LUND UNIVERSITY

Uncertainties in measuring heat and smoke release rates in the room/corner test and the SBI

Axelsson, Jesper; Andersson, Petra; Lönnermark, Anders; Van Hees, Patrick; Wetterlund, Ingrid

2001

Link to publication

Citation for published version (APA):
Axelsson, J., Andersson, P., Lönnermark, A., Van Hees, P., & Wetterlund, I. (2001). *Uncertainties in measuring heat and smoke release rates in the room/corner test and the SBI*. (SP RAPPORT; Vol. 2001:04). STATENS PROVNINGSANSTALT.

Total number of authors:
5

General rights
Unless other specific re-use rights are stated the following general rights apply:
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.
• Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
• You may not further distribute the material or use it for any profit-making activity or commercial gain
• You may freely distribute the URL identifying the publication in the public portal

Read more about Creative commons licenses: https://creativecommons.org/licenses/

Take down policy
If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

LUND UNIVERSITY

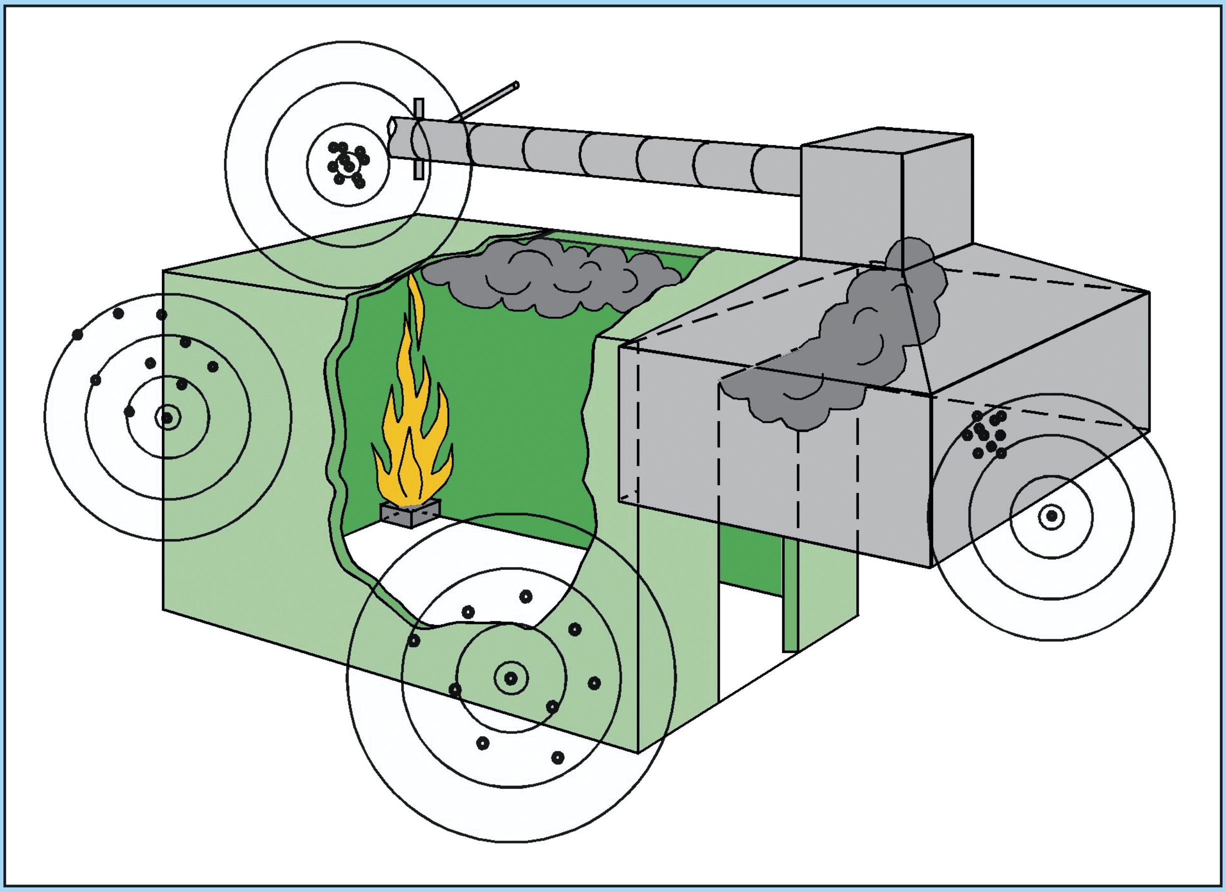
PO Box 117
221 00 Lund
+46 46-222 00 00

Download date: 20. Dec. 2025

Jesper Axelsson, Petra Andersson,
Anders Lönnermark, Patrick Van Hees,
Ingrid Wetterlund

Uncertainties in measuring heat and smoke release rates in the Room/Corner Test and the SBI

NT Techn Report 477
NORDTEST Project No. 1480-00



SP Swedish National Testing and Research Institute
SP Fire Technology
SP REPORT 2001:04

Abstract

When performing fire testing and classifying materials, Heat Release Rate (HRR) and Smoke Production Rate (SPR) are two of the most important quantities to determine. The calculation of HRR and SPR, however, involves several measurements and approximated constants. These all suffer from error, which may also depend on the experimental set-up. To give the total error of the HRR and the SPR, respectively, the individual contributions must be derived.

In this work, the individual sources of errors are defined for the HRR and the SPR calculations, with regard to the Room/Corner Test and the Single Burning Item (the SBI) test. From the individual errors the combined expanded uncertainty has been calculated, using a coverage factor of 2, which gives a confidence level of approximately 95 %.

For HRR measurements the uncertainty is presented for two different levels in the two different set-ups, i.e. 150 kW and 1 MW for the Room/Corner Test and 35 and 50 kW for the SBI. For the SPR the uncertainty is presented at 6 different levels for both tests ranging from 0.5 m^2/s to 10 m^2/s.

In addition, guidelines are given for estimating the individual errors and calculating the combined expanded uncertainty for HRR and SPR measurements in general.

Key words: Fire tests, uncertainty, error, the SBI, the Room/Corner Test, Heat Release, HRR, Smoke Production, SPR

SP Sveriges Provnings- och Forskningsinstitut
SP Rapport 2001:04
ISBN 91-7848-846-X
ISSN 0284-5172
Borås 2001

SP Swedish National Testing and Research Institute
SP Report 2001:04

Postal address:
Box 857,
SE-501 15 BORÅS, Sweden
Telephone: +46 33 16 50 00
Telex: 36252 Testing S
Telefax: +46 33 13 55 02
E-mail: info@sp.se

Contents

Acknowledgement

This work was sponsored by Nordtest, project 1480-00 which is gratefully acknowledged.

Part of the work presented here was performed as a group assignment in a course in uncertainty measurements in fire tests. Apart from the authors, Per Thureson, Joel Blom, Magnus Bobert, Patrik Johansson and Björn Sundström took part in this group assignment. Thomas Svensson at the SP Department of Mechanics supervised the course and gave very valuable advice for calculation and estimation of the different uncertainties presented in this report.

Sammanfattning

Den totala utökade mätosäkerheten för HRR- och rökmätningar i SBI och Room/Corner Test har beräknats. Dessutom ges riktlinjer för hur man tar fram mätosäkerheten i metoderna Room/Corner test och SBI.

För HRR i Room/Corner test får man en osäkerhet på i storleksordningen 10 % med ungefär 95 % täckningsgrad (11 % vid 150 kW och 7 % vid 1 MW) om man gör en enstaka mätning. Om man tittar på nivån på en kurva som man gör vid t.ex. kalibrering får man ett värde på i storleksordningen 1 % eftersom man i princip medelvärdesbildar över upp till 100 värden. Enligt SBI standarden är det 30 sekunders medelvärden för HRR man studerar vilket resulterar i en osäkerhet i storleksordningen 4 %. Tittar man på enstaka värden i SBI utrustningen har man en osäkerhet på ca 13 % vid 35 kW och 10 % vid 50 kW.

Osäkerheten i rökmätningen är inte lika tydligt apparatberoende, men befanns variera mycket beroende på vilken röktäthet man har i kanalen. Vid en hög röktäthet, t ex SPR = 1 m^2/s, är osäkerheten ca 10 % men vid låg röktäthet är den avsevärt större.

1 Introduction

According to EN ISO/IEC 17025[1] and ISO 10012-1[2] (EN ISO/IEC 17025 supersedes ISO/IEC Guide 25 and EN 45001) uncertainties should be reported in calibration and testing reports. General Principles for evaluating and reporting uncertainties are given in EAL-R2[3] and GUM[4]. These principles, however, need to be adopted to fire tests. Advice and guidelines are needed on how to compile the uncertainties in fire tests. This is especially important due to the forthcoming harmonization in the new European classification system for building products.

The Single Burning Item (SBI, prEN 13823)[5] and the Room/Corner Test (ISO 9705)[6] are both part of the EUROCLASS[7] system. Rather complicated measurements are included in the methods for measuring the Heat Release Rate (HRR) and the Smoke Production Rate (SPR). These data are then transformed into the FIGRA (Fire Growth Rate) and SMOGRA (Smoke Growth Rate) values[5, 6] which are crucial for the classification of the product according to the EUROCLASS[7] system. The test methods include general advice about uncertainties for each type of instrument used, but no advice on determining the total accuracy of the measurement.

Some publications are available on the estimation of the overall uncertainty in HRR measurements. Dahlberg[8] reports a relative error of 7 % for HRR measurements in the SP Industry Calorimeter when the HRR is in the range of 2 to 7 MW. Enright and Fleischmann[9] presented a relative error, in their own words 'as optimistic as it can be', of 3 % for a fictive measurement of a Heptane pool fire of 374 kW where it was assumed that the mass flow into the fire equals the flow in the measurement duct. The factors that contribute most to the uncertainty are the uncertainty in the oxygen concentration and the calibration constant (=1.08) for the bi-directional probe. The same authors later stated[10] that the variation in the overall calibration constant for HRR measurements "C" in the Cone Calorimeter obtained by calibrating against a specified methane fire is an indication of the overall uncertainty in the HRR measurement.

It is increasingly clear that accurate determination of these properties (i.e. HRR & SPR) is extremely important. A major factor in this determination is the definition of the uncertainty in the measurements. This report is in response to a need for guidance in defining these uncertainties.

In this report a short introduction to uncertainties in measurements in general is given together with a short description of the SBI and the Room/Corner Test methods. The estimation of the total uncertainty for HRR and SPR measurement in the SBI and the Room/Corner Test set-up used at SP is presented as an example of how to perform such estimates. In addition a guideline for performing these kinds of estimations is provided.

2 Uncertainty in measurements

Measurements always include errors. For example when performing temperature measurements the radiation from nearby surfaces gives an error in the temperature reading or when measuring the thickness of a slab, different results are achieved depending on where on the slab the measurement is made. The errors propagate through all calculations based on these measurements.

The errors can be systematic or random. Systematic errors result in a bias to the measured values while random errors results in a spreading of the values. It is considered as good practice to try to reduce the systematic errors as much as possible. However, if the value of a systematic error is unknown it may be regarded as a random error.

Uncertainty of a measurement is defined as "parameter, associated with the result of a measurement, that characterizes the dispersion of the values that could reasonable be attributed to the measurand"[4]. Another definition could be a measure of the possible error in the estimated value of the property being measured.

The qualitative concept of accuracy has to be quantified by the quantitative concept of uncertainty. Those two concepts varies inversely. The concept of accuracy, illustrated by Figure 2-1, consists of trueness and precision. Precision is expressed numerically with its opposite, i.e. the deviation or more precisely the standard deviation. Trueness is expressed numerically with its opposite as well, in this case the systematic error or the bias.

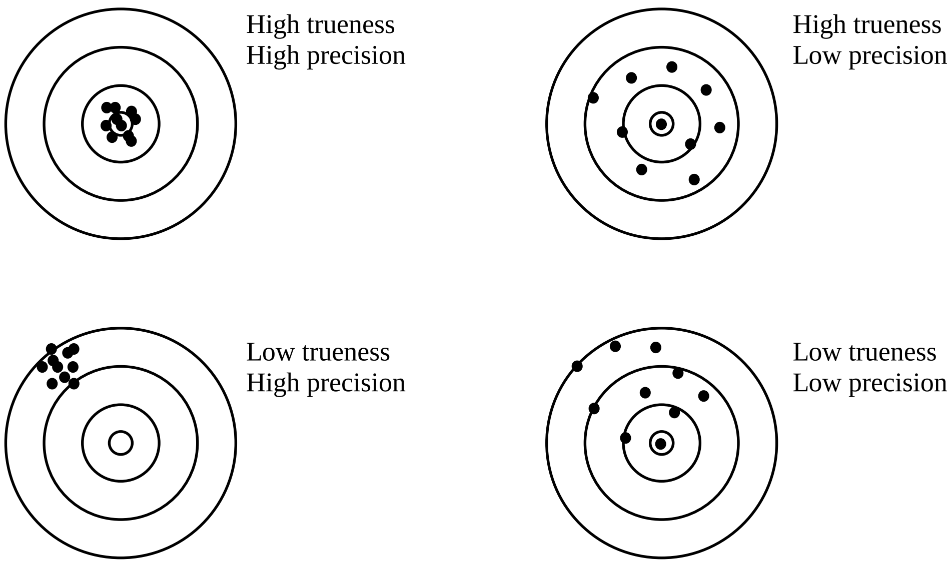


Figure 2-1 Different levels of accuracy as illustrated by targets

The distribution of results of measurements can be described with statistical methods. Figure 2-2 is a graphical illustration of this. The solid and the dotted curves represent the estimation of a measured value based on repeated observations. The dotted curve shows the results obtained at one single laboratory under repeatability conditions, while the solid line shows the reproducibility results obtained by several laboratories. In the example shown the locally systematic error is larger than the strictly systematic error. Repeatability is normally denoted by *"r"* in subscripts and reproducibility by *"R"*.

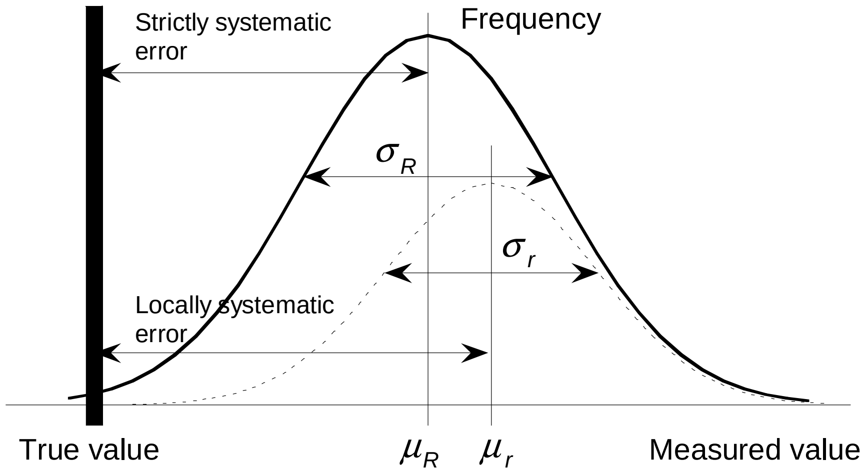


Figure 2-2 The distribution of measured values under different conditions

2.1 General principles of determination of uncertainty in measurements

For the purpose of this project, principles for determination of uncertainty in measurements as described in EAL-R2[3] and GUM[4] were used. The combined standard uncertainty, $u_c(y)$, is determined from the standard uncertainty of each input estimate, $u(x_i)$. Uncertainties are classified as Type "A" if their standard uncertainties are derived from data by statistical methods, provided sufficient data is available. When the evaluation of the standard uncertainties is based on judgements, specifications or experience, however, the uncertainties are classified as Type "B".

Using a simple mathematical model the result of a measurement can be expressed as:

$$y = \mu + \varepsilon_1 + \varepsilon_2 + ... + e_1 + e_2 + ... \qquad (2\text{-}1)$$

where y is the measured value, μ is the true, unknown value and ε_1, ε_2... and e_1, e_2... are the contributions from different sources of errors. ε_1, ε_2... are the Type "A" and e_1, e_2... are the Type "B" uncertainties.

The standard uncertainty of a Type "A" error is represented by the standard deviation. For Type "B" errors the evaluation of the uncertainty depends on the basis that has been used for the evaluation. Thus, for a digital instrument with a low resolution the measurement values are assumed to be distributed as a symmetrical rectangle, while for instance the scale readings of a flow meter can be assumed to be distributed as a symmetrical triangle. Figure 2-3 shows examples of rectangular and triangular distributions. Similar models can be used for all kinds of Type "B" errors. More examples of estimates used in the work presented in this report are given in Section 5.

The standard deviation of a rectangular distribution, s_{rect}, is calculated as a function of the width of the distribution as:

$$s_{rect} = \frac{\varepsilon_0}{\sqrt{3}}$$

where ε_0 is half the width of the distribution.

The standard deviation of a triangular distribution, s_{trian}, is calculated as a function of the width of the distribution as:

$$s_{trian} = \frac{\varepsilon}{\sqrt{6}}$$

where ε is half the width of the distribution.

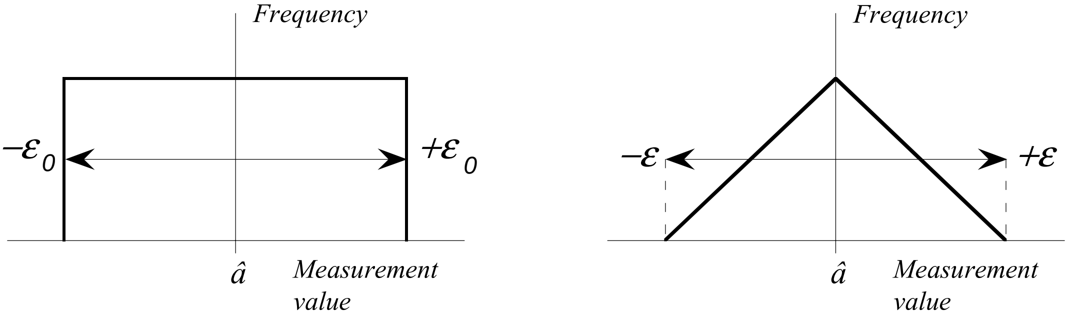


Figure 2-3 Examples of rectangular and triangular distributions

If the contributions of errors, ε_1, ε_2... and e_1, e_2..., can be regarded as independent of each other, the combined standard uncertainty, $u_c(y)$, can be calculated as:

$$u_c = \sqrt{d_1^2 s_1^2 + d_2^2 s_2^2 + ... + c_1^2 u_1^2 + c_1^2 u_2^2 + ...} \qquad (2\text{-}2)$$

where s_1, s_2... are the experimental standard deviations, u_1, u_2... are the standard uncertainties and d_1, d_2…, c_1, c_2….are the sensitivity coefficients. Sensitivity coefficients are used when the quantity of interest is a function of measured quantities. They express how much the result varies with changes in the input quantities. The sensitivity coefficient equals the partial derivative of the final result with respect to the measured quantity. They can be determined either by analytical partial derivation or numerically or experimentally by varying the parameter in question within the settled limits. If one prefers to work with relative errors then Equation 2-2 transforms to

$$\frac{u_c}{y} = \sqrt{\left(\frac{\partial f}{\partial x_1}\frac{x_1}{y}\frac{u(x_1)}{x_1}\right)^2 + \left(\frac{\partial f}{\partial x_2}\frac{x_2}{y}\frac{u(x_2)}{x_2}\right)^2 + ...} = \sqrt{c_{r,1}^2\left(\frac{u(x_1)}{x_1}\right)^2 + c_{r,2}^2\left(\frac{u(x_2)}{x_2}\right)^2 ...} \qquad (2\text{-}3)$$

for a function $y = f(x_1,x_2,...)$ with the relative sensitivity coefficients $c_{r,i}$. Especially in case of a simple multiplicative function, $y = x_1^{m_1} \cdot x_2^{m_2} \cdot \ldots$, the relative sensitivity coefficients according to *relative* uncertainty are easily determined from the exponents,

$$\left(\frac{u_c}{y}\right)^2 = m_1^2\left(\frac{u(x_1)}{x_1}\right)^2 + m_2^2\left(\frac{u(x_2)}{x_2}\right)^2 + \ldots \tag{2-4}$$

Since the standard uncertainty per definition in GUM[4] is expressed as the standard deviation, it has the coverage factor *k=1*. Thus, to finally obtain the expanded relative uncertainty, the combined relative standard uncertainty $u_c(y)$ is multiplied by a coverage factor *k*:

$$\frac{u_c}{y} = k\sqrt{c_{r,1}^2\left(\frac{u(x_1)}{x_1}\right)^2 + c_{r,2}^2\left(\frac{u(x_2)}{x_2}\right)^2 + \ldots} \tag{2-5}$$

The expanded relative uncertainty gives a confidence interval about the result. When using the coverage factor of 2 the confidence level is approximately 95 %.

2.2 Principles used in this project

The relative standard uncertainties of each quantity needed for calculating HRR and SPR were estimated and listed in tables together with their contribution to the combined relative uncertainty so that the quantities that contribute most could easily be identified. Relative standard uncertainties and relative sensitivity coefficients were used throughout the project. The standard uncertainty was calculated assuming a rectangular or triangular distribution of the maximum error. The expression “Relative error” in the tables refers to the estimated relative error. With relative error is meant the discrepancy between the measured and the true value. Methods used to evaluate the individual relative errors included studying the manuals and measuring drift of instruments during usage. In some cases the assumptions were based on the experience of the participants in the course.

The standard uncertainties used in this project were mainly classified as Type “B”, which is usually the case for fire tests since large series of tests very seldom are performed. By performing a series of repeated measurements each of the uncertainties can be transformed into Type “A”. It was not, however, deemed relevant for this study. No distinction between systematic and random errors was made. All uncertainties were regarded as random.

3 The principle of heat release rate measurements

When studying and comparing different fire scenarios, probably the most important property is the Heat Release Rate measurement. In addition to giving each fire an individual fingerprint the HRR is also the central determination in several fire test methods, correlations and classifications. It is therefore important to obtain as accurate measurements as possible of this quantity. The HRR is not obtained by a single measurement but is computed from several different quantities in a series of computational steps. The measuring and calculation of the HRR is performed in an identical way in both the ISO 9705 Room/Corner Test[6] and the prEN 13823 SBI test[5]. In this section the major equations for calculating the HRR are introduced together with the various parameters. The uncertainties in each of the parameters in the HRR calculation are considered in more detail in Section 5. In Section 5 the combined expanded uncertainty for HRR measurements is also calculated for two different HRR levels.

Sketches of the two experimental set-ups are shown below in Figure 3-1 and Figure 3-2. The measurement is made in the exhaust duct in the same way for both methods. Characteristic HRR levels are 30 – 100 kW for the SBI and 100 – 1000 kW for the Room/Corner Test and the duct flows are approximately 0.6 m^3/s and 2.5 m^3/s, respectively.

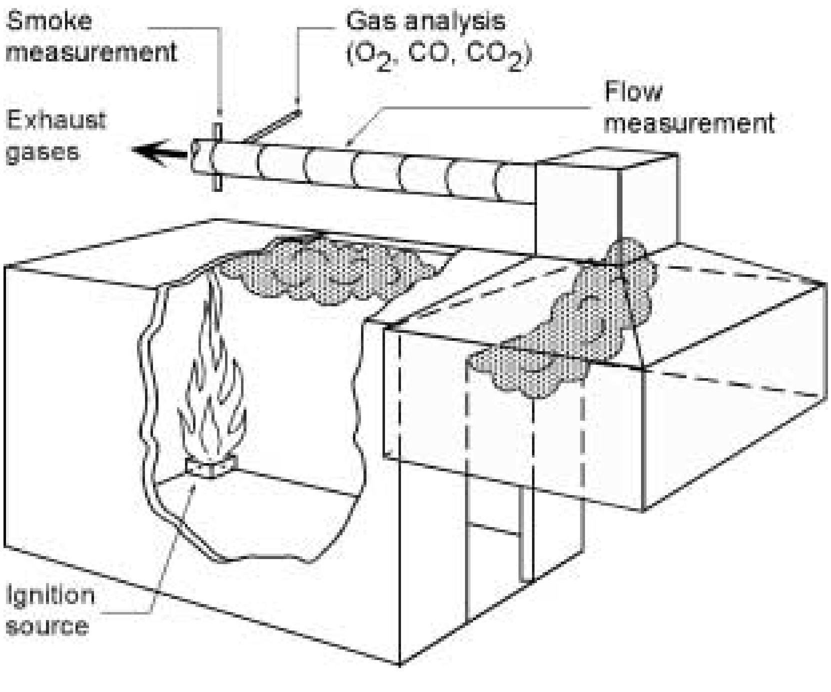


Figure 3-1 The ISO 9705 Room/Corner Test

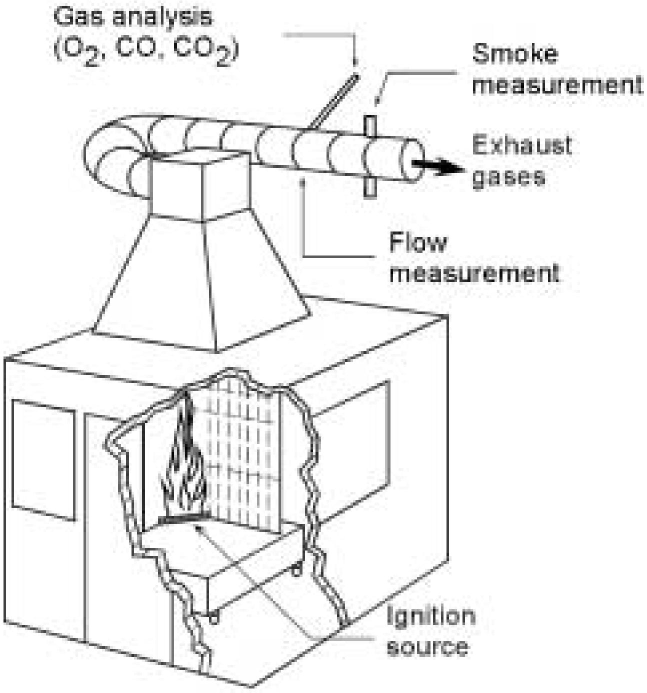


Figure 3-2 The prEN 13823 SBI Test

Two methods for calculating the HRR are the so-called oxygen consumption principle and the carbon dioxide generation principle. The latter can also include production of carbon monoxide, hydrocarbons and soot[11]. In almost all cases, however, the oxygen consumption principle is adopted[12,13]. This is due to the fact that many of the common materials, when burning, have shown to release about the same amount of energy per kilogram consumed oxygen. This implies the possibility to use appropriate average values, which are valid for a large range of fuels (see Section 5.4).

The equation normally used for calculating the HRR during a fire test using oxygen consumption principle is:

$$\dot{Q} = \frac{E \cdot \dot{m} \cdot \dfrac{M_{O_2}}{M_{air}} \cdot \left(1 - X^0_{H_2O}\right)}{\dfrac{\alpha - 1}{X^0_{O_2}} + \dfrac{1 - \dfrac{X_{O_2}}{1 - X_{CO_2}}}{X^0_{O_2} - \dfrac{X_{O_2} \cdot \left(1 - X^0_{CO_2}\right)}{1 - X_{CO_2}}}} \tag{3-1}$$

where

$\dot{Q}$ = the heat release rate from the fire, HRR [kW]

E = amount of energy developed per consumed kilogram of oxygen [kJ/kg]

$\dot{m}$ = mass flow in exhaust duct [kg/s]

M_{O_2} = molecular weight for oxygen [g/mol]

M_{air} = molecular weight for air (actually the molar weight for the gas flow in the duct, see Section 5.7) [g/mol]

α = ratio between the number of moles of combustion products including nitrogen and the number of moles of reactants including nitrogen (expansion factor)

$X_{O_2}^0$ = mole fraction for O_2 in the ambient air, measured on dry gases [-]

$X_{CO_2}^0$ = mole fraction for CO_2 in the ambient air, measured on dry gases [-]

$X_{H_2O}^0$ = mole fraction for H_2O in the ambient air [-]

X_{O_2} = mole fraction for O_2 in the flue gases, measured on dry gases [-]

X_{CO_2} = mole fraction for CO_2 in the flue gases, measured on dry gases [-]

4 The principle of smoke production rate measurements

Smoke produced by fires can essentially be measured in two ways. One way is to collect and filter some of the smoke gases and then measure the weight of the particles. The other way, used in the Room/Corner Test and the SBI, is to measure the transmission of light through the smoke. The main principle and calculations are the same in the SBI and the Room/Corner Test. Like the HRR, the SPR is calculated from several different parameters that are sources for uncertainty.

In both the SBI and the Room/Corner Test the smoke is collected by a hood and led into an exhaust duct where both the HRR and the smoke measurements are made, see Figure 3-1 and Figure 3-2. The transmission measurement is made as shown in Figure 4-1 with a light source aiming light through the duct onto a photocell on the opposite side. In the two methods studied in this report the light source is specified as a white light lamp, but other methods may use a laser source. A dynamic measure of the transmission is obtained by logging the signal from the photocell. The system is calibrated with optical filters and before each test a “clear-sight” baseline is recorded. Both the lamp and the photocell are kept in a slight overpressure by means of filtered compressed air in order to avoid soot accumulating on the optical surfaces.

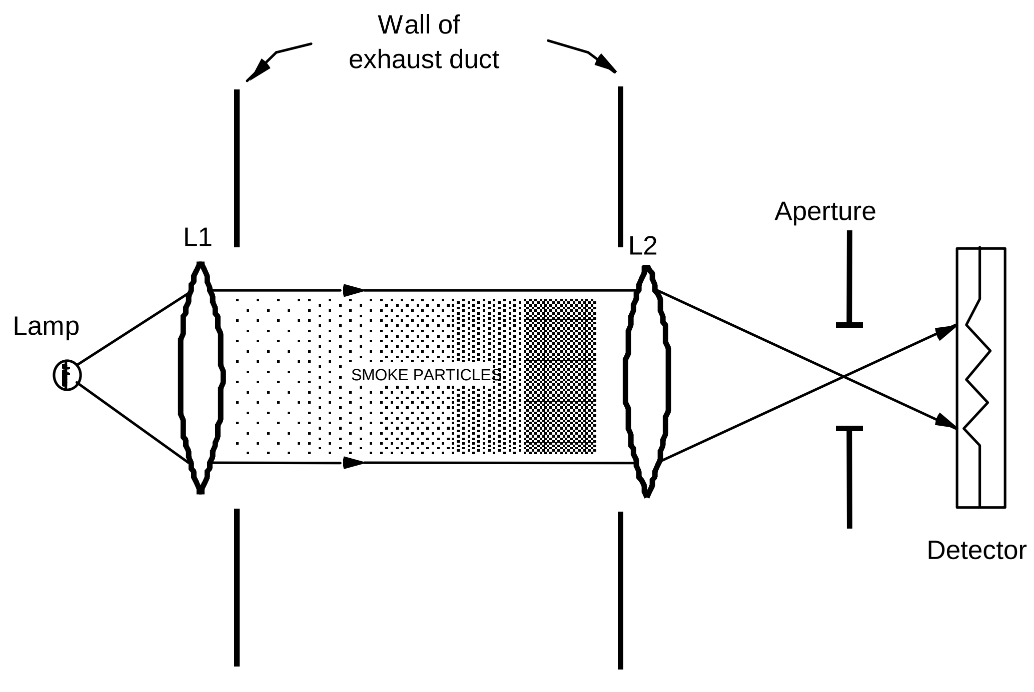


Figure 4-1 White light optical smoke measuring system

The DC signal from the photocell is used for calculating the SPR expressed in m^2/s. The SPR is calculated according to the following equations

$$SPR = k \cdot \dot{V}_{T_s} \tag{4-1}$$

with

$$k = \frac{1}{L} \cdot \ln\left(\frac{I_0}{I}\right) \tag{4-2}$$

$$\dot{V}_{T_s} = \frac{\dot{V}_{298} \cdot T_s}{298} \tag{4-3}$$

where

k = extinction coefficient [1/m]
$\dot{V}_{T_s}$ = volume flow rate at temperature T_s [m^3/s]
$\dot{V}_{298}$ = volume flow rate at temperature 298 K [m^3/s]

L = light path i.e. diameter of exhaust duct [m]

I = transmission (signal from photo cell) with smoke [V]

I_0 = zero value of transmission, i.e. without smoke (base line) [V]

T_s = gas temperature in exhaust duct [K]

5 Sources of uncertainty in heat release rate measurements

The uncertainty of each factor in the HRR calculation is discussed below. Some of the uncertainties were found to be dependent on the HRR and therefore the uncertainties were calculated for two different levels of HRR. For the Room/Corner Test calculations were performed for 150 kW (start level for calculations such as FIGRA at the 100 kW burner level) and 1 MW (defined as flashover level). For the SBI the levels chosen were 35 kW and 50 kW, which are interesting levels for classification of products.

5.1 Mass flow in duct

The volume flow, in the exhaust duct expressed in cubic metres per second, related to atmospheric pressure and an ambient temperature of 25 °C, $\dot{V}_{298}$, is given by the equation[6]

$$\dot{V}_{298} = A \frac{k_t}{k_p} \frac{1}{\rho_{298}} \sqrt{2 \Delta p T_0 \rho_0 / T_s} = 22.4 (A \cdot k_t / k_p) \sqrt{\Delta p / T_s} \tag{5-1}$$

where T_s is the gas temperature in the exhaust duct expressed in Kelvin (K), A is the cross section area, Δp is the pressure difference measured by the bi-directional probe (Pa), k_t is the ratio of the average volume flow per unit area to volume flow per unit area in the centre of the exhaust duct and k_p is the Reynolds number correction for the bi-directional probe suggested by McCaffrey and Heskestad[14]. The factor "22.4" involves the factor 2, T_0 (273.15 K) and the density of the gas at 0 °C, ρ_0, and at 298 K, ρ_{298}. The only uncertainty here is the density, which is assumed to be equal to the density of air.

The mass flow, $\dot{m}$, is obtained by multiplying the volume flow with the density of the gas or by

$$\dot{m} = \frac{k_t}{k_p} \cdot A \cdot \sqrt{2 \cdot \rho \cdot \Delta p} = \frac{k_t}{k_p} \cdot A \cdot \sqrt{2 \cdot \Delta p \cdot \rho_{298} \cdot \frac{298}{T_s}} \tag{5-2}$$

This means that the mass and volume flow only differs by a constant and can be treated in exactly the same manner when it comes to uncertainty analyses.

The uncertainties in the volume and mass flow consists of the uncertainties in each of the quantities in Equations (5-1) and (5-2). The summary with the total uncertainty for the Room/Corner Test and the SBI is given in Table 5-1 and Table 5-2 where each quantity is discussed in the subsections below, with emphasis on the Room/Corner Test.

5.1.1 The Room/Corner Test

The combined expanded relative standard uncertainty for the mass flow measurement in the Room/Corner Test was determined as ± 3.2 % using a coverage factor $k = 2$ as presented in Table 5-1 below. Each of the relative errors of the quantities and their standard uncertainties are discussed in Sections 5.1.3 – 5.1.8.

Table 5-1 Uncertainties in volume flow measurement in the Room/Corner Test.

Quantity x_i	Relative error (%)	Relative standard uncertainty $u(x_i)/x_i$ (%)	Relative sensitivity coefficient, $c_{r,i}$	Contribution to combined relative uncertainty of flow measurement $c_{r,i} \cdot u(x_i) / x_i = u_i(y)$ (%)
A (Area)	0.31	0.18	1	0.18
Factor "22.4"	0.3	0.3	1	0.3
k_t		1.0	1	1.0
Δp	0.33	0.19	0.5	0.095
T_s	0.87	0.50	0.5	0.25
k_p	2.0	1.2	1	1.2
Combined expanded relative standard uncertainty				**3.2 %**

5.1.2 The SBI

The combined expanded relative standard uncertainty for the mass flow measurement in the SBI was determined as ± 3.3 % using a coverage factor $k = 2$ as presented in Table 5-2 below. Each of the relative errors of the quantities and their standard uncertainties are discussed in Sections 5.1.3 – 5.1.8.

Table 5-2 Uncertainties in volume flow measurement in the SBI test

Quantity x_i	Relative error (%)	Relative standard uncertainty $u(x_i)/x_i$ (%)	Relative sensitivity coefficient, $c_{r,i}$	Contribution to combined relative uncertainty of flow measurement $c_{r,i} \cdot u(x_i) / x_i = u_i(y)$ (%)
A (Area)	negligible		1	
Factor "22.4"	0.3	0.3	1	0.3
k_t		1.0	1	1.0
Δp	1.7	0.96	0.5	0.48
T_s	0.5	0.29	0.5	0.15
k_p	2.0	1.2	1	1.2
Combined expanded relative standard uncertainty				**3.3 %**

5.1.3 Area

The duct of the Room/Corner Test, studied in this example is old and was considered to have an uncertainty in the cross section area. The uncertainties are due to the steel thickness in the duct, soot and corrosion. In addition the area might change during an experiment due to heat expansion. It was also found that the duct was not circular but slightly ellipsoidal. This did not, however, influence the area very much and was considered as negligible. The uncertainty in the diameter measurement and errors due to soot, rust and heat expansion was estimated by reasoning. The errors were assumed to be equally distributed. The relative sensitivity coefficient is 1.

For the SBI example the area uncertainty was considered as negligible since the tolerances given in the standard are very small.

5.1.4 The factor "22.4"

The error introduced when using the factor "22.4" in Equation (5-1) is due to the fact that it is assumed that the gas flowing in the duct has a density equal to air. This is not exactly the case when performing fire tests. The density difference can be estimated by performing calculations on several pure fuels assuming complete or not complete combustion. Based on these calculations one can conclude that a reasonable estimated relative standard deviation for the density is 0.5 % which gives a relative standard deviation of 0.3 % for the factor "22.4" since the density is included to the power of ½. The uncertainty in the factor decreases if the amount of fresh air sucked into the duct is increased. The relative sensitivity coefficient is 1. The calculation in Equation (5-1) is identical in the Room/Corner Test and the SBI.

5.1.5 k_t

The ratio of the average volume flow per unit area to the volume flow per unit area in the centre of the exhaust duct, k_t, is determined by measuring the velocity in the duct at several points in the cross section area[5,15]. The uncertainty is then estimated by repeating this and calculating the standard deviation considering all the measurements made. The relative uncertainty in k_t was then calculated using the t-distribution, which resulted in a relative standard uncertainty of 1.044 %. Another means to estimate the uncertainty is to study how the factor has varied over time if several earlier values are available. The relative sensitivity coefficient is 1. The Room Corner duct at SP has e.g. a k_t value of 0.87.

k_t is determined in the same way in the SBI and the same relative standard uncertainty is used here.

5.1.6 Δp

The uncertainty in measuring the pressure difference in the bi-directional probe is due to the reading of the pressure transducer, including the data-logger and the connection of the tubes between the transducer and the bi-directional probe. The uncertainty for the Room/Corner Test transducer at SP was estimated to 1 Pa, which results in a relative error of 0.33 % since the flow in the Room/Corner duct usually gives a pressure difference of 300 Pa. The relative sensitivity coefficient obtained by derivation is 0.5.

The SBI pressure transducer at SP has an uncertainty of 1 Pa and the normal Δp is approximately 60 Pa resulting in a relative error of 1.7 %.

5.1.7 Temperature

Measuring temperature is difficult. When using thermocouples, for example, care should be taken so that the cold junction temperature is measured correctly, that the thermocouple is mounted appropriately, etc. When estimating the errors in the temperature measurement it is assumed that the equipment is correctly installed.

The uncertainty in the temperature reading is due to the quality of the thermocouple, ageing of the thermocouple, the data logger and radiation. The accuracy of the data logger is ± 0.5 °C. The quality of the thermocouple results in a maximum error of ± 2.5 °C. The ageing results in a maximum error of 5 °C and the radiation in a maximum error of 4 °C. The ageing effect was based on the manuals from the manufacturer. The ageing effect results in a too high reading and the radiation results in a too low reading in the beginning of the test, which usually is the most interesting part of the test. The radiation error is due to the cold duct in the beginning of the test; at the end of the test the temperature of the gas is probably lower than the temperature of the duct. The radiation error was calculated from representative values of the temperature, velocity in the duct and the diameter of the thermocouple. All errors were assumed equally distributed. The relative sensitivity coefficient obtained by derivation is therefore 0.5.

When there is an error that adds on only at the negative side or the positive side one should correct for that error. However, in this case we have one error on each side resulting in only 1 °C error and thus no correction is made. However, the standard uncertainty is calculated from all the uncertainty factors splitting the errors that only occurs on one side to be on both the negative and positive side, i.e. ± 0.25 °C (logger), ± 2.5 °C (quality), ± 2.5 °C (ageing) and ± 2 °C (radiation). These errors result in a relative standard uncertainty for the temperature reading in the Room/Corner Test of 0.5 %.

The same values can be adopted for both the Room/Corner Test and the SBI tests. The SBI does however use three thermocouples and therefore the relative standard uncertainty is reduced by a factor of $\sqrt{3}$.

5.1.8 k_p

The error in k_p is estimated from the data by McCaffrey and Heskestad[14]. The maximum error is estimated to 2 % if the Reynolds number is > 3800 which is the case in the Room/Corner Test and the SBI. An equal distribution is assumed which gives a relative standard uncertainty of 1.15 %. The relative sensitivity coefficient is 1. The same uncertainty in k_p can be used for the Room/Corner Test and the SBI.

5.2 Oxygen concentration

Anyone who is experienced in HRR measurements knows that the O_2 concentration is by far the most important property. This also clearly appears in the relative sensitivity coefficients calculated in Appendix A1. Therefore much effort was put into trying to find possible sources of error in the O_2 measurement. In this example study the same analyser rack was used for both the SBI and the Room/Corner Test. The combined uncertainty has been calculated at two levels of HRR, 150 kW and 1 MW for the Room/Corner Test, corresponding to O_2 concentrations of approximately 20.5 % and 18 % O_2. In the SBI the levels chosen were 35 kW and 50 kW, corresponding to approximately 20.65 % and 20.5 % O_2.

5.2.1 The Room/Corner Test

The combined expanded relative standard uncertainty for the two HRR/O_2 levels chosen is presented in Table 5-3. The result is a sum of many possible error sources which are presented in detail in Appendix A1. In this appendix the relative sensitivity coefficients for O_2 in the HRR equation are also calculated. The relative uncertainty of O_2 at the 1 MW level is much larger than on the 150 kW level but the relative sensitivity coefficient for the 150 kW level is larger than the 1 MW level. In both cases the uncertainty in the oxygen concentration measurement has a strong influence on the uncertainty of the HRR determination.

Table 5-3 Summary of uncertainty in O_2 measurement for two levels of HRR in the Room/Corner Test

Oxygen concentration	Relative standard uncertainty $u(x_i)$ (%)	Relative sensitivity coefficient in HRR equation $c_{r,i}$
20.5 % (150 kW)	0.082	-57
18 % (1 MW)	0.33	-6.6

5.2.2 The SBI

The relative sensitivity coefficients for the SBI are calculated in the same way as in the Room/Corner Test case, according to Appendix A1. The uncertainties are naturally of the same order as the 20.5 % level in the Room/Corner Test.

Table 5-4 Summary of uncertainty in O_2 measurement for two levels of HRR in the SBI

Oxygen concentration	Relative standard uncertainty $u(x_i)$ (%)	Relative sensitivity coefficient in HRR equation $c_{r,i}$
20.65 % (30 kW)	0.078	-81
20.5 % (50 kW)	0.082	-53

5.3 CO_2 concentration

From information in the manual the relative error was estimated to be 2 % for X_{CO_2}. A triangular distribution was assumed which results in a relative standard uncertainty of 0.82 %. The relative sensitivity coefficient was obtained by a parameter study, which gave -0.18 for the 150 kW case and -0.13 for the 1 MW case in the Room/Corner Test. For the SBI levels the relative sensitivity coefficient obtained by parameter study was -0.18 for the 50 kW case and -0.19 for the 35 kW case.

The sensitivity coefficients are evidently much lower for CO_2 compared with the O_2 coefficients. Therefore errors in the CO_2 measurement are not as greatly influencing the HRR uncertainty.

5.4 The E-factor

The E-factor is the amount of energy released per kilogram consumed oxygen. The E-factor is available for several fuels in the literature[16,17,18] and can be calculated from the heat of formation or heat of combustion.

In many practical situations the E-factor is unknown since the burning material consists of several fuels. However, comparisons between several different fuels have shown that for most common organic fuels the E-factor is about 13.1 MJ/kg O_2[6] with a variation of 5 %[16]. Using this uncertainty and assuming a triangular distribution one obtains a relative standard uncertainty of 2 %. The relative sensitivity coefficient is 1. When the fuel is known one should use the E-factor for that particular fuel and thus the uncertainty is reduced and can be neglected in the case of complete combustion of the test products.

However, the E-factors reported in the literature and the 13.1 MJ/kg value is valid for complete combustion of the fuel, i.e. no CO is formed etc. This is the case for well-ventilated fires. In some situations where the fire is ventilation controlled, e.g. at a flashover, soot, CO and unburned hydrocarbons are produced and therefore the uncertainty in the E-factor increases. If CO is produced then the E-factor decreases and if soot is formed the E-factor increases. In those cases it is possible to use an alternative HRR calculation taking into account the CO concentration. Further analysis of the E-factor has not been included in the uncertainty calculation in this project.

During calibration of heat release equipment, known fuels, such as propane, are commonly used in well-ventilated conditions. In these cases the E-factor is known and the correct values is used instead of 13.1 MJ/kg.

The uncertainty in the E-factor is in most cases independent of the experimental apparatus, assuming ventilated fires below flashover level.

5.5 Ambient pressure

Ambient pressure could potentially influence the measurement of several of the quantities in Equation (3-1), such as for example the oxygen concentration. The ambient pressure is also included as a factor in the calculation of the water content or humidity in the ambient air. However the uncertainty in the humidity depending on the ambient pressure was considered to be negligible.

5.6 Humidity

The humidity in ambient air, $X^0_{H_2O}$, is given by

$$X^0_{H_2O} = \frac{RH}{100} \cdot \frac{p_s(T_0)}{p_0} \qquad (5\text{-}3)$$

where

RH	= relative humidity (%)
$p_s(T_0)$	= saturation pressure for water vapour at temperature T_0 (Pa)
T_0	= ambient temperature (K)
p_0	= Ambient pressure (Pa)

$p_s(T_0)$ is tabulated in the literature but it is desired to calculate this automatically and this is possible using (5-4) for ambient temperature between 0 and 50 °C
($273 \text{ K} \leq T_0 \leq 323 \text{ K}$) [13]:

$$p_s = e^{\left(23{,}2 - \frac{3816}{T_0 - 46}\right)} \tag{5-4}$$

The temperature of ambient air is included in Equations (5-3) and (5-4). The uncertainty in this measurand is not taken into account in the calculation of the uncertainty of the humidity. Worst case is assumed to be when no *RH*-measurement is made and only a guess of 50 % *RH* is input into the calculation. If the actual *RH* is assumed to vary between 20 and 80 % a guess of 50 % results in maximum relative error of 150 %. This error is input into the calculation of the total HRR uncertainty.

The relative sensitivity coefficient can be derived from the above equations which results in

$$c_{r,RH} = \frac{-1}{\dfrac{100 p_0}{RH \cdot p_s(T_0)} - 1} \tag{5-5}$$

where $c_{r,RH} = -0.0038$ if the ambient temperature equals 290 K, the ambient air pressure 101325 Pa and $RH = 20$ %. This means that despite the high relative error of 150 % for the *RH*, the overall uncertainty for the HRR is not affected very much. These values are independent of apparatus.

5.7 The molecular weight of the gas species

The relative error in the molecular weight of the gas species in the exhaust duct was estimated to 1 %. The estimation was made out of the same calculations as that for the density in the exhaust duct since the density is a function of the molecular weight. The relative sensitivity coefficient for the molecular weight of the exhaust gases equals 1. The uncertainty of the molecular weight is scenario dependent but not apparatus dependent, i.e. the ventilation matters. The more diluted smoke gas the less error.

5.8 The expansion factor, α

The expansion factor α is the ratio of the number of moles of combustion products to the number of moles of reactants. The nitrogen content of the air is included in the ratio in both the nominator and denominator. The relative error in this ratio is estimated to 10 %[13], independent of the apparatus. The relative sensitivity coefficient for α is calculated from

$$c_{r,\alpha} = \frac{-\alpha}{\alpha - 1 + \dfrac{1 - \dfrac{X_{O_2}}{1 - X_{CO_2}}}{X_{O_2}^0 - X_{O_2} \cdot \dfrac{1 - X_{CO_2}^0}{1 - X_{CO_2}}} \cdot X_{O_2}^0} \tag{5-6}$$

which for the Room/Corner Test results in a sensitivity coefficient of -0.025 for 150 kW and -0.16 for 1 MW and for the SBI in -0.017 for 35 kW and -0.025 for 50 kW.

6 Combined uncertainty in heat release rate measurements

The combined expanded relative standard uncertainty with a 95 % confidence interval is calculated according to Equation 2-5. The results for the two HRR levels chosen for the Room/Corner Test and the SBI is presented below in tables. The main contributors to the total uncertainty are easily recognised in the tables.

6.1.1 The Room/Corner Test

Using the uncertainties presented in the sections above, the combined expanded relative standard uncertainty for the HRR measurement at the 150 kW level is determined to 10.6 % using a coverage factor $k = 2$ as presented in table 6-1 below. It is easily recognized in the table that the uncertainty in the oxygen concentration contributes most, followed by the E-factor and the mass flow in the exhaust duct.

Table 6-1 HRR uncertainty at the 150 kW level

Quantity x_i	Relative error (%)	Relative standard uncertainty $u(x_i)/x_i$ (%)	Relative sensitivity coefficient, $c_{r,i}$	Contribution to combined relative uncertainty of HRR measurement $c_{r,i} \cdot u(x_i)/x_i = u_i(y)$ (%)
Mass flow in duct		1.6	1	1.6
O_2		0.08	-57	4.6
CO_2	2	0.82	-0.18	0.2
E-factor	5	2.0	1	2.0
α	10	5.8	-0.025	0.1
Humidity	150	61.2	-0.0038	0.2
Molecular weight of gas species	1	0.58	1	0.6
Ambient pressure				negligible (included in O_2 error)
Combined expanded relative standard uncertainty				**10.6 %**

Table 6-2 HRR uncertainty at the 1 MW level

Quantity x_i	Relative error (%)	Relative standard uncertainty $u(x_i)/x_i$ (%)	Relative sensitivity coefficient, $c_{r,i}$	Contribution to combined relative uncertainty of HRR measurement $c_{r,i} \cdot u(x_i)/x_i = u_i(y)$ (%)
Mass flow in duct		1.6	1	1.6
O_2		0.3	-6.6	2.2
CO_2	2	0.82	-0.13	0.1
E-factor	5	2.0	1	2.0
α	10	5.8	-0.16	0.9
Humidity	150	61.2	-0.0038	0.2
Molecular weight of gas species	1	0.58	1	0.6
Ambient pressure				negligible (included in O_2 error)
Combined expanded relative standard uncertainty				**7.1 %**

For the 1 MW case the combined expanded relative standard uncertainty for the HRR measurement was determined to 7.1 % using a coverage factor *k* = 2 as presented in table 6-2. Also in this case the uncertainty in the oxygen concentration, the E-factor and the mass flow in the exhaust duct are the most important parameters. A higher HRR means less oxygen in the duct and thus the difference between the ambient concentration and the concentration in the duct increases, which makes the uncertainty in determining the difference less.

6.1.2 The SBI

The combined expanded relative standard uncertainty for the SBI is presented in table 6-3 and 6-4 below. Most of the data from the Room/Corner Test study can be directly applied to the SBI apparatus. However, some parameters have a different uncertainty as explained in Section 5.

Table 6-3 HRR uncertainty at the 35 kW level

Quantity x_i	Relative error (%)	Relative standard uncertainty $u(x_i)/x_i$ (%)	Relative sensitivity coefficient, $c_{r,i}$	Contribution to combined relative uncertainty of HRR measurement $c_{r,i} \cdot u(x_i) / x_i = u_i(y)$ (%)
Mass flow in duct		1.7	1	1.7
O_2		0.078	-81	6.3
CO_2	2	0.82	-0.18	0.15
E-factor	5	2.0	1	2.0
α	10	5.8	-0.017	0.1
Humidity	150	61.2	-0.0038	0.2
Molecular weight of gas species	1	0.58	1	0.6
Ambient pressure				negligible (included in O_2 error)
Combined expanded relative standard uncertainty				**13.5 %**

Table 6-4 HRR uncertainty at the 50 kW level.

Quantity x_i	Relative error (%)	Relative standard uncertainty $u(x_i)/x_i$ (%)	Relative sensitivity coefficient, $c_{r,i}$	Contribution to combined relative uncertainty of HRR measurement $c_{r,i} \cdot u(x_i) / x_i = u_i(y)$ (%)
Mass flow in duct		1.7	1	1.7
O_2		0.08	-53	4.2
CO_2	2	0.82	-0.18	0.15
E-factor	5	2.0	1	2.0
α	10	5.8	-0.025	0.1
Humidity	150	61.2	-0.0038	0.2
Molecular weight of gas species	1	0.58	1	0.6
Ambient pressure				negligible (included in O_2 error)
Combined expanded relative standard uncertainty				**10.0 %**

The tables for the SBI show quite a high HRR uncertainty, mainly due to the O_2 uncertainty. At the 35 kW level, 13.5 % means ± 4.7 kW for a single value. This is, however, a conservative value as the calculation in the SBI standard requires 30 s averaged values and measurements are made every third second. The combined expanded relative standard uncertainty for the 30 s averages is 4.3 % (= $13.5\% / \sqrt{10}$) for the 35 kW level and 3.2 % for the 50 kW level. See further Section 9 for a discussion on averaging.

7 Sources of uncertainty in smoke release rate measurements

The size of the different uncertainty contributions for the SPR is not constant over the whole measurement range. Therefore the uncertainty at several different levels of SPR was estimated, breaching the range of interest considering smoke classification criteria. Some of the parameters included in Equations (4-1) and (4-2) also emerge in the HRR equation, i.e. $\dot{V}_{T_s}$ and L. The uncertainty contributions from these parameters are compiled in Section 5.

The smoke measurement in the two test methods studied is almost identical, using white light lamps and the same calculations. Therefore the uncertainty sources are the same for both test methods.

7.1 Mass flow in duct and gas temperature

The error contribution from the mass flow and the temperature was studied thoroughly for the HRR in Section 5.1 and the same values are used for the smoke error analysis.

7.2 Soot accumulation on lenses

During a test there is a risk for soot accumulation on the lenses in the optical system, which will disturb the measurement. To reduce this problem an overpressure is created with compressed air around the lenses on both sides of the duct. But even with the air system in use there is a risk for soot deposition when testing products producing excessive amounts of smoke.

7.2.1 The Room/Corner Test

The soot accumulation error can be detected comparing the baseline before the test with a base line after the test with no smoke. In practice it is difficult to record the base line after a test of products which produce a large amount of smoke as it will take a long time before absolutely no smoke is passing the optical system. When studying several calibration tests a maximum error of 1 % of the transmission could be detected. This is, of course, assuming that the overpressure at the lenses is maintained and produced in a functional way.

7.2.2 The SBI

In the SBI, there is a better check of the signal after the test and also a criterion for the maximum allowed difference between before- and after-test conditions (2 %).

7.3 Filter calibration

The optical system should be calibrated at least every six months using neutral optical density filters with a known optical density value in the range 0.02 – 2.0. The relative error in the actual filter density is 1 % according to the calibration of the filters[19].

The calibration of the optical system studied in the Room/Corner Test was performed with five different filters and the maximum deviation from the filter value was ± 2.5 % of the transmission.

The same type of filters is used for the SBI and therefore the same uncertainty is assumed as a conservative estimate.

7.4 Noise and drift

The uncertainty contributions from noise and drift can be determined by letting the optical system run for 30 min without any fire but with exhaust flow through the duct. The drift is then computed by fitting a straight line through the data from 0 to 30 min and comparing the values of this line at t = 0 and t = 30 min respectively. The noise is determined by taking the RMS (Root-Mean-Square), of the data deviation from the fitted straight line. An example for the Room/Corner Test is shown below.

In this report, however, the maximum allowed value, i.e. 0.5 %, was chosen both as the noise and drift error for both the Room/Corner Test and the SBI.

In the example from the Room/Corner Test the drift can be determined as 0.4 mV (0.3 % of start value) and the noise as 0.29 mV (0.23 % of start value), see Figure 7-1. One way to minimise possible drift problems is to mount the system free standing from the duct.

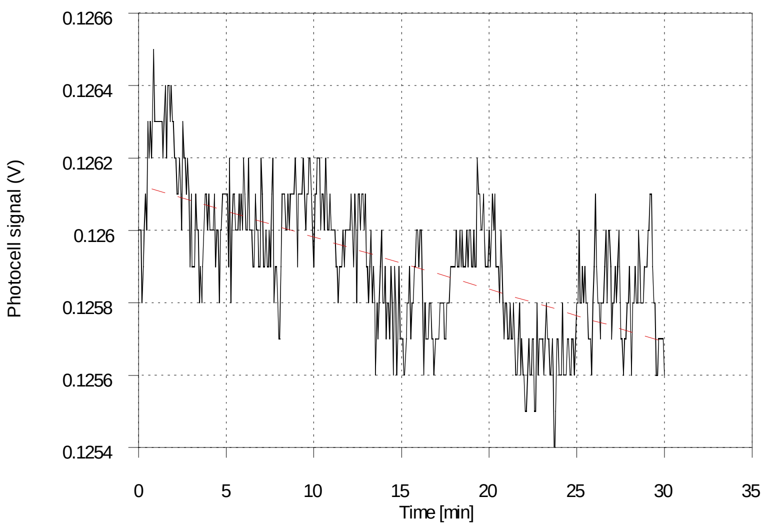


Figure 7-1 Photocell signal from the Room/Corner Test with a fitted straight line, drift and noise check.

7.5 Temperature influence

One source of error when measuring smoke is the thermal expansion of the duct during a test. This can cause the focus of the light to be diverted slightly from the photocell. A laser light system is, however, much more sensitive to thermal movement than a white light system because of the precision of the beam. Another source of error can be the photocell being sensitive to temperature increase. Some photocells without filters may also pick up infrared radiation coming from hot duct walls but this is regarded negligible.

To investigate the influence of temperature on the photocell signal in the Room/Corner Test, pure methanol giving very little smoke was burned under the hood while measuring the light signal. Three tests were performed with a peak HRR of about 250 kW. The light signal changed slightly in each test but never more than 1.5 mV. The same influence is assumed in the SBI.

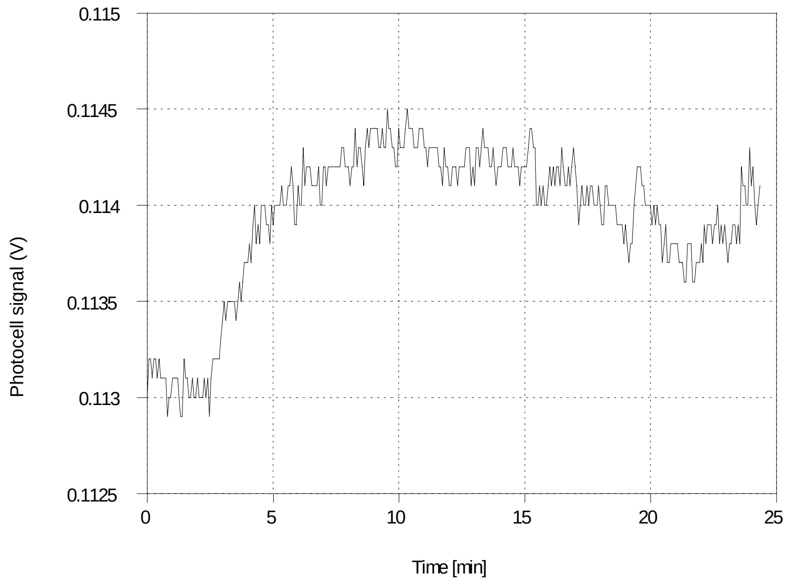


Figure 7-2 Example of temperature influence on photocell signal in the Room/Corner Test.

7.6 Length of extinction beam

The optical path length through the smoke, L, equals the diameter of the duct since the optical system is mounted across the duct. The uncertainty in the duct diameter L is discussed in Section 5.1.3.

8 Combined uncertainty in smoke production rate measurements

All the sources of error catalogued in Section 7 are added according to Equation 2-5 in order to calculate the combined expanded relative standard uncertainty of the SPR. The error is very dependent on the level of SPR and in Table 8-1 below, the uncertainty is presented for several levels. For details on the calculations and the individual contribution from each error source, see appendix A2. Only one table is presented for both the Room/ Corner Test and the SBI as the contributions are of almost identical magnitude. The most interesting result is the very high uncertainty on the low SPR levels, a fact that should be considered when classifying products that produce little smoke.

Table 8-1 Summary of uncertainty for different levels of SPR

SPR level (m^2/s)	Combined expanded relative standard uncertainty (%)
0.1	103
0.3	35.0
0.5	21.5
1.0	11.6
5.0	6.2
10.0	4.9

9 Discussion

The total expanded uncertainty presented in this report is the uncertainty when measuring the HRR or SPR as one record. In fire tests, a dynamic measurement is made and it is usually the level of a curve varying in time that is studied.

Especially when performing calibrations of the HRR, a fire producing a constant HRR is used and measurements are made under several of minutes. This results in that the uncertainty is decreased by a factor of $\sqrt{n}$, where n is the number of records, provided that the errors are random. For example, if the HRR is calculated as a mean value of 100 measurements then the uncertainty in the HRR decreases by a factor of $\sqrt{100}$, which results in a relative uncertainty of about 1 %. This value is in close agreement with calibration uncertainties previously reported[20] for calibration of HRR measurements in the Room/Corner Test.

If a fire scenario with a narrow peak in HRR is studied then the relative uncertainty is in the order of 10 % since the relative uncertainty for a single value at the 150 kW level is 11 % and 7 % at the 1 MW level in the Room/Corner Test. However, mean values are usually studied in fire tests. Especially in the SBI, 30 s averages are studied which reduces the uncertainty by a factor $\sqrt{10}$ if measurements are performed every third second as defined in the standard.

The results in this report clearly indicate which parameters in the SPR and HRR measurements that contribute most to the uncertainty. For the HRR, the oxygen concentration contributes most followed by the E-factor and the mass flow. The uncertainty in the oxygen measurement depends on the instrument used and the size of the fire. The E-factor is independent of the experimental apparatus but depends on the fuel used. If the fuel is known then the uncertainty decreases. The uncertainty in the velocity profile in the duct and the bi-directional probe constant are the most important for the mass flow. The uncertainty in the velocity profile can be decreased by designing the duct correctly and determining the velocity profile more precisely. For the SPR the most important factors are the calibration of the filters used for calibrating the equipment together with the temperature sensitivity of the photocell. The most interesting result is the very high uncertainty on the low SPR levels, a fact that should be considered when classifying products that produce little smoke.

Another means to estimate the overall uncertainty in HRR and SPR measurements is to study how much the measurements fluctuate when conducting measurements on a constant level of HRR and SPR. It is important to note that when making this kind of estimate no information on which parameters contributes most is identified.

The overall uncertainties presented here are in the same order of magnitude for the HRR measurements as those reported by Dahlberg[8] and Enright and Fleischmann[9]. The same parameters are identified as the most important, i.e. the oxygen and the mass flow measurement.

Estimating the uncertainty in the measurements as described in this report is very useful since the areas where special care should be taken to perform the measurements as well as possible are identified. In addition the people taking part in the process learn a lot about the measurements.

10 Guidelines

Guidelines on how to estimate the combined expanded relative standard uncertainty in HRR and SPR measurements are given below:

10.1 Estimation of relative standard uncertainty

Estimate the relative standard uncertainty for all parameters in the calculation by statistical methods, studying the manuals for the instruments, performing experimental studies of the signals (drift, noise, etc.) and/or making expert judgements. In cases where the maximum relative error is estimated, the relative standard uncertainty is obtained by dividing the maximum relative error by $\sqrt{3}$ if a rectangular distribution is assumed and by $\sqrt{6}$ if a triangular distribution is assumed. If the standard uncertainty u_i is due to several errors u_{i1}, u_{i2}… then it is calculated as

$$u_i = \sqrt{u_{i1}^2 + u_{i2}^2 + ...} \qquad (10\text{-}1)$$

Some standard uncertainties used in this report are directly applicable to all estimates of uncertainty in HRR and SPR measurements. These include the E-factor, the expansion due to combustion, α, the bi-directional probe constant, k_p, and the ambient air conditions:

- The maximum relative error is 5 % for the E-factor which results in a relative standard uncertainty of 2 % assuming a triangular distribution of the E-factor. If the fuel is known then the correct value for the E-factor should be used and the standard uncertainty for the E-factor can be omitted if complete combustion is assumed. However, if the combustion is incomplete then the uncertainty of the E-factor should be increased.

- For the expansion factor, α, the maximum relative error is 10 % which results in a relative standard uncertainty of 5.8 %, assuming a rectangular distribution.

- The relative standard uncertainty for bi-directional probe constant, k_p, is 1.2 %.

- The uncertainty in the ambient pressure and humidity measurement can be considered as negligible since even a very large error in these affects the HRR very little.

The following uncertainties must be evaluated for each test set up. The values given apply to the conditions of the test set ups at SP:

- The uncertainty of the internal cross section area of the duct is estimated by statistical methods or, as in this report, by reasoning and performing some measurements.

- The standard uncertainty in the factor “22.4” is due to the unknown density of the gas in the duct. A higher dilution of the smoke gases in the duct means a lower uncertainty. The relative standard uncertainty used in this report is 0.3 % for all cases.

- The uncertainty in the ratio between the average volume flow per unit area and the volume flow per area in the centre, k_t, is best determined by determining the k_t several times and calculating the relative standard uncertainty assuming a t-distribution of k_t.

- The uncertainty in the measurement of the pressure difference in the bi-directional probe is due to the reading of the pressure transducer, including the data-logger and the connection of the tubes between the transducer and the bi-directional probe. This can be estimated using data from the manual of the pressure transducer.

- The uncertainty in the temperature reading depends on the quality of the thermocouple, ageing of the thermocouple, radiation effects and the logger used for registering the temperature. In many cases the error in the logger is most likely negligible. The error due to the quality of the thermocouple is obtained from the thermocouple supplier. Ageing of the thermocouple results in a too high reading. The error due to radiation results in a too low reading in the beginning of the test which is the most important part of the test. When there is an error that adds on only at the positive or the negative side one should correct for that error. In this case, however, the radiation and ageing error has opposite signs and therefore they are subtracted from each other and no correction of the temperature is probably needed. For example an ageing error of 5 °C and a radiation error of 4 °C gives an error of 1 °C. All errors should be included in the uncertainty calculation however. The radiation error is calculated from representative values of temperatures and velocities in the duct. The uncertainty due to the thermocouple quality has an unknown sign and therefore adds up the uncertainty according to Equation 9-1.

- The uncertainty of the CO_2 concentration is due to the analyser used and the calibration of the analyser. The uncertainty is estimated from data in the manual of the analyser and calibration procedures.

- The relative standard uncertainty in the molecular weight of the gaseous species in the duct can be estimated to 0.6 % assuming a dilution of the gases in the duct by a factor of 5. However, the uncertainty decreases with increased dilution of the smoke gases in the duct.

- The uncertainty in the oxygen measurements is due to several factors. If a paramagnetic oxygen analyser is used then the uncertainty is due to changes in ambient pressure during a test, how steady the gas flow through the analyser is, changes in ambient temperature during a test, the accuracy of the calibration gases and cross sensitivity of e.g. NO and CO_2. The possible variations of each of the parameters are estimated and then the manual of the oxygen analyser is studied to estimate how much each of the parameters influences the oxygen concentration measurement. In addition noise and drift are studied by measuring the oxygen concentration of the ambient air without a fire source.

- The error in the path length of the light in the SPR measurements can be estimated in a similar manner as for the cross sectional area of the duct.

- The error in the transmission of light through the smoke measurements is due to soot accumulation on the lenses, temperature influence of the photocell, uncertainties when calibrating using filters, errors in the filters used for calibration, noise and drift. Each parameter is estimated in a similar manner as for the oxygen analyser and added according to Equation 10-1.

10.2 Calculation of relative sensitivity coefficients

Calculate the relative sensitivity coefficient, $c_{r,i}$, of each of the "computed" parameters according to Equation 10-2 :

$$c_{r,i} = \frac{\partial y}{\partial x_i} \cdot \frac{x_i}{y} \tag{10-2}$$

by partial derivation of the equations or by doing a parameter study.

Most parameters have a relative sensitivity coefficient of 1, these include the factor "22.4", k_t, k_p, the area of the duct, the volumetric or mass flow in the duct, the E-factor, the molecular weight of the gases in the duct and the path length in the transmission measurements. Some have a relative sensitivity coefficient of 0.5, these include the differential pressure in the bi-directional probe and the temperature.

The relative sensitivity coefficient for the oxygen concentration is given by

$$c_{r,O_2} = \frac{\dfrac{X^0_{O_2} + X^0_{CO_2} - 1}{1 - X_{CO_2}}}{\left(X^0_{O_2} - X_{O_2} \cdot \dfrac{1 - X^0_{CO_2}}{1 - X_{CO_2}} \right)^2 \cdot \left(\dfrac{\alpha - 1}{X_{O_2} \cdot X^0_{O_2}} + \dfrac{\dfrac{1}{X_{O_2}} - \dfrac{1}{1 - X_{CO_2}}}{X^0_{O_2} - X_{O_2} \cdot \dfrac{1 - X^0_{CO_2}}{1 - X_{CO_2}}} \right)} \tag{10-3}$$

and the relative sensitivity coefficient for α is obtained from

$$c_{r,\alpha} = \frac{-\alpha}{\alpha - 1 + \dfrac{1 - \dfrac{X_{O_2}}{1 - X_{CO_2}}}{X^0_{O_2} - X_{O_2} \cdot \dfrac{1 - X^0_{CO_2}}{1 - X_{CO_2}}} \cdot X^0_{O_2}} \tag{10-4}$$

For both I_0 and I in the SPR calculations the relative sensitivity coefficient equals

$$c_{r,I} = \frac{1}{\ln \dfrac{I}{I_0}} \tag{10-5}$$

As we can see the coefficients are dependent of the actual measurement value.

10.3 Calculation of combined relative standard uncertainty

Calculate the combined relative standard uncertainty according to

$$\frac{u_c}{y} = \sqrt{c_{r,1}^2 \frac{u_1^2}{x_1} + c_{r,2}^2 \frac{u_2^2}{x_2} + \ldots.} \qquad (10\text{-}6)$$

10.4 Calculation of combined expanded relative standard uncertainty

Multiply the combined relative standard uncertainty by a factor of 2 in order to get the combined expanded relative standard uncertainty with approximately a 95 % confidence interval.

11 References

[1] *European and International Standard – General requirements for the competence of testing and calibration laboratories*. EN ISO/IEC 17025:2000 (ISO/IEC 17025:1999) (E). CEN/CENELEC Central Secretariat, Brussels (2000) and International Organization for Standardization, Geneva 1999.

[2] *International Standard – Quality assurance requirements for measuring equipment – Part 1: Metrological confirmation system for measuring equipment*. ISO 10012-1:1992 (E). International Organization for Standardization, Geneva 1992.

[3] EAL-R2, *Expression of the uncertainty of measurement in calibration,* European cooperation for Accreditation of Laboratories.

[4] GUM*, Guide to the expression of uncertainty in measurement,* BIPM/IEC/IFCC/ISO/IUPAC/ IUPAP/OIML, ISBN 92-67-10188-9

[5] *Draft European Standard – Reaction to fire tests for building products – Building products excluding floorings exposed to the thermal attack by a single burning item*. prEN 13823:2000 (E). CEN Central Secretariat, Brussels 2000.

[6] *International Standard – Fire tests -- Full-scale room test for surface products*. ISO 9705:1993(E). International Organization for Standardization, Geneva, 1993.

[7] *Draft European Standard – Fire Classification of construction products and building elements - Part 1 Classification using test data from reaction to fire tests.* prEN 13501-1 (E). CEN Central Secretariat, Brussels 2000.

[8] M. Dahlberg, *Error Analysis for Heat Release Rate Measurement with the SP Industry Calorimeter*, SP REPORT 1994:29, Borås 1993.

[9] T. Enright and C. Fleischmann, *An Uncertainty Analysis of Calorimetric Techniques,* Poster Notes – 5th International Symposium on Fire Safety Science, pp1332 (Melbourne, March 1997)

[10] T. Enright and C. Fleischmann, *Uncertainty of Heat Release Rate Calculation of the ISO5660-1 Cone Calorimeter Standard Test Method*, Fire Technology, Vol. 35, No. 2, 1999.

[11] A. Lönnermark and V. Babrauskas, *TOXFIRE - Fire Characteristics and Smoke Gas Analyses in Under-ventilated Large-scale Combustion Experiments: Theoretical Background and Calculations* SP REPORT 1996:49, Borås 1997

[12] W. J. Parker, *Calculations of the Heat Release Rate by Oxygen Consumption for Various Applications* NBSIR 81-2427, National Bureau of Standards, 1982

[13] M. Janssens and W. J. Parker, *Oxygen consumption calorimetry*, "Heat release in fires", V. Babrauskas, S. J. Grayson, Eds. (E & FN Spon), pp. 31-59, London, UK, 1995

[14] B.J. McCaffrey and G. Heskestad, *Brief Communications: A Robust Bidirectional Low-Velocity Probe for Flame and Fire Application,* Combustion and Flame 26 (1976)

[15] *International Standard – Measurement of fluid flow in closed conduits – Velocity area method using Pitot static tubes.* ISO 3966:1977 (E). International Organization for Standardization, Geneva, 1977.

[16] C. Huggett, *Estimation of Rate of Heat Release by Means of Oxygen Consumption Measurements,* Fire and Materials 4, pp. 61-65, 1980

[17] A. Tewarson, *Generation of heat and chemical compounds in fires,* "SFPE Handbook of Fire Protection Engineering", P.J. DiNenno, et al., Eds. The National Fire Protection Association, USA 1995

[18] V. Babrauskas, *Heat of combustion and potential heat*, "Heat release in fires", V. Babrauskas, S. J. Grayson, Eds. E & FN Spon), pp. 207-223, London, UK, 1995

[19] SP Calibration Report 01-F97034

[20] B. Sundström, P. Van Hees and P. Thureson, *Results and Analysis from Fire Tests of Building Products in ISO 9705, the Room/Corner Test*, SP REPORT 1998:11, Borås 1998.

Appendix

The uncertainties involved in measuring the oxygen concentration and the SPR are presented in more detail below together with the derivation of the relative sensitivity coefficients.

A1 Detailed analysis of error sources and relative sensitivity coefficients for the oxygen concentration

The uncertainty in the oxygen measurements is due to several factors. If a paramagnetic oxygen analyser is used then the uncertainty is due to changes in:

- ambient pressure during a test
- how steady the gas flow through the analyser is
- changes in ambient temperature during a test
- the accuracy of the calibration gases and cross sensitivity of e.g. NO and CO_2

The uncertainty was studied for two levels of HRR and oxygen concentration in both the Room/Corner Test and the SBI. Each parameter that might be an error source contributing to the uncertainty in the O_2 measurement is presented in Tables A1-1 – A1-3 below. All uncertainties are assumed to have a rectangular distribution. The O_2 concentration is about the same (20.5 %) for the Room/Corner Test at 150 kW and the SBI at 35 kW why only the Room/Corner Test values are presented for these cases. The possible variations of each of the parameters were estimated and then the manual of the oxygen analyser was studied to estimate how much each of the parameters influences the oxygen concentration measurement.

The noise and drift of the analyser signal was studied by making several oxygen measurements without a HRR source over a relevant time period. Measurements were performed both on ambient air and with a calibration gas containing 16 % O_2. The influence of measuring range was also studied, i.e. the analyser can be set to measure
0 – 21 % or 16 – 21 %.

Improper drying of the sample gas has a big impact on the oxygen measurement but we have assumed that the sample gas is dried with a proper and fresh drying agent.

It is important to keep in mind that the uncertainty contributions are very much depending on the analyser and type of analyser.

Table A1-1 Estimate of the expanded uncertainty for O_2 concentration in the Room/Corner Test at 20,5 % O_2 (≈150 kW)

Quantity x_i	Relative error (%)	Relative standard uncertainty $u(x_i)/x_i$ (%)	Relative sensitivity coefficient, $c_{r,i}$	Contribution to combined relative uncertainty of O_2 measurement $c_{r,i} \cdot u(x_i) / x_i = u_i(y)$ (%)
Ambient pressure	0.05	0.03	1	0.03
Flow	0.03	0.02	1	0.02
Voltage supply	negligible			
Ambient temperature	0.120	0.07	1	0.07
Reference gas 16 %	0.007	0.004	1	0.004
Noise	0.029	0.02	1	0.02
Drift	0.024	0.01	1	0.01
Humidity from dessicant	see text above			
Cross sensitivity NO 100 ppm	0.02	0.01	1	0.01
Combined expanded relative standard uncertainty				**0.16 %**

Table A1-2 Estimate of the expanded uncertainty for O_2 concentration in the Room/Corner Test at 18 % O_2 (≈ 1 MW)

Quantity x_i	Relative error (%)	Relative standard uncertainty $u(x_i)/x_i$ (%)	Relative sensitivity coefficient, $c_{r,i}$	Contribution to combined relative uncertainty of O_2 measurement $c_{r,i} \cdot u(x_i) / x_i = u_i(y)$ (%)
Ambient pressure	0.53	0.31	1	0.31
Flow	0.03	0.02	1	0.02
Voltage supply	negligible			
Ambient temperature	0.142	0.08		
Reference gas 16 %	0.089	0.05	1	0.08
Noise	0.034	0.02	1	0.05
Drift	0.028	0.02	1	0.02
Humidity from desiccant	see text above		1	0.02
Cross sensitivity NO 100 ppm	0.03	0.02	1	0.02
Combined expanded relative standard uncertainty				**0.65 %**

Table A1-3 Estimate of the expanded uncertainty for O_2 concentration in the SBI at 20,65 % O_2 (≈35 kW)

Quantity x_i	Relative error (%)	Relative standard uncertainty $u(x_i)/x_i$ (%)	Relative sensitivity coefficient, $c_{r,i}$	Contribution to combined relative uncertainty of O_2 measurement $c_{r,i} \cdot u(x_i)/x_i = u_i(y)$ (%)
Ambient pressure	0.03	0.017	1	0.017
Flow	0.03	0.02	1	0.02
Voltage supply	negligible			
Ambient temperature	0.120	0.07	1	0.07
Reference gas 16 %	0.005	0.003	1	0.003
Noise	0.029	0.02	1	0.02
Drift	0.024	0.01	1	0.01
Humidity from dessicant Drierite	see text above			
Cross sensitivity NO 100 ppm	0.02	0.01	1	0.01
Combined expanded relative standard uncertainty				**0.15 %**

When calculating the combined expanded uncertainty for HRR the standard uncertainties for each parameters are used, not the expanded parameter uncertainty (i.e. without the coverage factor of 2).

The HRR dependence on the oxygen concentration is rather complex (see Equation 2.1) and calculating the relative sensitivity coefficient c_{r,O_2} becomes somewhat complicated. The coefficient is obtained by partial derivation of Equation 2.1 with respect to X_{O_2}. Since relative errors are used then the relative sensitivity coefficient should be of the form

$$\frac{\Delta HRR}{HRR}\left(X_{O_2}\right) = c_{r,O_2} \cdot \frac{\Delta X_{O_2}}{X_{O_2}} \tag{A1-1}$$

which is a very useful form. Performing the derivation and rearranging result in:

$$c_{r,O_2} = \frac{\dfrac{X_{O_2}^0 + X_{CO_2}^0 - 1}{1 - X_{CO_2}}}{\left(X_{O_2}^0 - X_{O_2} \cdot \dfrac{1 - X_{CO_2}^0}{1 - X_{CO_2}}\right)^2 \cdot \left(\dfrac{\alpha - 1}{X_{O_2} \cdot X_{O_2}^0} + \dfrac{\dfrac{1}{X_{O_2}} - \dfrac{1}{1 - X_{CO_2}}}{X_{O_2}^0 - X_{O_2} \cdot \dfrac{1 - X_{CO_2}^0}{1 - X_{CO_2}}}\right)} \tag{A1-2}$$

Another way to determine the relative sensitivity coefficient is to perform a sensitivity study where the parameter X_{O_2} is varied and the influence on the HRR is observed. The results from using Equation (A1-2) are presented in Table A1-4. For two cases a sensitivity study was performed to check the reasonableness of the derived values.

Table A1-4 The absolute value of the relative sensitivity coefficients for X_{O_2} in HRR calculations calculated from Equation (A1-2)

Scenario	c_{r,O_2} from (A1-2)	c_{r,O_2} from parameter variation
The Room/Corner Test at 150 kW	57	55
The Room/Corner Test at 1 MW	6.6	7.1
The SBI at 35 kW	80.7	-
The SBI at 50 kW	53.1	-

A2 Detailed analysis of error sources and relative sensitivity coefficients for the Smoke Production Rate

As mentioned in Section 4 the SPR is calculated according to Equations (4-1) – (4-3) in both the SBI and the Room/Corner Test. In order to calculate the relative sensitivity coefficients the partial derivatives for each variable are presented below. The results are rearranged to a convenient form.

$$\frac{dSPR}{dL} = -\frac{SPR}{L}, \qquad \frac{dSPR}{dI_0} = \frac{SPR}{I_0 \cdot \ln\left(\frac{I_0}{I}\right)},$$
$$\frac{dSPR}{dI} = -\frac{SPR}{I \cdot \ln\left(\frac{I_0}{I}\right)}, \qquad \frac{dSPR}{dV_{T_s}} = \frac{SPR}{V_{T_s}}, \tag{A2-3}$$
$$\frac{dSPR}{dT_s} = \frac{SPR}{T_s}$$

The absolute uncertainty of the SPR can be written

$$\Delta SPR = \sqrt{\left(\frac{dSPR}{dL}\Delta L\right)^2 + \left(\frac{dSPR}{dI_0}\Delta I_0\right)^2 + \left(\frac{dSPR}{dI}\Delta I\right)^2 + \left(\frac{dSPR}{dV_{T_s}}\Delta V_{T_s}\right)^2} \tag{A2-4}$$

taking into account all relevant error sources. The temperature uncertainty is included in the uncertainty of the volume flow.

Inserting the partial derivatives in Equation (A2-3) for each variable and expressing the errors as relative errors results in

$$\frac{\Delta SPR}{SPR} = \sqrt{\left(\frac{\Delta L}{L}\right)^2 + \left(\frac{1}{\ln\left(\frac{I_0}{I}\right)} \cdot \frac{\Delta I_0}{I_0}\right)^2 + \left(\frac{1}{\ln\left(\frac{I_0}{I}\right)} \cdot \frac{\Delta I}{I}\right)^2 + \left(\frac{\Delta V_{T_s}}{V_{T_s}}\right)^2} \tag{A2-5}$$

One can now identify the relative sensitivity coefficients. An example is presented in Table A2-5 for a specific SPR level of 0.5 m^2/s assuming that the baseline intensity generates signal, I_0, of 150 mV. In the table each error source is presented along with the variable that it influences (in parenthesis). This same calculation procedure can be performed for different levels of SPR giving an estimate of the uncertainty over the whole range of interest, see Table 8-1.

Table A2-5 Overview of error sources in SPR measurement. Example for SPR=0.5 m^2/s

Quantity x_i (and affected variable)	Relative error (%)	Relative standard uncertainty $u(x_i)/x_i$ (%)	Relative sensitivity coefficient, $c_{r,i}$	Contribution to combined relative uncertainty of SPR measurement $c_{r,i} \cdot u(x_i) / x_i = u_i(y)$ (%)
Soot (I)	0.011	0.063	$1/\ln(I_0/I)$	0.08
Calibration (I)	0.027	0.016	$1/\ln(I_0/I)$	0.20
Temp. Influence (I)	1.08	0.63	$1/\ln(I_0/I)$	7.8
Filter (I)	1.0	0.58	$1/\ln(I_0/I)$	7.2
Noise (I)	0.005	0.0031	$1/\ln(I_0/I)$	0.04
Drift (I)	0.005	0.0031	$1/\ln(I_0/I)$	0.04
Volume flow	see Section 5.1	1.6	1	1.6
Temperature influence (L)	0.13	0.07	1.00	0.07
Combined expanded relative standard uncertainty				**21.5 %**

SP Swedish National Testing and Research Institute
Box 857, SE-501 15 BORÅS, Sweden
Telephone: + 46 33 16 50 00, Telefax: + 46 33 13 55 02
E-mail: info@sp.se, Internet: www.sp.se

SP REPORT 2001:04
ISBN 91-7848-846-X
ISSN 0284-5172