circ} \left(1 - \frac{X_{O_2}^A}{(1 - X_{CO_2}^A)} \right)} \quad (84)$$

Taking the partial derivative to the different components x_i results in the corresponding sensitivity coefficients c_i :

$$c_{XO_2^A}^\phi \equiv \frac{\partial \phi}{\partial X_{O_2}^A} = \frac{1}{(1 - X_{CO_2}^A - X_{O_2}^A)} \left[\phi + \frac{(X_{CO_2}^{A^\circ} - 1)}{X_{O_2}^{A^\circ}} \right] \quad (85)$$

$$c_{XCO_2^A}^\phi \equiv \frac{\partial \phi}{\partial X_{CO_2}^A} = \frac{\phi - 1}{(1 - X_{CO_2}^A - X_{O_2}^A)} \quad (86)$$

$$c_{XO_2^{A^\circ}}^\phi \equiv \frac{\partial \phi}{\partial X_{O_2}^{A^\circ}} = \frac{(1 - X_{CO_2}^A) - (1 - X_{CO_2}^A - X_{O_2}^A) \phi}{(1 - X_{CO_2}^A - X_{O_2}^A) X_{O_2}^{A^\circ}} \quad (87)$$

$$c_{XCO_2^{A^\circ}}^\phi \equiv \frac{\partial \phi}{\partial X_{CO_2}^{A^\circ}} = \frac{X_{O_2}^A}{(1 - X_{CO_2}^A - X_{O_2}^A) X_{O_2}^{A^\circ}} \quad (88)$$

2.3.6 Combined standard uncertainty on the initial O₂-concentration ($X^{D^\circ O_2}$)

The initial concentration of oxygen in the exhaust duct is function of the relative humidity, temperature and absolute pressure and is given by

$$X_{O_2}^{D^\circ} = X_{O_2}^{A^\circ} \left[1 - \frac{\varphi}{100p} \exp \left\{ 23,2 - \frac{3816}{T_{room} - 46} \right\} \right] \quad (89)$$

Taking the partial derivative to the different components x_i results in the corresponding sensitivity coefficients c_i :

$$c_{X_{O_2}^{A^\circ}}^{X_{O_2}^{D^\circ}} \equiv \frac{\partial X_{O_2}^{D^\circ}}{\partial X_{O_2}^{A^\circ}} = \frac{X_{O_2}^{D^\circ}}{X_{O_2}^{A^\circ}} \quad (90)$$

$$c_{\varphi}^{X_{O_2}^{D^\circ}} \equiv \frac{\partial X_{O_2}^{D^\circ}}{\partial \varphi} = \frac{1}{\varphi} (X_{O_2}^{D^\circ} - X_{O_2}^{A^\circ}) \quad (91)$$

$$c_p^{X_{O_2}^{D^\circ}} \equiv \frac{\partial X_{O_2}^{D^\circ}}{\partial p} = -\frac{1}{p} (X_{O_2}^{D^\circ} - X_{O_2}^{A^\circ}) \quad (92)$$

$$c_{T_{room}}^{X_{O_2}^{D^\circ}} \equiv \frac{\partial X_{O_2}^{D^\circ}}{\partial T_{room}} = \left(\frac{3816}{(T_{room} - 46)^2} \right) (X_{O_2}^{D^\circ} - X_{O_2}^{A^\circ}) \quad (93)$$

and to the combined standard uncertainty

$$u(X_{O_2}^{D^\circ}) = \sqrt{\left(c_{X_{O_2}^{A^\circ}}^{X_{O_2}^{D^\circ}} u(X_{O_2}^{A^\circ}) \right)^2 + \left(c_{\varphi}^{X_{O_2}^{D^\circ}} u(\varphi) \right)^2 + \left(c_p^{X_{O_2}^{D^\circ}} u(p) \right)^2 + \left(c_{T_{room}}^{X_{O_2}^{D^\circ}} u(T_{room}) \right)^2} \quad (94)$$

Since the uncertainty contribution to the HRR is low it can be neglected and will be set to zero.

2.3.7 Combined standard uncertainty on the volume flow rate (V_{D298})

The volume flow rate - referenced to 298 K - in the exhaust duct is given by

$$V_{D298}(t) = cA \frac{k_t}{k_p} \sqrt{\frac{\Delta p(t)}{T_{ms}(t)}} \quad (95)$$

Taking the partial derivative to the different components x_i results in the corresponding sensitivity coefficients c_i :

$$c_c^{V_D} \equiv \frac{\partial \dot{V}_{D298}}{\partial c} = \frac{\dot{V}_{D298}}{c} \quad (96)$$

$$c_A^{V_D} \equiv \frac{\partial \dot{V}_{D298}}{\partial A} = \frac{\dot{V}_{D298}}{A} \quad (97)$$

$$c_{k_t}^{V_D} \equiv \frac{\partial \dot{V}_{D298}}{\partial k_t} = \frac{\dot{V}_{D298}}{k_t} \quad (98)$$

$$c_{k_p}^{V_D} \equiv \frac{\partial \dot{V}_{D298}}{\partial k_p} = -\frac{\dot{V}_{D298}}{k_p} \quad (99)$$

$$c_{\Delta p}^{V_D} \equiv \frac{\partial \dot{V}_{D298}}{\partial \Delta p} = \frac{1}{2} \frac{\dot{V}_{D298}}{\Delta p} \quad (100)$$

$$c_{T_{ms}}^{V_D} \equiv \frac{\partial \dot{V}_{D298}}{\partial T_{ms}} = -\frac{1}{2} \frac{\dot{V}_{D298}}{T_{ms}} \quad (101)$$

2.3.8 Combined standard uncertainty on the air density (ρ_{air})

The molecular weight of air is significantly affected by the presence of water vapour. Jones gives an extensive development and comes to the formula below for density of air as a function of temperature (K), pressure (Pa) and relative humidity (ϕ):

$$\rho_{air} = \left(\frac{0,0034847}{T} \right) \left[p - 0,003796 * 1,7526^{E+11} \phi \exp\left(\frac{-5315,56}{T} \right) \right] \quad (102)$$

Taking the partial derivative to the different components x_i results in the corresponding sensitivity coefficients c_i :

$$c_T^{\rho_{air}} \equiv \frac{\partial \rho_{air}}{\partial T} = \frac{1}{T^3} \left[-0,0034847 * p * 5315,56 + \rho_{air} T (5315,56 - T) \right] \quad (103)$$

$$c_p^{\rho_{air}} \equiv \frac{\partial \rho_{air}}{\partial p} = \frac{0,0034847}{T} \quad (104)$$

$$c_\phi^{\rho_{air}} \equiv \frac{\partial \rho_{air}}{\partial \phi} = -\frac{0,0034847}{T} 0,003796 * 1,7526^{E+11} \exp\left(\frac{-5315,56}{T} \right) \quad (105)$$

and to the combined standard uncertainty

$$u(\rho_{air}) = \sqrt{\left(c_T^{\rho_{air}} u(T) \right)^2 + \left(c_p^{\rho_{air}} u(p) \right)^2 + \left(c_\phi^{\rho_{air}} u(\phi) \right)^2} \quad (106)$$

2.3.9 Combined standard uncertainty on specimen heat release rate ($Q_{specimen}$)

The specimen HRR is defined as the global HRR minus the HRR contribution of the burner. The contribution of the burner is calculated as the mean HRR measured in the time interval 210 – 270 s.

The uncertainty contribution of the burner is given by

$$u(Q_{burner}) = \frac{1}{21} \sqrt{\sum_{i=210s}^{270s} [u(Q(t_i))]^2} \quad (107)$$

and of the specimen heat release rate by

$$u(Q_{specimen}) = \sqrt{u(Q_{burner})^2 + u(Q_{total})^2} \quad (108)$$

Despite the relatively short time interval (60 s; 21 measurements @ $f_s = 1/3$ s) to calculate the burner contribution, all 21 measurements will be considered independent from each other ($r = 0$) as discussed in 2.3.2.

2.3.10 Combined standard uncertainty on the average heat release rate (Q_{av})

The average heat release rate is based on a running average over 30 s of the specimen heat release rate contribution.

Although this filtering dampens out higher frequency events such as noise, thus removing the uncertainty contribution of noise, it can be argued that it hardly changes anything to the global uncertainty so that $u(Q_{av}) \cong u(Q_{specimen})$.

As discussed in 2.3.2 however, the measurements to calculate this running average are assumed to be independent.

2.3.11 Combined standard uncertainty on FIGRA

The combined standard uncertainty on FIGRA is composed of the uncertainty related to the average HRR $u(Q_{av})$ and the uncertainty related to the time elapsed for reaching this HRR level $u(t)$. Since the value $Q_{av}(t)$ could be reached anywhere in the interval $[t - t_s/2 ; t + t_s/2]$, the uncertainty distribution on 't' will be assumed rectangular with a resulting standard uncertainty

$$u(t) = \frac{t_s}{2\sqrt{3}} = \frac{\sqrt{3}}{2} \quad (109)$$

The uncertainty on FIGRA now becomes

$$u(FIGRA) = \frac{1}{t - 300} \sqrt{(1000 \cdot u(Q_{av}))^2 + (FIGRA \cdot u(t))^2} \quad (110)$$

2.3.12 Combined standard uncertainty on THR600s

The combined standard uncertainty on the total heat release in the first 600 s of the test will be estimated out of

$$u(THR_{600s}) = \frac{3}{1000} \sqrt{\sum_{300s}^{900s} (u(Q_{specimen}))^2} \quad (111)$$

The assumption is that this time interval includes enough variation to justify the assumption of independent measurements.

2.3.13 Combined standard uncertainty on the volume flow (V(t))

$$V(t) = V_{298}(t) \frac{T_{ms}(t)}{298}$$

$$u(V(t)) = u(V_{298}(t)) \quad (112)$$

since the square root $T_{ms}(t)$ is either in the numerator for $V_{298}(t)$ or the denominator for $V(t)$.

2.3.14 Combined standard uncertainty on the smoke production rate (SPR)

$$SPR_{total}(t) = \frac{V(t)}{L} \left[\frac{\bar{I}(30s...90s)}{I(t)} \right] \quad (113)$$

Taking the partial derivative to the different components x_i results in the corresponding sensitivity coefficients c_i

$$c_V^{SPR_{total}} \equiv \frac{\partial SPR_{total}}{\partial V} = \frac{SPR_{total}}{V} \quad (114)$$

$$c_L^{SPR_{total}} \equiv \frac{\partial SPR_{total}}{\partial L} = -\frac{SPR_{total}}{L} \quad (115)$$

$$c_{\bar{I}}^{SPR_{total}} \equiv \frac{1}{I} \frac{V}{L} \frac{I}{\bar{I}} = \frac{V}{L \cdot \bar{I}} \quad (116)$$

$$c_I^{SPR_{total}} \equiv -\frac{\bar{I}}{I^2} \cdot \frac{V}{L} \cdot \frac{I}{\bar{I}} = -\frac{V}{L \cdot I} \quad (117)$$

and to the combined standard uncertainty

$$u(SPR_{total}) = \sqrt{\left(c_V^{SPR_{total}} u(V)\right)^2 + \left(c_L^{SPR_{total}} u(L)\right)^2 + \left(c_{\bar{I}}^{SPR_{total}} u(\bar{I})\right)^2 + \left(c_I^{SPR_{total}} u(I)\right)^2} \quad (118)$$

2.3.15 Combined standard uncertainty on specimen smoke production rate (SPR)

The specimen SPR is defined as the total SPR minus the SPR contribution of the burner. The contribution of the burner is calculated as the mean SPR measured in the time interval 210 – 270 s.

The uncertainty contribution of the burner is given by

$$u(SPR_{burner}) = \frac{1}{21} \sqrt{\sum_{i=210s}^{270s} [u(SPR_{total})]^2} \quad (119)$$

and of the specimen heat release rate by

$$u(SPR_{specimen}) = \sqrt{u(SPR_{burner})^2 + u(SPR_{total})^2} \quad (120)$$

Despite the relatively short time interval (60 s; 21 measurements @ fs = 1/3 s) to calculate the burner contribution, all 21 measurements will be considered independent from each other (r = 0) as discussed in 2.3.2.

2.3.16 Combined standard uncertainty on the average smoke production rate (SPR_{av})

The average SPR is based on a running average over 60 s of the specimen SPR contribution.

Although this filtering dampens out higher frequency events such as noise, thus removing the uncertainty contribution of noise, it can be argued that it hardly changes anything to the global uncertainty so that $u(SPR_{av}) \cong u(SPR_{specimen})$.

As discussed in 2.3.2 however, the measurements to calculate this running average are assumed to be independent.

2.3.17 Combined standard uncertainty on SMOGRA

The combined standard uncertainty on SMOGRA is composed of the uncertainty related to the average SPR $u(SPR_{av})$ and the uncertainty related to the time elapsed for reaching this SPR level $u(t)$. Since the value $SPR_{av}(t)$ could be reached anywhere in the interval $[t - t_s/2; t + t_s/2]$, the uncertainty distribution on 't' will be assumed rectangular with a resulting standard uncertainty

$$u(t) = \frac{t_s}{2\sqrt{3}} = \frac{\sqrt{3}}{2} \quad (121)$$

The uncertainty on SMOGRA now becomes

$$u(\text{SMOGR}_A) = \frac{1}{t-300} \sqrt{(10000 \cdot u(\text{SPR}_{av}))^2 + (\text{SMOGR}_A \cdot u(t))^2} \quad (122)$$

2.3.18 Combined standard uncertainty on TSP600s

The combined standard uncertainty on the total smoke production in the first 600 s of the test will be estimated from

$$u(\text{TSP}_{600s}) = \frac{3}{1000} \sqrt{\sum_{300s}^{900s} (u(\text{RSP}_{\text{specimen}}))^2} \quad (123)$$

The assumption is that this time interval includes enough variation to justify the assumption of independent measurements.

2.4 Confidence interval classification parameters

Out of the population of a product to be evaluated, three samples are randomly selected and the classification parameters estimated. The mean value of the population will be estimated by means of the average taken from the three samples.

To evaluate the confidence interval, some estimate of the standard deviation σ of the total population shall be made. The most obvious candidate is the sample standard deviation s . But the use of s introduces an additional source of unreliability, especially if the sample is small. To retain the confidence interval, the interval shall be widened. This is done by using the t distribution instead of the standard normal distribution. For a 95 % (two tails of 2,5 %) confidence interval the uncertainty is estimated by

$$t_{0,025} \frac{s}{\sqrt{n}} = 4,30 \frac{s}{\sqrt{n}} \quad (124)$$

Only three samples are used to estimate s . Therefore there are two degrees of freedom ($n - 1$) and $t_{0,025}$ becomes 4,30. For higher number of samples this value would reduce and ultimately approach 1,96 for an infinite number of samples. 's' is calculated as explained in 2.2.1.

The three values used to calculate the average classification parameter value have an uncertainty related to their measurement as discussed in 2.3. The uncertainty of the average value will be taken as the average of the uncertainties since – irrespective of the number of samples tested – the uncertainty related to the measurement remains.

As an example for FIGRA, the expanded uncertainty (95 % confidence interval) on the average classification parameter now becomes

$$U(\overline{\text{FIGRA}}) = \sqrt{1,96 \left(\frac{u(\text{FIGRA}(x_1)) + u(\text{FIGRA}(x_2)) + u(\text{FIGRA}(x_3))}{3} \right)^2 + \left(4,30 \frac{s}{\sqrt{3}} \right)^2} \quad (125)$$

to obtain the final statement

$$\Pr(\overline{X} - U(\overline{\text{FIGRA}}) < \mu < \overline{X} + U(\overline{\text{FIGRA}})) = 95\% \quad (126)$$

The probability that the 'true' FIGRA value lies in the interval $\overline{X} - U(\overline{\text{FIGRA}})$ to $\overline{X} + U(\overline{\text{FIGRA}})$ is 95 %.

The other classification parameters shall be calculated in an analogue way.

The following statement shall be included in the classification report:

The uncertainty calculation both includes the variation due to sampling and the variation due to the measurement and assumes that sampling is done randomly to truly represent the population. This is the responsibility of the certification body in the context of a System 1 Assessment and Verification of Constancy of Performance or of the manufacturer in the context of a System 3.

2.5 Standard uncertainty on the different components

2.5.1 Uncertainty on the data acquisition (DAQ)

Not only the measuring sensors contribute to the overall uncertainty, also the DAQ system introduces an uncertainty.

Based on a detailed uncertainty analysis of data acquisition systems on existing SBI's the following values in Table 2 may be taken by default. Other values may be taken only if proven by a detailed uncertainty analysis.

Table 2 — Default standard uncertainties associated with the DAQ system

Measurand	Range	Standard uncertainty
Temperature by means of K-type T/C	-50 °C - 1 250 °C	1,0 °C
Temperature by means of RTD (Pt-100)	0 - 150 Ω	0,12 Ω 0,3 K
Volt	0 - 10 V	6 mV
Current	0 - 20 mA	0,03 mA

2.5.2 Transient error

Due to the response times of the gas analysis system, the thermocouples and the differential pressure system, which are – or at least can be approximated by – first order systems with time constant τ , an error $e(t)$ for each component is introduced equal to

$$e(t) = \tau \frac{dy(t)}{dt}. \quad (127)$$

whereby $y(t)$ is the measured output.

Within TC127 WG4 TG4 – revision of the SBI standard – it was agreed to reduce the bandwidth of the SBI system (reduce highest frequency of interest) considering not relevant fast events and to further ignore the uncertainty related to it.

In order to do so, it is of primary importance that all laboratories have the same BW for their test facility. This is realized by actually measuring the response time of the different equipment and to mathematically adjust the response time to one common response time for all laboratories.

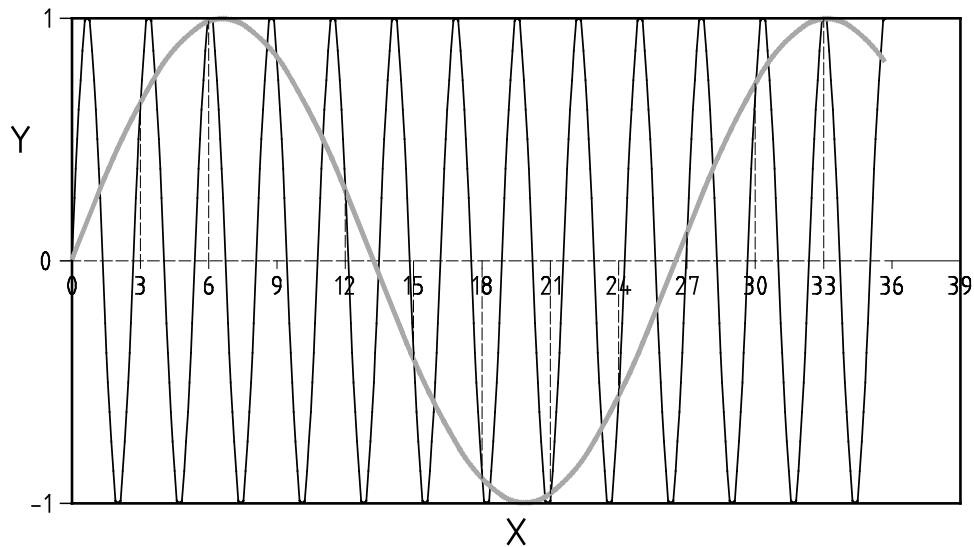
2.5.3 Aliasing error

One of the fundamental rules of discretization of signals is that the sampling frequency is at least twice the maximum frequency existing in the signal. If this rule is not respected, the reconstruction of the original analogue signal becomes impossible and spurious information is added to the digitized signal. This spurious information does not exist in the analogue part and is created by the sampling procedure. This effect is called aliasing.

Considering an oscillation of $f_k = 0,371$ Hz on the signal of an oxygen analyser and sampling with a frequency of $f_s = 1/3$ Hz, an apparent frequency f_0 will be measured whereby

$$f_0 = f_k - f_s \quad (128)$$

In this specific case $f_0 = 0,0377$ Hz ($T_0 = 26,5$ s), see Figure 4.



Key

- X time (s)
- Y amplitude
- $f(x)$
- sampled
- aliasing

Figure 4 — Example of aliasing effect

In general, all sines with frequency $f_k = f_0 + kf_s$ ($k = 0, 1, 2, \dots$) have the same value at the sampling intervals $t = nT_s$.

Within TC127 WG4 TG4 the decision was made to assume all measurement data to be free from aliasing.

2.5.4 Uncertainty on data synchronicity

There is also an uncertainty associated with the scan rate and time shifting of the data. In practice, the DAQ system often incorporates a multiplexing switching module that senses one data channel after the other. For high accuracy measurements, typical integration times, i.e. time required to do the actual measurement, is 1 PLC (Power Line Cycle = 20 ms @ 50 Hz). Adding to this the switching and stabilization time, the time elapsed between two consecutive measurement channels can easily reach 50 to 100 ms. This is dependent on other factors like the measurement range, whether the display is turned on or off, etc. In the SBI, the strict minimum of channels to be measured is nine, which makes that the time between the sensing of the first and the last channel can easily reach half a second.

Another reason why data might not be synchronized is because of delay times. In general, there is a delay time of several seconds (up to a maximum of 30 s is allowed in the standard) in between a change in HRR and the actual change in the measured gas concentration. Shifting of the data with n -times ($n = 0, 1, 2, \dots$) the sampling interval $n \cdot \Delta t$ only allows to partially eliminate the delay time.

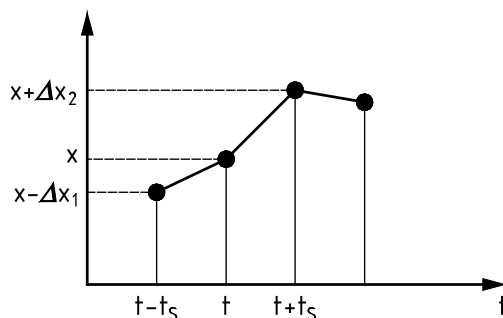


Figure 5 — Sampled signal at regular intervals

Assuming that the data signal in between consecutive measurements of a same channel varies linearly and assuming that the non-synchronicity is somewhere in the interval $\pm t_s/2$, a rectangular distribution applies with a width $\Delta x/2$. The associated standard uncertainty becomes

$$u(\Delta t) = \frac{\Delta x}{2\sqrt{3}} \quad (129)$$

In order to keep symmetry in the uncertainty interval, the variation Δx is set equal to the maximum variation forward (Δx_2) or backwards (Δx_1) in time $\Delta x = \text{MAX}[\Delta x_1, \Delta x_2]$.

2.5.5 Uncertainty on the component E and E'

It has been established by Thornton [18] that most organic liquids and gases release a more or less constant net amount of heat per unit mass of oxygen consumed for complete combustion. In 1980 Hugget [12] rediscovered this study and showed that this is also true for most plastics and solid materials used in buildings. He concluded that the heat release from fires involving conventional organic fuels is $E = 13,1$ kJ per gram of oxygen consumption, and this with an accuracy of $\pm 5\%$ or better. He also concluded that incomplete combustion and variation in fuel have only a minor effect on this result.

For the uncertainty analysis distinction is made between the case where the chemical composition of the fuel is known, and the case where it is not known beforehand what is being burnt. The standard uncertainties for the different fuel types is given in Table 3 [11]:

Table 3 — Uncertainty related to E'

Substance	Purity (%) SBI standard	E' (MJ/m ³ O ₂) SBI standard	Estimated st. unc. E' (%)
Propane [1]	≥ 95	16,8	0,28
n-Heptane [1]	≥ 99	16,5	0,23
Unknown	-	17,2	0,44

Uncertainty on the components $X_{O_2}^A$

The oxygen concentration is by far the most critical measurand when calculating the HRR using the oxygen depletion technique. Unfortunately, manufacturers of paramagnetic oxygen analysers typically report accuracies in the range 0,5 - 1,0 % [19] of its full scale deflection, which is an order of magnitude higher than what is required by the standards [1] [2]. Enright [19] proposes to use the noise and drift over a 30 min period instead but this only gives an estimate of the standard uncertainty for an analyser working around its calibration point.

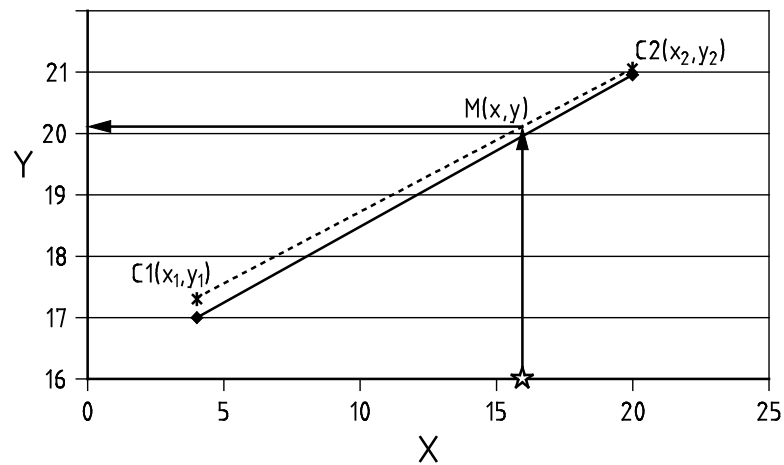
In 'reaction to fire' tests like the SBI [1] and the cone calorimeter however, the working range is between 17 Vol % and 21 Vol %. In the Room Corner [2] test this range is even expanded to 0 - 21 Vol %.

The overall uncertainty associated with the oxygen concentration is very much related to the gas analyser used, the gas preparation and the test and calibration procedure.

The calibration procedure used in the SBI is as follows:

1. Every testing morning, calibration gas is fed into the instrument: O_2 ($X_{O_2}^{CG}$ Vol%), CO_2 ($X_{CO_2}^{CG}$ Vol%) and the balance gas Nitrogen. When the analyser reaches steady-state, the output signal (C1) is recorded. This is done for all analysers present (O_2 , CO_2 , CO , ...). In the SBI only O_2 and CO_2 concentrations are measured.
2. Prior to every test, when the sample gas is still composed of ambient air, the output signals (C2) of the analysers are recorded. Those values correspond to the following gas concentrations O_2 (20,95 Vol%), CO_2 (0,04 Vol%), CO (0,00 Vol%). This is true because practically all water is removed from the gas sample prior to the analysis and these concentrations apply for dry air. By calibrating for C2 prior to every single test, the uncertainty related to C2 can be minimized to a strict minimum. Alternatively, a second calibration gas (synthetic air) can be used.

Any measured new output signal relates to a certain gas concentration which can be found by means of linear interpolation between points C1 and C2.



Key
 X Signal (mA)
 Y X_{O_2} (Vol%)
 —◆— X_{O_2} (Vol%)
 --*-- calibration

Figure 6 — Calibration principle gas analyser

The gas concentration y is derived out of calibrations $C1(x_1, y_1)$ and $C2(x_2, y_2)$, and a measurement signal x . The values y_1 and y_2 are gas concentrations. The values x_1 and x_2 are the corresponding signal outputs.

$$y = y_1 + \frac{(y_2 - y_1)}{(x_2 - x_1)}(x - x_1) \tag{130}$$

The combined standard uncertainty related to y is given by

$$u(y) = \frac{1}{(x_2 - x_1)} \sqrt{[u(y_1)(x_2 - x)]^2 + [u(y_2)(x - x_1)]^2 + [u(x)(y_2 - y_1)]^2 + \left[u(x_1) \frac{(y_2 - y_1)(x - x_2)}{(x_2 - x_1)} \right]^2 + \left[u(x_2) \frac{(y_2 - y_1)(x - x_1)}{(x_2 - x_1)} \right]^2} \quad (131)$$

The uncertainty contributions on x , x_1 , x_2 , y_1 , y_2 , are obtained from Tables 4 and 5. The entry fields in yellow are data that comes directly from the SBI noise and drift calibration. The input fields in blue are specific for each type of gas analyser and should be modified correspondingly. Two examples are given for two different measuring ranges of a same analyser.

Uncertainty on the component $X_{CO_2}^A$

The carbon dioxide concentration in the combustion gases is measured by means of an infrared analyser. Compared to the oxygen concentration measurement, the sensitivity coefficient for carbon dioxide is much lower. Uncertainty on CO_2 will therefore influence the HRR less than uncertainty on O_2 . Treatment is similar as for O_2 and an example is shown in Table 6.

Table 4 — Example of uncertainty contributions on x_1 , x_2 , y_1 , y_2 for a measuring range of 17 to 21 Vol% O₂

Oxygen analyser		Measuring range	4 Vol%		Probability distribution	Standard uncertainty (ppm)
Measuring range (MR)	Specification	Expected variations	Units	Uncertainty (ppm)	Coverage factor	Standard uncertainty (ppm)
17-21 Vol%						
Uncertainty contribution measurement $u(x)$						
Ambient air temperature	<0.5% on MR/10K	2	K	40	3	13
Pressure measuring gas	<0.2% on MR/1% pressure variance	100	Pa	8	3	3
Power supply	<0.1% on MR for +10%			40	3	13
Linearity	Linear					
Noise	SBI Noise & Drift calibration			27	1	27
Drift (half an hour)	Drift actual test according to SA.3.2			58	1	33
$u(M)$						47
Uncertainty contribution calibration point two $u(x_2)$						
Noise	SBI Noise & Drift calibration	(20 samples)		27	1	6
$u(C_2)$						6
Uncertainty contribution calibration point one $u(x_1)$						
Drift (considered as max-min over a period of 10 hours; 95% confidence interval)						
Ambient air temperature	<0.5% on MR/10K	5	K	100	3	33
Pressure measuring gas	<0.2% on MR/1% pressure variance	1000	Pa	80	3	27
Power supply	<0.1% on MR for +10%			40	3	13
Linearity	Linear					
Noise	SBI Noise & Drift calibration			27	1	27
Drift (one working day)	SBI Noise & Drift calibration			37	1	21
$u(C_1)$						56
Uncertainty contribution calibration gas one $u(y_1)$						
Calibration gas	0.02 Vol% ABS (17Vol%)			200	2	100
Uncertainty contribution calibration gas two $u(y_2)$						
Dry ambient air	20.95 Vol% by definition			0	1	0

Table 5 — Example of uncertainty contributions on x , x_1 , x_2 , y_1 , y_2 for a measuring range of 0 to 21 Vol% O_2

Oxygen analyser		Measuring range		21 Vol%		Probability distribution		Standard uncertainty (ppm)	
Measuring range (MR)	Specification	Expected variations	Units	Uncertainty (ppm)	Coverage factor	Probability distribution	Standard uncertainty (ppm)		
Uncertainty contribution measurement $u(x)$									
Ambient air temperature	< 0.5% on MR/10K	2	K	210	3	normal	70		
Pressure measuring gas	< 0.2% on MR/1% pressure variance	100	Pa	42	3	normal	14		
Power supply	< 0.1% on MR for +10%			210	3	normal	70		
Linearity	Linear								
Noise	SBI Noise & Drift calibration			27	1	normal	27		
Drift (half an hour)	Drift actual test according to SA.3.2			58	1	rectangular	33		
$u(M)$							109		
Uncertainty contribution calibration point two $u(x_2)$									
Noise	SBI Noise & Drift calibration	(20 samples)		27	1	normal	6		
$u(C_2)$							6		
Uncertainty contribution calibration point one $x(x_1)$									
Drift (considered as max-min over a period of 10 hours; 95% confidence interval)									
Ambient air temperature	< 0.5% on MR/10K	5	K	525	3	normal	175		
Pressure measuring gas	< 0.2% on MR/1% pressure variance	1000	Pa	420	3	normal	140		
Power supply	< 0.1% on MR for +10%			210	3	normal	70		
Linearity	Linear								
Noise	SBI Noise & Drift calibration			27	1	normal	27		
Drift (one working day)	SBI Noise & Drift calibration			37	1	rectangular	21		
$u(C_1)$							237		
Uncertainty contribution calibration gas one $u(y_1)$									
Calibration gas	0.02 Vol% ABS (1.7Vol%)			200	2	normal	100		
Uncertainty contribution calibration gas two $u(y_2)$									
Dry ambient air	20.95 Vol% by definition			0	1		0		

Table 6 — Example of uncertainty contributions on x , x_1 , x_2 , y_1 , y_2 for a measuring range of 0 to 4 Vol% CO₂

Carbon dioxide analyser		Measuring range		4 Vol%		Probability distribution		Standard uncertainty (ppm)	
Measuring range (MR)	Specification	Expected variations	Units	Uncertainty (ppm)	Coverage factor	Probability distribution	Standard uncertainty (ppm)		
Uncertainty contribution measurement $u(x)$									
Ambient air temperature	<1% on MR/10K	2	K	80	3	normal	27		
Pressure measuring gas	<0.15% on MR/1% pressure variance	100	Pa	6	3	normal	2		
Power supply	<0.1% on MR for +-10%			40	3	normal	13		
Linearity	<0.5% on MR			200	3	normal	67		
Noise	SBI Noise & Drift calibration			39	1	normal	39		
Drift (half an hour)	Drift actual test according to SA.3.2			25	1	rectangular	14		
$u(M)$							84		
Uncertainty contribution calibration point two $u(x_2)$									
Noise	SBI Noise & Drift calibration	(20 samples)		39	1	normal	9		
$u(C_2)$							9		
Uncertainty contribution calibration point one $u(x_1)$									
Drift (considered as max-min over a period of 10 hours; 95% confidence interval)									
Ambient air temperature	<1% on MR/10K	5	K	100	3	normal	33		
Pressure measuring gas	<0.15% on MR/1% pressure variance	1000	Pa	60	3	normal	20		
Power supply	<0.1% on MR for +-10%			40	3	normal	13		
Linearity	non applicable (calibration point)								
Noise	SBI Noise & Drift calibration			39	1	normal	39		
Drift (one working day)	SBI Noise & Drift calibration			36	1	rectangular	21		
$u(C_1)$							60		
Uncertainty contribution calibration gas one $u(y_1)$									
Calibration gas	0.5% REL (3.5Vol%)			175	2	normal	88		
Uncertainty contribution calibration gas two $u(y_2)$									
Dry ambient air	0.04 Vol% by definition			0	1		0		

2.5.6 Uncertainty on the component φ

The relative humidity φ together with the barometric pressure and the room temperature are used to calculate the humidity in ambient air X_{H20}^0 . The SBI [1] standard prescribes the use of a relative humidity sensor 'having an accuracy of $\pm 5\%$ within the range 20 % to 80 %'.

An example of how to calculate the uncertainty contribution is given below.

Suppose a hygrometer has a bias not more than 2,1 % in the range 20 % to 80 % with a standard deviation not more than 0,25 %. In other words, the 'trueness' of the instrument is to within 2,1 % and the standard deviation on the precision is not more than 0,25 %.

Assuming a rectangular distribution with width 2,1 %, the standard uncertainty related to trueness becomes 1,21 %. Combining this with the uncertainty on the measurement and the uncertainty of the data acquisition system (DAQ), the overall standard uncertainty is estimated to be 1,25 % as shown in Table 7.

Table 7 — Estimated uncertainty contribution of a hygrometer (example)

Quantity X_i	Estimate x_i (range)	'Uncertainty'	Probability distribution	Standard uncertainty $u(x_i)$	Sensitivity coefficient c_i	Uncertainty contribution $u_i(y)$
φ_{bias}	20 - 80 %	2,1 %	rectangular	1,21 %	1,0	1,21 %
$\varphi_{\text{st.dev.}}$	20 - 80 %	0,25 %	normal	0,25 %	1,0	0,25 %
φ_{DAQ}	20 - 80 %	0,028 mA	normal	0,18 %	1,0	0,18 %
φ	20 - 80 %					1,25 %

The sensitivity coefficient at a relative humidity concentration of 50 % is three times lower than the sensitivity coefficient of the room temperature. The standard uncertainty is estimated to be 1,25 %.

2.5.7 Uncertainty on the component p_{atm}

The barometric pressure together with the relative humidity φ and the room temperature are used to calculate the humidity in ambient air X_{H20}^0 . The SBI [1] standard prescribes the use of a barometric pressure sensor 'having an accuracy of ± 200 Pa'.

Comparing the sensitivity coefficients of the barometric pressure measurement with the humidity measurement (2.3.6; $\varphi = 50\%$, $P = 101\,325$ Pa) a variation of 1 % on φ causes an equal variation on the heat release as a variation of 2 000 Pa (20 mbar) on p_{atm} .

The uncertainty on p_{atm} is therefore considered to be negligible.

2.5.8 Uncertainty on the component T_{room}

The room temperature together with the relative humidity φ and the barometric pressure are used to calculate the humidity in ambient air X_{H20}^0 . The SBI [1] standard prescribes the use of a K-type thermocouple in accordance with EN 60584-1 [20] with a diameter of (2 ± 1) mm.

The sensitivity coefficients of the temperature measurement is a factor 3 higher than the sensitivity coefficient for the humidity measurement (2.3.6; $\varphi = 50\%$, $t = 298$ K).

— Tolerance on a new thermocouple t_t :

The tolerance allowed on new Class 2 thermocouples according to EN 60584-2 [4] is:

- $\pm 2,5$ °C in the range -40 °C to 333 °C

- $\pm 0,0075 t$ (t in $^{\circ}\text{C}$) in the range 333°C to $1\,200^{\circ}\text{C}$

— Effect of ageing t_a :

Since K-type thermocouples are subject to calibration changes on temperature cycling to 500°C or above (like in fire resistance tests), and since no temperatures above 400°C are to be expected in the SBI, ageing effects will be considered to be negligible.

— Effect of data acquisition and extension wires t_{DAQ} :

The uncertainty related to the data acquisition, extension wires and connectors is estimated (2.5.1) to be $1,0\text{ K}$.

— Radiation error t_r :

Since the thermocouple is supposed to measure the ambient room temperature the radiation error is considered to be negligible.

However, care should be taken that the thermocouple does not see hot surfaces like furnaces, heaters, etc. nor that it is exposed to direct sunlight. (add remark in SBI standard)

— Velocity error t_v :

The air velocities at the height of the probe are estimated to be smaller than 1 m/s . No velocity error needs therefore to be introduced.

— Conduction error t_c :

Negligible.

— Transient error t_{τ} :

Negligible.

Table 8 — Room temperature measurement by means of thermocouple

Quantity X_i	Estimate x_i (range)	'Uncertainty'	Probability distribution	Standard uncertainty $u(x_i)$	Sensitivity coefficient c_i	Uncertainty contribution $u_i(y)$
t_t	0°C	$2,5^{\circ}\text{C}$	rectangular	$1,44^{\circ}\text{C}$	1,0	$1,44^{\circ}\text{C}$
t_a	0°C	0°C	-	0°C	1,0	0°C
t_{DAQ}	0°C	$1,0^{\circ}\text{C}$	normal	$1,0^{\circ}\text{C}$	1,0	$1,0^{\circ}\text{C}$
t_r	0°C	0°C	-	0°C	1,0	0°C
t_v	0°C	0°C	-	0°C	1,0	0°C
t_c	0°C	0°C	-	0°C	1,0	0°C
t_{τ}	0°C	0°C	-	0°C	1,0	0°C
T	0°C					$1,8^{\circ}\text{C}$

The use of class 1 thermocouples:

- $\pm 1,5^{\circ}\text{C}$ in the range -40°C to 375°C

- $\pm 0,004$ t (t in °C) in the range 375 °C to 1 000 °C

would reduce the uncertainty contribution to 1,3 °C.

2.5.9 Uncertainty on the component α

The expansion factor α is defined as the ratio of the number of moles of combustion products to the number of moles of dry air fully depleted of its oxygen. It is related to β by

$$\alpha = 1 + 0,2095(\beta - 1) \quad (132)$$

where β is defined as the ratio of the moles of combustion products formed to the moles of oxygen consumed. As an example the expansion factor α of propane is calculated as



$$\alpha = 1 + 0,2095\left(\frac{3+4}{5} - 1\right) = 1,0838 \quad (134)$$

If the fuel composition and the reaction chemistry is known, β and α are known.

It is assumed that the nitrogen contained in the fuel is released as molecular nitrogen. (Temperatures in building fires are usually not high enough to produce noticeable amounts of nitrogen oxides.)

As the composition of the fuel is usually not known, some average value has to be used for α . Complete combustion of pure carbon (no H₂O formation) results in $\alpha = 1$, while complete combustion of hydrogen (no CO₂ formation) results in $\alpha = 1,21$. A recommended value in the literature [10] is $\alpha = 1,105$, which is correct for methane. This is also the value that has been adopted in most fire test standards.

Table 9 — Uncertainty on the expansion factor

Quantity X_i	Estimate x_i (range)	'Uncertainty'	Probability distribution	Standard uncertainty $u(x_i)$	Sensitivity coefficient c_i	Uncertainty contribution $u_i(y)$
α	1,105	0,105	rectangular	0,061	1,0	0,061
α	1,105					0,061

Assuming a rectangular distribution from $\alpha = 1$ to 1,21, the standard deviation on α is equal to 5,5 %.

2.5.10 Uncertainty on the component c

The component c is given by the following formula and is – by the standard – defined to be 22,4

$$c = \sqrt{\frac{2T_{298}}{\rho_{298}}} = 22,4 \quad (135)$$

with corresponding uncertainty estimate ($T_{298} = 298,15$ K):

$$u(c) = \sqrt{\left(\frac{c \cdot u(\rho)}{2\rho}\right)^2} = \frac{c \cdot u(\rho)}{2\rho} \quad (136)$$

This introduces an error due to the fact that it is assumed that the gas flowing in the exhaust duct has a density equal to dry air. The molecular weight of air is however significantly affected by the presence of

water vapour. Jones gives an extensive development and comes to the following formula for density of air as a function of temperature (K), pressure (Pa) and relative humidity (ϕ).

$$\rho_{air} = \left(\frac{0,0034847}{T} \right) (p - 0,003796 p_s \phi) \quad (137)$$

where the saturation pressure is related to temperature by

$$p_s = (1,7526E + 11) e^{\left(\frac{-5315,56}{T} \right)} \quad (138)$$

Since the ambient temperature, the barometric pressure and the relative humidity are used in the calculation of the depletion factor ϕ they are readily available to correct for the effect of moisture content on the c-factor through the air density.

The 'constant' c does vary with barometric pressure and relative humidity and introduces a standard uncertainty of $\pm 0,7\%$ ($c = 22,4 \pm 0,16$). This uncertainty can be reduced by actually calculating the c-factor. The uncertainty contribution $u(c)$ may then be taken as $u(c) = 0,074$ ($c = 22,4 \pm 0,074$) as illustrated in Table 10.

Table 10 — Uncertainty contribution if c is calculated (T_{room} via thermocouple)

Quantity X_i	Estimate x_i (range)	'Uncertainty '	Probability distributio n	Standard uncertainty $u(x_i)$	Sensitivit y coefficien t c_i	Uncertainty contribution $u_i(y)$
T	293 K	$\pm 1,8$ K	normal	$\pm 1,8$ K	$-4,41E-03$	$\pm 0,0079$
ϕ	50 %	$\pm 1,23$ %	normal	$\pm 1,23$ %	$-1,046E-04$	$\pm 0,000129$
p	101 325 Pa	± 100 Pa	normal	± 100 Pa	$1,19E-05$	$\pm 0,00119$
ρ_{air}	1,200 kg/m ³			$\pm 0,008$ kg/m ³	-9,284	$\pm 0,074$
c	22,282					$\pm 0,074$

Sensitivity coefficients calculated around the estimate values.

2.5.11 Uncertainty on the component A and L

The cross sectional area of the exhaust duct is governed by the roundness and the diameter. The actual diameter of the duct should be measured to within $\pm 0,5$ mm at different angles.

Also soot deposit might change the cross sectional area of the duct. Measurements in seven laboratories have shown that soot deposit varied considerably by lab. Based on those measurements, it was agreed that the roundness of the duct falls to within $\pm 0,5$ mm (rectangular interval) of the nominal value and that the soot deposit is agreed to fall within the range $1,0 \pm 1,0$ mm (95 % confidence interval).

In addition, due to the nature of the testing, the duct wall temperature will increase over the test, resulting in a higher cross sectional area. The steel used for the inner duct is stainless steel 304 (18/8 steel) which has a linear expansion coefficient of 1,7 mm per m and per 100 °C temperature rise.

From experience, the maximum temperature rise of the inner duct is found to be of the order of 85 °C over a test (case heptane calibration). A triangular distribution will further be assumed.

In order to remove a bias¹, the measured diameter will be reduced with 1 mm (example: 315 – 1 = 314).

Table 11 — Standard uncertainty related to the cross section area

Quantity Xi	Estimate xi (range)	'Uncertainty'	Probability distribution	Standard uncertainty u(xi)*	Sensitivity coefficient ci	Uncertainty contribution ui(y)*
D _{radius}	0,314 m	± 0,5E-03 m	rectangular	± 0,289E-03 m	0,495	± 0,143E-03
D _{soot}	0,314 m	± 1,0E-03 m	95 % conf.	± 0,500E-03 m	0,495	± 0,248E-03
D _{temperature}	0,314 m	± 0,228E-03 m	Triangular (asymm.)	± 0,107E-03 m	0,495	± 0,053E-03
A (m ²)	77,44E-03					± 0,29E-03

The length of the light path through the exhaust duct is equal to D_{radius} as shown above.

2.5.12 Uncertainty on the component q_{gas}

q_{gas} represents the 'theoretical' heat release rate as obtained out of: 1) a mass flow measurement of propane gas that feeds the burner and 2) the lower heat of combustion of propane gas.

$$q_{gas}(t) = \Delta h_{c,eff} m_{gas}(t) \quad (139)$$

The value of q_{gas} when the burner is running at a 30 kW level is used to calibrate the test instrument (k_t-factor, see 2.5.15).

The lower heat of combustion of commercial grade propane and its standard uncertainty are estimated at (46 340 ± 50) kJ/kg.

The global uncertainty related to the mass flow measurement is taken as ± 1 % of the measurement value plus ± 0,2 % of the full scale (or ± 1 % of the full scale, whichever is the lowest) although the manufacturers often specify lower values [11]. The resulting estimated standard uncertainty is 0,51 kW for the burner running at 30 kW (1,7 %). This requires linearization or a polynomial calibration of the mass flow controller.

2.5.13 Uncertainty on the component k_t

2.5.13.1 Introduction

The velocity profile correction factor k_t accounts for the fact that the velocity measured by means of a bi-directional probe on the axis of the exhaust duct is a factor k_t higher than the mean velocity in the duct. The k_t factor used in the standard is defined as the average of three independent calibrations being the 'step calibration' (k_{t,qgas}), the 'heptane calibration' (k_{t,qheptane}) and the 'velocity profile measurement' (k_{t,v}).

k_t is directly proportional to the volume flow and therefore to the heat release rate and its derived parameters FIGRA and THR600, and to the SPR and its derived parameters SMOGRA and TSP600.

In medium to large scale heat release testing equipment, the k_t factor is used to correct for all measurement errors, and this at the moment of calibration. One way to 'calibrate' the test equipment is to burn a combustible with a well-known heat of combustion and to fit the k_t factor so that the

¹ There will always be some soot present with an assumed mean thickness of 0,5 mm thus reducing the effective duct diameter with 1 mm.

measured heat release corresponds to the theoretic value. In the SBI the k_t factor is the mean value of three calibrations, two of which are based on the burning of a known combustible ($k_{t,qgas}$ and $k_{t,qheptane}$).

First the uncertainty related to k_t and its measurement and calculation procedure is estimated by determining the uncertainty on the three composing k_t factors.

Next, the intrinsic variation on k_t is estimated as described in [17].

2.5.13.2 Uncertainty on the component $k_{t,v}$

The velocity profile correction factor obtained out of a direct measurement of the velocities in some discrete points results in $k_{t,v}$. The measurements are taken at 90° intervals on 5 different radii (v_n ; $n = 1...5$) and at the centre position making use of a pitot tube or a hot wire anemometer. The profile factor $k_{t,v}$ is then:

$$k_{t,v} = \frac{1}{5} \sum_{n=1}^5 \frac{v_n}{v_c} \quad (140)$$

Taking the partial derivative to the different components x_i results in the corresponding sensitivity coefficients c_i :

$$c_1 \equiv \frac{\partial k_{t,v}}{\partial v_n} = \frac{1}{5v_c} = \frac{k_{t,v}}{\sum v_n} \quad (141)$$

$$c_2 \equiv \frac{\partial k_{t,v}}{\partial v_c} = -\frac{k_{t,v}}{v_c} \quad (142)$$

and to the combined standard uncertainty

$$u(k_{t,v}) = k_{t,v} \sqrt{\sum_i \left(\frac{u(v_i)}{\sum_n v_n} \right)^2 + \left(\frac{u(v_c)}{v_c} \right)^2} \quad (143)$$

The estimated uncertainty (see 2.2.2) on the velocity components for a 95 % confidence interval and 3 degrees of freedom (4 measurement positions; $t_{0,025} = 3,18$) shall be calculated. An example is given below:

Table 12 — Standard uncertainty related to $k_{t,v}$

Quantity X_i	Estimate x_i	Standard deviation s	Probability distribution	95 % confidence interval	Sensitivity coefficient c_i	Uncertainty contribution $u_i(y)$ [95 %]
v_1	7,00	1,132	t (d.f. = 3)	1,799	0,0198 $k_{t,v}$	0,0355 $k_{t,v}$
v_2	9,39	0,412	t (d.f. = 3)	0,655	0,0198 $k_{t,v}$ v	0,0129 $k_{t,v}$
v_3	10,62	0,531	t (d.f. = 3)	0,845	0,0198 $k_{t,v}$	0,0167 $k_{t,v}$
v_4	11,25	0,180	t (d.f. = 3)	0,287	0,0198 $k_{t,v}$	0,0057 $k_{t,v}$
v_5	12,37	0,223	t (d.f. = 3)	0,355	0,0198 $k_{t,v}$	0,0070 $k_{t,v}$
v_c	12,39	0,636	t (d.f. = 3)	1,011	-0,0807 $k_{t,v}$	-0,0816 $k_{t,v}$
$k_{t,v}$	$k_{t,v} = 0,817$					0,092 $k_{t,v}$

which finally results in an uncertainty of 9,2 % for a 95 % confidence interval.

The uncertainty related to the position of the measurement head (estimated accurate to within 0,5 mm) for the outer radius where the velocity gradient is highest, is estimated at 1,2 % based on the theoretical velocity profile as proposed by Schlichting [9] at a Reynolds number of around 160 000. This means that this uncertainty, in comparison with the values in Table 12, can be neglected.

Using the last N calibrations instead of just the recent one – in fact taking the mean of N measurements considered to be independent – could further reduce the standard uncertainty for the population mean by a factor \sqrt{N} .

2.5.13.3 Uncertainty on the component $k_{t,qgas}$

The component $k_{t,qgas}$ follows out of a so-called ‘Step Calibration’ which consists of burning a known combustible, in this case propane, with a well-known heat of combustion and to fit the k_t factor until the measured heat release rate, Q_{step} , corresponds to the theoretic value, q_{gas} .

$$k_{t,qgas} = k_t \frac{q_{gas}}{Q_{step}} \quad (144)$$

whereby k_t is the flow profile factor used for the calculation of Q_{step} . Both the nominator and denominator on the right hand side of the formula contain k_t , so k_t drops out and thus the uncertainty on k_t can be set to zero.

The uncertainty on Q (2.3.4) thus reduces slightly. This is also because the fuel is known namely ‘commercial grade propane’.

The combined standard uncertainty on $k_{t,qgas}$ is estimated by:

$$u(k_{t,qgas}) = k_{t,qgas} \sqrt{\left(\frac{u(\dot{q}_{gas})}{\dot{q}_{gas}}\right)^2 + \left(\frac{u(Q_{step})}{Q_{step}}\right)^2} \quad (145)$$

Using the last N calibrations instead of just the recent one – in fact taking the mean of N measurements considered to be independent – could further reduce the standard uncertainty for the population mean by a factor \sqrt{N} .

2.5.13.4 Uncertainty on the component $k_{t,qheptane}$

The component $k_{t,heptane}$ follows out of a so called ‘Heptane Calibration’ which consists of burning a given quantity of a known combustible, in this case heptane, with a well-known heat of combustion and to fit the k_t factor until the measured total heat release, $Q_{heptane}$, corresponds to the theoretic value, $q_{heptane}$.

$$k_{t,heptane} = k_t \frac{q_{heptane}}{Q_{heptane}} = k_t \frac{\Delta h_{c,heptane} m_{heptane}}{Q_{heptane}} \quad (146)$$

whereby k_t is the flow profile factor used for the calculation of $Q_{heptane}$. Both the nominator and denominator on the right hand side of the formula contain k_t , so k_t drops out and thus the uncertainty on k_t can be set to zero.

The uncertainty on $Q_{heptane}$ (2.3.4) thus reduces slightly. This is also because the fuel is known namely ‘99 % pure heptane’.

$$Q_{heptane} = \sum_{i=180s}^{end} \dot{Q}_{heptane}^i t_s \quad (147)$$

$$u(Q_{hep\ tan\ e}) = \sqrt{\sum_{i=180s}^{end} [u(Q_{hep\ tan\ e}^i) t_s]^2} \quad (148)$$

The combined standard uncertainty on $k_{t,heptane}$ is estimated out of

$$u(k_{t,hep\ tan\ e}) = k_{t,hep\ tan\ e} \sqrt{\left(\frac{u(\Delta h_{c,hep\ tan\ e})}{\Delta h_{c,hep\ tan\ e}}\right)^2 + \left(\frac{u(m_{hep\ tan\ e})}{m_{hep\ tan\ e}}\right)^2 + \left(\frac{u(Q_{hep\ tan\ e})}{Q_{hep\ tan\ e}}\right)^2} \quad (149)$$

whereby $\Delta h_{c,heptane} = (44\ 550 \pm 50)$ kJ/kg and $m_{heptane} = (2,840 \pm 0,001)$ kg.

Using the last N calibrations instead of just the recent one – in fact taking the mean of N measurements considered to be independent – could further reduce the standard uncertainty for the population mean by a factor \sqrt{N} .

Since k_t is calculated as the average of three values $k_{t,v}$, $k_{t,qgas}$ and $k_{t,qheptane}$, which are independent measurements, the standard uncertainty on k_t reduces to

$$u(k_t) = \frac{1}{3} \sqrt{u^2(k_{t,v}) + u^2(k_{t,qgas}) + u^2(k_{t,qhep\ tan\ e})} \quad (150)$$

This is the uncertainty on k_t related to both the natural variation and to the method by which it is obtained. This value should be used in the calculations. By using the last N calibrations of the individual $k_{t,x}$ calibrations instead of only the recent one, the standard uncertainty for mean value (out of N calibrations) could further reduce by a factor \sqrt{N} .

The evolution in time of the different $k_{t,x}$ calibration values can also be used as a warning signal for a major revision of the test instrument.

This means that there is still some room left for improvement of the measurement procedure and equipment (1,8 %/-2,7 % versus 0,6 %).

2.5.14 Uncertainty on the component k_p

In the paper ‘Critical considerations on the use of a bi-directional probe in heat release measurements’ [15], it is shown that the pressure probe currently used in the SBI is Reynolds dependant. Since the pressure probe factor k_p is considered to be constant, this introduces an additional uncertainty on k_p .

An alternative and probably better solution would be to move away from the actual probe design, which includes a steel supporting rod that heavily disturbs the flow around the pressure chambers, and to introduce either the design of McCaffrey and Heskestad [13] or the design of Sette [16]. This has been agreed within CEN TC127 WG4 TG4 but is subject of a next revision of the SBI standard.

The related standard uncertainties are summarized in Table 13.

Table 13 — Uncertainty contribution if c is taken constant

Quantity X_i	Estimate x_i (range)	'Uncertainty'	Probability distribution	Standard uncertainty $u(x_i)$	Sensitivity coefficient c_i	Uncertainty contribution $u_i(y)$
$k_{p,SBI,1997}$	1,080					$\pm 0,021$
$k_{p,McCaffrey}$ and H.	1,046					$-0,011/+0,009$
$k_{p,Sette}$	1,224					$\pm 0,008$

Until these alternative probes are allowed by the standard, the standard uncertainty will be taken as $u(k_p) = 0,021$.

2.5.15 Uncertainty on the component Δp

The volume flow through the exhaust duct is measured by means of a bi-directional velocity pressure probe. The probe is basically a device that relates the velocity of the exhaust gases to a differential pressure.

The expected velocity range at the height of the probe in the SBI lies between 5 and 16 m/s ($t = 288 \dots 600$ K; $V_{298} = 0,4 \dots 0,7$ m³/s; $k_t = 0,8 \dots 0,9$). This corresponds to differential pressures roughly between 20 and 150 Pa.

Assuming, as an example, a pressure transducer to measure the differential pressure over the probe with a range from 0 to 250 Pa with the following specifications:

- a linearity of $\pm 0,5$ % FS (Full Span);
- an hysteresis of 0,1 % FS;
- no zero drift because of automatic zero set function;
- a temperature effect on the span value of 0,03 %/K in the range +10 °C –50 °C;
- the transducer was calibrated at 20 °C.

Assuming:

- a rectangular distribution;
- the instrument is operating between +10 °C and +30 °C;
- the effect causing nonlinearity, hysteresis and the temperature effect are independent the one from the other;

the standard deviation is estimated to be 0,38 % (0,95 Pa).

Table 14 — Uncertainty contribution of the differential pressure meter

Quantity X_i	Estimate x_i (range)	'Uncertainty'	Probability distribution	Standard uncertainty $u(x_i)$	Sensitivity coefficient c_i	Uncertainty contribution $u_i(y)$
$\Delta p_{\text{linearity}}$	Δp	0,5 % FS	rectangular	0,29 % FS	1,0	0,29 % FS
$\Delta p_{\text{hysteresis}}$	Δp	0,1 % FS	rectangular	0,058 % FS	1,0	0,058 % FS
$\Delta p_{\text{temperature}}$	Δp	0,3 % FS	rectangular	0,17 % FS	1,0	0,17 % FS
Δp_{DAQ}	Δp	0,3 % FS	rectangular	0,17 % FS	1,0	0,17 % FS
Δp	Δp					0,95 Pa
*FS: Full Span (250 Pa)						

2.5.16 Uncertainty on the component T_{ms}

The combustion gas temperature at the height of the measuring section (ms) is measured by means of three K-type, sheathed and insulated, thermocouples having an outside diameter of 0,5 mm. The position of the tips is at a radius of (87 ± 5) mm from the axis and with 120° mutual angular distance.

— Tolerance on a new thermocouple t_t :

The tolerance allowed on new Class 2 thermocouples according to EN 60584-2 [4] is:

- $\pm 2,5$ °C in the range -40 °C to 333 °C
- $\pm 0,0075 t$ (t in °C) in the range 333 °C to 1200 °C

— Effect of ageing t_a :

Due to ageing effects an additional uncertainty should be taken into account. Based on ageing effects of K-type sheathed thermocouples after 50 h of use inside a furnace for fire resistance tests [5] a variance of ± 2 °C can be expected for temperature measurements around 120 °C. Since K-type thermocouples are subject to calibration changes on temperature cycling to 500 °C or above (like in fire resistance tests), and since no temperatures above 400 °C are to be expected in the SBI, it is reasonable to say that ageing effects will be limited to ± 2 °C around the nominal value.

— Effect of data acquisition and extension wires t_{DAQ} :

The uncertainty related to the data acquisition, extension wires and connectors is estimated (2.5.1) to be $1,0$ K.

— Radiation error t_r :

Another important effect is the radiation error. Due to the thermal inertia of the duct system, the thermocouple will initially see a 'cold' surface when gas temperatures start to rise. This results in an underestimation of the real gas temperature. Further on in the test when temperatures decay, the thermocouple sees a 'hot' duct surface and will overestimate the gas temperature. This effect is nonlinear and is judged to have a standard uncertainty of $\pm 2,2$ °C [11].

— Velocity error t_v :

The error related to the velocity has its origin in the fact that not all of the kinetic energy of the fluid is recovered when a gas is brought to rest near a thermocouple. Ideally the gas should be brought to rest adiabatically. The recovery factor is $\alpha = 0,68 \pm 0,07$ for wires normal to the flow. The error associated with the velocity is given by

$$(1 - \alpha) \frac{v^2}{2c_p} \quad (151)$$

whereby v is the mean velocity, c_p is the specific heat of the thermocouple material and α is the recovery factor.

Initially the velocity at the height of the thermocouples in the SBI is around 8 m/s. This value can increase to approximately 16 m/s when the gas temperature rises to 300 °C and keeps the mass flow constant.

Assuming that:

- $\alpha = 0,68$
- $v = 16$ m/s

- $c_p = 500 \text{ J/kg.K}$

the overestimation of the temperature is 0,08 K

- Conduction error t_c :

The thermocouples are inserted into the exhaust duct perpendicular to the flow over a length of about 7 cm. Conduction errors can therefore be neglected.

- Transient error t_τ :

The transient error associated with the response time τ of the thermocouple is given by

$$\tau \frac{dT}{dt} \quad (152)$$

τ is estimated theoretically to be approximately $\tau = 1,15 \text{ s}$ [11] for flow gases around room temperature. For higher temperatures the time constant decreases slightly resulting in a reduced error.

For a heptane calibration according to the SBI standard the maximum initial temperature rise is of the order of $2,5 \text{ °C/s}$ which results in a maximum underestimation of about $2,84 \text{ °C}$. This calibration can be seen as the maximum temperature rise of the smoke gases at the height of the measuring section.

Table 15 — Uncertainty contribution of the temperature measurement

Quantity X_i	Estimate x_i (range)	'Uncertainty'	Probability distribution	Standard uncertainty $u(x_i)$	Sensitivity coefficient c_i	Uncertainty contribution $u_i(y)$
t_t	0 °C	2,5 °C	rectangular	1,44 °C	1,0	1,44 °C
t_a	0 °C	2,0 °C	rectangular	1,15 °C	1,0	1,15 °C
t_{DAQ}	0 °C	1,0 °C	normal	1,0 °C	1,0	1,0 °C
t_r	0 °C	2,2 °C	normal	2,2 °C	1,0	2,2 °C
t_v	0,04 °C	0,04 °C	rectangular	0,023 °C	1,0	0,023 °C
t_c	0,0 °C	0,0 °C	-	0,0 °C	1,0	0,0 °C
t_τ	0 °C	2,84 °C	triangular	1,16 °C	1,0	1,16 °C
T	0 °C					3,2 °C

If type 1 thermocouples would be used, the uncertainty contribution would slightly reduce to 3,0 °C.

2.5.17 Uncertainty on the component I

I is the signal of the light receiver expressed in per cent.

In line with the standard, the linearity of the system should be equal or better than 1 % in the range

The range of 33 % - 100 % will be – in a conservative approach – expanded to 1 % - 100 % and a rectangular distribution will be assumed.

In addition to this there might be a drift on the system due to soot clogging to the lenses causing a drift of maximum 2 %. If the drift is lower, the lower value may be used as measured at the end of the test.

An asymmetric rectangular distribution will be assumed since the soot clogging can take place at any one time in the test.

$$\frac{\text{drift}}{\sqrt{12}} \quad (153)$$

Table 16 — Estimated uncertainty contribution of the initial transmission value

Quantity X_i	Estimate x_i (range)	'Uncertainty'	Probability distribution	Standard uncertainty $u(x_i)$	Sensitivity coefficient	Uncertainty contribution $u_i(y)$
$I_{\text{st.dev.}}$	100 %	1 %	rectangular	0,58 %	1,0	0,58 %
I_{DAQ}	100 %	0,028 mA	normal	0,18 %	1,0	0,18 %
\bar{I}	100 %					0,61 %

Table 17 — Estimated uncertainty contribution of the transmission value

Quantity X_i	Estimate x_i (range)	'Uncertainty'	Probability distribution	Standard uncertainty $u(x_i)$	Sensitivity coefficient	Uncertainty contribution $u_i(y)$
I_{drift}	33 - 100 %	2 %	Rectangular assymetric	0,58 %	1,0	0,58 %
$I_{\text{linearity}}$	33 - 100 %	1 %	rectangular	0,58 %	1,0	0,58 %
I_{DAQ}	33 - 100 %	0,028 mA	normal	0,18 %	1,0	0,18 %
I	33 - 100 %					0,92 %

Annex A (informative)

List of symbols and abbreviations

A	cross sectional area exhaust duct	[m ²]
c	$\sqrt{2T_{298}/\rho_{298}} \cong 22.4$	[K.m ³ /kg] ^{1/2}
c_x^y	sensitivity coefficient of x with respect to y	[J/kg.K]
c_p	heat capacity	[m]
D	diameter	
e	error	
E	heat of combustion per unit volume of oxygen (at 298 K) consumed	[MJ/Nm ³ O ₂]
E'	heat of combustion per unit mass of oxygen consumed	[MJ/kg O ₂]
f_s	sampling frequency	[Hz]
F	view factor	[-]
h	convective heat transfer coefficient	[W/m ² .K]
Δh_c	heat of combustion	[kJ/kg]
H	enthalpy	[kJ/kg]
k	coverage factor	[-]
k	thermal conductivity	[W/m.K]
k_t	velocity profile correction factor (relation between mean velocity and velocity on axis)	[-]
k_p	pressure probe factor	[-]
L	length	[m]
m	mean value	
\dot{m}	mass flow	[kg/s]
n or N	number of samples	
Nu	Nusselt number	[-]
O(·)	order of	
p	barometric pressure	[Pa]
P(x)	probability function	
Pr	Prandtl number	[-]
\dot{Q}	heat release rate	[kW]
r	repeatability limit	

$r(x_i, x_j)$	Pearson correlation coefficient	[-]
Re	Reynolds number	[-]
s	estimated standard deviation	
s^2	estimated variance	
s_r	standard deviation estimates on repeatability	
s_R	standard deviation estimates on reproducibility	
t	time	[s]
t_s	sampling interval	[s]
T	temperature	[K]
$u(x)$	standard uncertainty on x	
U	expanded uncertainty	
v	velocity	[m/s]
V	volume	[m ³]
\dot{V}_{D298}	volume flow through the duct (298 K)	[m ³ /s]
w_i	weighing factor	
\bar{x}	estimated mean value	
X_{O_2}	Concentration of, in this case O ₂ , in the gas considered	[Vol%]
$X_{O_2}^{D^\circ}$	Initial oxygen concentration in the exhaust duct	[Vol%]
$X_{O_2}^{A^\circ}$	Initial oxygen concentration as measured by the analyser	[Vol%]
$X_{O_2}^A$	Actual oxygen concentration as measured by the analyser	[Vol%]

Greek Symbols

α	expansion factor	
δ	bias	
Δ	difference operator	
ε	emissivity	[-]
μ	mean value	
ν	kinematic viscosity	[m ² /s]
ρ	density	[kg/m ³]
σ	standard deviation	
σ^2	variance	
τ	time constant	[s]
φ	relative humidity	[%]
ϕ	depletion factor	
$\Phi(\omega)$	phase shift in the frequency domain	

ω circular frequency [rad/s]

Subscripts

A[°] initial analyser value
atm atmosphere
av average
b bias
c combined
D[°] initial value measured in the duct
eff effective
f formation
ms measuring section
rect rectangular
st.dev standard deviation
trap trapezoidal
trian triangular

Superscripts

° initial
l l
u upper

List of abbreviations

ABS Absolute
CEN European Committee for Standardization
CPD Construction Products Directive; 89/106/CE
DAQ Data acquisition system
DMM Digital Multi Meter
EGOLF The European Group of Organisations for Fire testing, Inspection and Certification
EN European Standard
FIGRA Fire Growth Rate
FA Full Span
GUM Guide to the expression of uncertainty in measurement [6]
HRR Heat Release Rate
ISO International Organization for Standardization
LMSE Local Mean Square Error

MAX	Maximum of
MDF	Medium Density Fibreboard
MR	Measuring Range
PLC	Power Line Cycle
PLC	Programmable Logic Controller
ppm	Parts per million
PVDF	Polyvinylidene fluoride
REL	Relative
RC	Room corner test; ISO 9705-1 [2]
RTD	Resistive Temperature Detector
SBI	Single burning item test; EN 13823 [1]
SBI RR1	First round robin exercise on the SBI held in 1997
SBI RR2	Second round robin exercise on the SBI held in 2003 – 2004
SMOGRA	Smoke growth rate
SPR	Smoke production rate
THR600s	Total heat released over the first 10 min
TSP600s	Total smoke production over the first 10 min

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