INTERNATIONAL RECOMMENDATION

OIML R 147

Edition 2016 (E)

Standard blackbody radiators for the temperature range from –50 °C to 2500 °C.

Calibration and verification procedures

Corps noirs étalons dans la gamme de température –50 °C à 2500 °C.

Procédures d'étalonnage et de vérification

OIML R 147 Edition 2016 (E)

ORGANISATION INTERNATIONALE
DE MÉTROLOGIE LÉGALE

INTERNATIONAL ORGANIZATION
OF LEGAL METROLOGY

Contents

Foreword

The International Organization of Legal Metrology (OIML) is a worldwide, intergovernmental organization whose primary aim is to harmonize the regulations and metrological controls applied by the national metrological services, or related organizations, of its Member States.

The main categories of OIML publications are:

- **International Recommendations (OIML R),** which are model regulations that establish the metrological characteristics required of certain measuring instruments and which specify methods and equipment for checking their conformity. OIML Member States shall implement these Recommendations to the greatest possible extent;
- **International Documents (OIML D),** which are informative in nature and which are intended to harmonize and improve work in the field of legal metrology;
- **International Guides (OIML G),** which are also informative in nature and which are intended to give guidelines for the application of certain requirements to legal metrology; and
- **International Basic Publications (OIML B),** which define the operating rules of the various OIML structures and systems.

OIML Draft Recommendations, Documents and Guides are developed by Project Groups linked to Technical Committees or Subcommittees which comprise representatives from the Member States. Certain international and regional institutions also participate on a consultation basis. Cooperative agreements have been established between the OIML and certain institutions, such as ISO and the IEC, with the objective of avoiding contradictory requirements. Consequently, manufacturers and users of measuring instruments, test laboratories, etc. may simultaneously apply OIML publications and those of other institutions.

International Recommendations, Documents, Guides and Basic Publications are published in English (E) and translated into French (F) and are subject to periodic revision.

Additionally, the OIML publishes or participates in the publication of **Vocabularies (OIML V)** and periodically commissions legal metrology experts to write **Expert Reports (OIML E)**. Expert Reports are intended to provide information and advice, and are written solely from the viewpoint of their author, without the involvement of a Technical Committee or Subcommittee, nor that of the CIML. Thus, they do not necessarily represent the views of the OIML.

This publication – reference OIML R 147, Edition 2016 – was developed by Project Group 3 in OIML Technical Subcommittee TC 11/SC 3 *Radiation thermometers*. It was approved for final publication by the International Committee of Legal Metrology in 2016 and was submitted to the International Conference on Legal Metrology in 2016 for formal sanction.

OIML Publications may be downloaded from the OIML website in the form of PDF files. Additional information on OIML Publications may be obtained from the Organization's headquarters:

Bureau International de Métrologie Légale
11, rue Turgot - 75009 Paris – France
Telephone: 33 (0)1 48 78 12 82
Fax: 33 (0)1 42 82 17 27
E-mail: biml@oiml.org
Internet: www.oiml.org

Introduction

This Recommendation deals with the metrological control in manufacturing and operating blackbody radiators (hereafter called “BBR”) with controlled temperature in OIML Member States. It can be used as a basis for calibration, verification and certification of these instruments.

Currently the majority of manufactured radiation thermometers are verified and calibrated using blackbody radiators. With the growth in the number of radiation thermometers, the number of manufactured blackbody radiators has increased. However, no international documents describing calibration and verification of such blackbody radiators are available. Therefore the present Recommendation is of utmost importance.

1 Scope

The present Recommendation applies to BBR intended for the calibration, verification and engineering work in the production, maintenance and adjustment of reference and working radiation thermometers, thermal imaging instruments and radiometers in the temperature range from –50 °C to +2500 °C; it describes methods and procedures for their calibration and verification.

2 Terms, definitions, units and references

2.1 General terms and definitions

2.1.1 accreditation (ISO/IEC 17000:2004; 5.6) [1][1]

third-party attestation related to a conformity assessment body conveying formal demonstration of its competence to carry out specific conformity assessment tasks

2.1.2 calibration (OIML V2-200:2012, 2.39) [2]

operation that, under specified conditions, in a first step, establishes a relation between the quantity values with measurement uncertainties provided by measurement standards and corresponding indications with associated measurement uncertainties and, in a second step, uses this information to establish a relation for obtaining a measurement result from an indication

2.1.3 certification (ISO/IEC 17000:2004, 5.5) [1]

third-party attestation related to products, processes, systems or persons

2.1.4 maximum permissible measurement error (OIML V2-200:2012; 0.05) [2]

extreme value of a measurement error, with respect to a known reference quantity value, permitted by specifications or regulations for a given measurement, measuring instrument, or measuring system

2.1.5 verification (OIML V2-200:2012; 2.44) [2]

provision of objective evidence that a given item fulfils a specified requirement

confirmation that performance properties or legal requirements of a measuring system are achieved

[1] See bibliography in Annex C

2.2 Specific terms and definitions

2.2.1 permissible uncertainty U_{pBB}

expanded uncertainty at a specified confidence level ($p = 0.95$ or $p = 0.99$) declared in the technical documentation, at which the BBR is considered fit for its intended use. The standard uncertainty $u_{\text{pBB}} = U_{\text{pBB}}/k(p)$ is calculated from either $k(p = 0.95) = 2$ or $k(p = 0.99) = 3$

2.2.2 temperature instability, T_{ki}

instability of the BBR temperature maintained [or 'controlled'] in a specified stationary temperature mode

2.2.3 temperature drift, T_d

temperature drift of the BBR during its operation in a specified stationary temperature mode

2.2.4 transition time, t_t

required time for the BBR to pass from one stationary temperature mode to another

2.2.5 warm-up time, t_w

time elapsed from the moment of turning on the BBR until it reaches the specified working stationary temperature mode when it is allowed to determine the metrological characteristics of the BBR

2.2.6 demountable contact sensor

contact thermometric sensor which can be removed from the BBR without dismantling it for the purpose of a separate calibration and/or verification

2.2.7 permanent jointed contact sensor

contact sensor of an internal or external thermometer that cannot be removed from the BBR without dismantling the latter

2.2.8 BBR own thermometer

built-in sensor connected to an internal or external device having an output signal (showing the device or the interface or the transmitter transforming a signal of the sensor into a normal electric signal) correlated with the temperature of the BBR radiation

2.2.9 pyrometer

thermometer using the optical radiation of a source and indicating temperature values which are calibrated and traceable to (inter)national standards[2]

2.2.10 pyrometer-comparator

device using the optical radiation of sources and indicating their temperature differences with no traceability needed (see 2.2.9)

2.2.11 emissivity

ratio of the radiance of an object to the radiance of a blackbody at the same temperature as that of the object

2.2.12 effective emissivity

apparent emissivity of a blackbody cavity or a surface of a flat-plate blackbody radiator. This should take into account the intrinsic emissivity of the surface, the geometrical factor, the temperature distribution, and the ambient thermal radiation

2.2.13 spectral selectivity

wavelength range over which the BBR specifications are valid

---

[2] The term '*pyrometer*' is a synonym of the term *'radiation thermometer'* in this Recommendation.

3 Description of the category of instrument

blackbody radiator (BBR)

source of thermal radiation with an effective emissivity ε close to 1 (as a rule, $\varepsilon \geq 0.95$ for radiators with a radiating cavity, and $\varepsilon \geq 0.9$ for the radiators with an extended flat surface)

4 Units of measurement

Degrees Celsius (ºC) or Kelvin (K) are used in this Recommendation as units for temperature or temperature difference (drift, instability, etc.).

5 Metrological requirements and tested characteristics of blackbody radiators (BBR)

In the process of testing for calibration and verification, the metrological characteristics of BBR listed below shall be determined:

a) temperature range (or fixed values);
b) size of the radiating area of the BBR;
c) warm-up time required for the BBR to reach the specified stationary mode at the lower and upper levels of the working temperature range of the BBR;
d) transition time required for the BBR to pass from one stable mode to another;
e) temperature drift during the operation in specified stable modes;
f) instability of temperature control at specified levels;
g) corrections to the readings of the BBR's own thermometer (or output signal);
h) expanded uncertainty of the BBR temperature at a specified confidence level.

6 Technical requirements for BBRs

6.1 Types of BBRs

6.1.1 BBRs have a radiating area that is composed of a cavity or a flat surface.

6.1.2 BBRs can be intended for working with temperature fixed points (fixed points - blackbody) or for a variable temperature range (variable temperature - blackbody) and shall have a temperature adjustment system.

6.1.3 BBRs are subdivided with respect to the method of the radiance temperature measurement into the following types:

- BBRs with demountable contact sensors;
- BBRs with permanent mounted contact sensors that are either included in the automatic temperature adjustment system, or that operate offline;
- BBRs with non-contact sensors that are either included in the automatic temperature adjustment system, or that operate offline.

6.1.4 BBRs can be portable or stationary installed.

6.1.5 Requirements for the design of BBRs

BBRs should be equipped with a temperature control, an automatic temperature adjustment system, and a temperature display and/or a terminal for an output signal (analogue or digital) correlated with the BBR temperature value.

6.1.6 It is desirable (for verification: required) that the following characteristics of the BBR be given in its technical documentation (hereafter referred to as “TD”):

a) the working temperature range (or fixed values);
b) the radiating area;
c) the temperature instability;
d) the drift;
e) the effective emissivity;
f) the spectral selectivity;
g) the permissible uncertainty of the BBR temperature;
h) the warm-up time;
i) the transition time; and
j) the correction factor or value to the readings of the BBR own thermometer.

All the above values are the results of measurements. Either the associated expanded $k = 2$ uncertainty, or more frequently the interval of minimum and maximum values specifying a rectangular probability distribution, shall be clearly stated.

If any of the characteristics are not reported in the TD, its actual value together with the associated expanded $k = 2$ uncertainty can be defined at calibration, and is not checked at verification.

The main task during calibration of BBR temperature is the determination of the correction factor or value to the readings of a BBR’s own thermometer, associated with the appropriate expanded uncertainty and a clear statement as to which coverage factor or coverage probability $p = 0.95$ or $p = 0.99$ was used for calculation.

Note 1: Among the above-mentioned characteristics, the effective emissivity is the hardest to evaluate separately (calibrated, verified), because it considerably depends on the BBR design, on the form of the radiating area and on the materials used.

It is therefore impossible within the framework of this Recommendation, which does not deal with the technological and constructive differences of BBRs, to regulate specific requirements and operations which allow calculations or measurement of this quantity. The effective emissivity should be taken into account in the correction value applied to the readings of the BBR’s own thermometer and determined by the comparison with a standard BBR traceable to the International Temperature Scale.

Note 2: The spectral selectivity of the BBR is also considerably dependent on the BBR design, the shape of the radiating area and the materials used. This dependence is well-defined for BBRs with a cavity-type radiating element and can be significant for BBRs with a radiating surface with special coating to ensure a high spectral emissivity. In the latter case it is necessary to know the spectral curve of the dependence of emissivity (or reflectance) on the wavelength and this curve shall be given in the specifications.

6.1.7 Generally, the result of the calibration of BBR temperature shall be stated for a coverage probability $p = 0.95$ using a coverage factor $k(p = 0.95) = 2$. For some applications, to use a BBR the regulations define a higher coverage probability $p = 0.99$ with a corresponding coverage factor $k(p = 0.99) = 3$. Therefore, the appropriate expanded uncertainty is determined from the standard uncertainty by multiplying by the related coverage factor $k(p)$.

6.1.8 Depending on the intended use of a BBR as a standard for temperature measurements the TD shall also state the permissible uncertainty of the BBR temperature.

7 Metrological controls

This element shall specify the requirements concerning the calibration and verification conditions.

7.1 Process of verification and calibration

The process of verification and calibration shall be carried out in a stable indoor environment within the measurement conditions (temperature relative humidity range) accepted in each country, unless the other conditions are specified by the customer; the conditions shall be noted in the calibration certificate. A BBR shall not be affected by shocks, vibrations, external electromagnetic fields, or extraneous radiation sources that might influence the readings of measuring instruments.

7.2 Accreditation

The calibration shall preferably be carried out in an accredited calibration laboratory. The need for accreditation depends on national legislation.

8 Methods for calibration and verification of BBRs: report format

8.1 Methods

8.1.1 Methods for the calibration and verification

The actual temperature $T_X = c \cdot (Y_X + \Delta Y_X)$ measured by a pyrometer is calculated from the reading Y_X and a correction value ΔY_X. The factor $c \equiv 1$ with a value defined as unity converts the reading Y_X from arbitrary units $[Y_X]$ into the unit $[T_X]$ required for the temperature. Thus, the unit of the factor $[c] = [T_X]/[Y_X]$ is just the ratio of the units of the temperature and the reading.

The symbols "T_X" and "Y_X" stand for actual temperatures and for readings of pyrometers specified for the device by index "X". The indices "b" and "sb" replacing index "X" refer to the BBR to be calibrated and a standard BBR used as the reference, while the indices "p" and "sp" refer to an external pyrometer-comparator and a standard pyrometer used as the reference.

The calibration of a BBR assigns a value to the correction value ΔY_b to the BBR's own thermometer with associated combined standard uncertainty $u(\Delta Y_b)$. Finally, the standard uncertainty is converted into an expanded uncertainty $U(\Delta Y_b) = k \cdot u(\Delta Y_b)$ by multiplication by the coverage factor k with values either $k = 2$ or $k = 3$ depending on the fraction p of probability defined for the application.

There are two fundamental methods to determine this correction value:

- direct measurement where traceability to the national standard is obtained via a calibrated external standard pyrometer;
- comparison method where traceability to the national standard is obtained via direct comparing of the BBR unit under test and the calibrated standard BBR with traceability to the national standard according to ITS-90.

8.1.2 Direct measurement: The BBR temperature $T_b = c \cdot (Y_b + \Delta Y_b)$ indicated by readings Y_b of the BBR's own thermometer is measured by an external standard pyrometer $T_{sp}(T_b) = c \cdot (Y_{sp}(T_b) + \Delta Y_{sp})$, which is certified with the correction value ΔY_{sp}. Then the correction value ΔY_b of the BBR-thermometer reads:

$$\Delta Y_b = T_{sp}(T_b)/c - Y_b \; with \; \{ T_{sp}(T_b) = c \cdot (Y_{sp}(T_b) + \Delta Y_{sp}) \qquad (1)$$

where: Y_b , $\mathit{\Delta} Y_b$ reading, correction value for the BBR's own thermometer;

T_b , $T_{\rm sp}(T_b)$ BBR temperature, indicated by the standard pyrometer;

$c \equiv 1$ factor to match the units;

$Y_{\rm sp}(T_b), \mathit{\Delta} Y_{\rm sp}$ reading, correction value of the standard pyrometer.

8.1.3 Substitution method: The BBR temperature $T_b = c \cdot (Y_b + \mathit{\Delta} Y_b)$ indicated by its own thermometer is measured by the pyrometer-comparator $T_p(T_b) = c \cdot (Y_p(T_b) + \mathit{\Delta} Y_p)$. The temperature $T_{\rm sb} = c \cdot (Y_{\rm sb} + \mathit{\Delta} Y_{\rm sb})$ of a standard BBR indicated by its own thermometer is also measured by the pyrometer-comparator $T_p(T_{\rm sb}) = c \cdot (Y_p(T_{\rm sb}) + \mathit{\Delta} Y_p)$. A combination of the two equations cancels out the correction value $\mathit{\Delta} Y_p$ and the correction value $\mathit{\Delta} Y_b$ of the BBR thermometer reads:

$$\Delta Y_{\rm b} = T_{\rm sb}/c - Y_{\rm b} + \Delta Y_{\rm p}(T_{\rm b}) \quad \textit{with} \quad \begin{cases} T_{\rm sb} = c \cdot (Y_{\rm sb} + \Delta Y_{\rm sb}) \\ \Delta Y_{\rm p}(T_{\rm b}) = Y_{\rm p}(T_{\rm b}) - Y_{\rm p}(T_{\rm sb}) \end{cases} \qquad (2)$$

where:

Y_b , $\mathit{\Delta} Y_b$ reading, correction value of the BBR's own thermometer;

T_{sb} temperature of the standard BBR;

$c \equiv 1$ factor to match the units;

$Y_{\rm sb}$, $\mathit{\Delta} Y_{\rm sb}$ reading, correction value of the standard BBR's own thermometer;

$\mathit{\Delta} Y_p(T_b)$ difference of indications of the external pyrometer-comparator;

$Y_p(T_b), Y_p(T_{\rm sb})$ indication of the pyrometer-comparator for the BBR, standard BBR.

8.2 Operations and means for calibration and verification of BBRs

8.2.1 The operations and measuring instruments to be used for calibration and verification are listed in Table 1.

Table 1: Operations and measuring instruments

No.	Operation	Item	Verification instruments and their characteristics	Obligation of a verification procedure	
				Initial	Periodic
1	2	3	4	5	6
1	External examination	8.3	-	Yes	Yes
2	Testing	8.4	-	Yes	Yes
3	Evaluation of the BBR radiating geometry	8.5	- linear (length) measuring instrument with a scale factor to perform the measurement of the size of the radiating area with an uncertainty less than 5 %.	Yes	No
4	Evaluation of the warm-up time, temperature drift and transition time of the BBR from one stationary mode to another	8.6	- chronometer; - pyrometer-comparator with a temperature measuring range corresponding to that of the BBR and with a combined uncertainty u_{p1} from contributions of instability and limited resolution of the thermometer has to be $u_{p1} \le u_{pBB}/3$ - the field of view has to be smaller than the output apertures of both the standard BBR and the tested BBRs; - a device to measure the BBR thermometer output signal (if necessary) the uncertainty contribution u_{p2} of the limited resolution of the thermometer has to be $u_{p2} \le u_{pBB}/3$	Yes	Yes
5	Evaluation of the BBR temperature keeping instability	8.7	Equipment from item 4 in this Table	Yes	Yes
6	Evaluation of the correction to the readings of the sensor of the BBR to be calibrated (verified)	8.8	- standard BBR with variable temperature in a corresponding measurement temperature range or with temperatures of the fixed points (depends on the tested BBR); the combined uncertainty of all characteristics specified in lines 3–7 of this Table shall be valid $u_{p3} \le u_{pBB}/3$; - emissivity has to be $\varepsilon \ge 0{,}99$; - pyrometer-comparator with a corresponding temperature measurement range; its combined uncertainty u_{p4} from contributions of instability and temperature resolution has to be valid $u_{p4} \le u_{pBB}/3$; its field of view has to be smaller	Yes	Yes

No.	Operation	Item	Verification instruments and their characteristics	Obligation of a verification procedure	
				Initial	Periodic
1	2	3	4	5	6
			than the output apertures of both the standard BBR and the tested BBR; the size-of-source effect of the pyrometer-comparator shall be sufficiently small so that the effect of the different aperture sizes can be neglected; - a device to measure or decode an output signal (if necessary) with resolution $\delta Y \leq u_{\mathrm{pBB}}/3$.		
7	Calculation of the expanded uncertainty of the BBR temperature	8.9	Calculation of the uncertainty shall be carried out according to Annex A.	Yes	Yes

8.2.2 Measuring instruments specified in Table 1 shall be calibrated and traceable to national standards. The corresponding documents relative to their verification or calibration shall be provided.

8.2.3 The standard BBR and the standard radiation thermometer shall be calibrated by radiance temperature and traceable to national standards in accordance with the International Temperature Scale (ITS-90).

8.2.4 Measuring instruments are prepared for operation in accordance with their valid documentation.

8.2.5 Demountable BBR own thermometers shall have valid calibration or verification certificates based on the type of sensor.

8.3 External examination

The following points shall be checked during external examination:

8.3.1 Correspondence of the completeness of the BBR and associated equipment to the requirements of its valid documentation.

8.3.2 Correspondence of the BBR to the safety requirements specified in the TD.

8.3.3 Absence of external damage of the calibrated (verified) BBR and associated equipment that may adversely affect its metrological performance and main functions.

8.3.4 A BBR that does not comply with the requirements of 8.3.3 shall not be subject to calibration or verification.

8.4 Testing for serviceability

8.4.1 The BBR is connected to a power supply and its serviceability is tested in compliance with the valid documentation.

8.4.2 A BBR in which a defect was found during testing (for example: inability to see/read the display readout, apparent instability, etc.) is rejected for a further calibration (verification).

8.5 Evaluation of the BBR's radiating geometry

8.5.1 The outlet diameter of the BBR's radiating size and the cavity depth (in the case of a cavity BBR)[3] shall be measured once. The difference between the measured values and the values specified in the TD shall not exceed the limits ± 5 % with reference to the declared values.

8.5.2 If the relative differences calculated according to 8.5.1 exceed the limits ± 5 %, the calibration (verification) certificate shall specify the actual dimensions and the recommendation to the customer to amend the TD and to update (verify) the emissivity value.

8.6 Evaluation of the warm-up time, temperature drift and transition time for the BBR to pass from one stationary mode to another

8.6.1 The warm-up time of the BBR is interrelated with its temperature drift. Therefore, these parameters shall be determined simultaneously.

8.6.2 The warm-up time of the BBR at the lower temperature limit is determined by setting the value corresponding to the lower temperature limit on the temperature control device of the BBR control unit. The BBR is turned on and entered into the specified stationary mode in compliance with the TD.

8.6.3 When the BBR reaches the stationary mode after the time t_W, its radiance temperature is determined every (10 to 15) seconds during 15 minutes by the readings of the radiance temperature measuring device having a sufficient resolution (see Table 1). Simultaneously, the indicated reading of the BBR's own thermometer is also recorded.

8.6.4 The average temperature values are determined in accordance with the measurement results during the first five minutes, second five minutes and third five minutes. The difference between the average temperature values shall not exceed the temperature drift value specified in the TD.

8.6.5 The calculation is carried out for the radiance temperature values and for the indicated temperatures of the BBR's own thermometer.

8.6.6 If in the process of verification the maximum difference between the average temperature values of the BBR is bigger than the temperature drift value, the BBR is rejected as defective.

8.6.7 The warm-up time of the BBR is determined with more precision through additional measurements during the calibration process. To do this, the operations in 8.6.3–8.6.4 are repeated until the measured temperature drift becomes equal to the value specified in the TD.

8.6.8 If the measured temperature drift value agrees with the value specified in the TD, the BBR warm-up time being less than $2 \times t_W$, a new value of the BBR warm-up time is indicated in the TD.

8.6.9 If the measured drift value exceeds the value specified in the TD at the BBR warm-up time being equal to $2 \times t_W$, the BBR is rejected as defective.

8.6.10 The BBR transition time from one stationary mode to another (t_t) is determined by setting, on the temperature control device of the BBR unit, the value corresponding to the next temperature mode of the BBR, and, after the time specified in the TD as the transition time from one stationary mode to another expires, the operations mentioned in 8.6.2–8.6.6 are repeated.

8.6.11 The transition time of the BBR to the stationary mode at the upper temperature limit is determined after disconnecting the BBR from the power supply and cooling it down to room temperature. Then the value corresponding to the upper temperature limit is set on the temperature control device of the BBR unit. The BBR is turned on again and, when the

[3] It must be kept in mind that it is impossible to insert any instruments into the blackbody cavity which could damage the coating.

transition time of the BBR to the stationary mode at the upper temperature limit (t_{W2}) expires, the operations in 8.6.2–8.6.6 are repeated, and the values t_{W2} and $2 \times t_{W2}$ substitute the values t_W and $2 \times t_W$.

8.7 Evaluation of the temperature control instability of the BBR

8.7.1 The value corresponding to the lower temperature limit is set to the temperature handle method of the BBR control unit and then the BBR is adjusted to this temperature value according to its operation manual.

8.7.2 When the BBR reaches stationary mode, the radiance temperature value T_i is measured every (10 to 15) seconds during (15 to 20) minutes by the readings of the temperature measuring device with a resolution no lower than 0.1 °C ($\delta T \le 0{,}1\,°C$).

The average temperature value T_a during the period $15 \le t/\text{min} \le 20$, the empirical standard deviation $\sigma(T_i)$ of the current temperature value T_i and standard uncertainty type B *u(T)* are calculated using the formulae:

$$T_a = \frac{\sum_{i=1}^{n} T_i}{n}; \qquad u(T_a) = \frac{\sigma(T_i)}{\sqrt{n}}, \qquad \text{with} \quad \sigma(T_i) = \sqrt{\frac{\sum_{i=1}^{n}(T_i - T_a)^2}{n-1}} \tag{3}$$

where

T_a	average temperature value;
T_i	the ***i***-th temperature measurement result;
n	number of independent readings;
$\sigma(T_i)$	empirical standard deviation of readings;
$u(T_a)$	standard uncertainty type B equals the empirical standard deviation of the mean of readings.

8.7.3 A similar procedure is carried out for values of temperature which are indicated by the BBR's own thermometer.

8.7.4 For calculations of an expanded uncertainty, the largest of the average temperature values obtained in 8.7.1–8.7.3 are used.

8.7.5 The expanded uncertainty of the temperature control instability depends on the confidence probability p, and is equal to the standard deviation multiplied by the coverage factor k (e.g. $k = 2$ when $p = 0.95$).

8.7.6 If the standard deviation exceeds half of the temperature control instability specified in the TD, the BBR shall be rejected as defective.

8.7.7 The operations in 8.7.1–8.7.4 are repeated for the BBR with regulated temperature at the mid and maximum temperature values in the working range.

8.8 Evaluation of the correction to apply to the readings of the BBR's own thermometer

8.8.1 The correction to the readings of the BBR's own thermometer is determined by comparing it with a standard BBR by a pyrometer-comparator, or by direct measurement of its radiance temperature with a standard radiation thermometer.

A standard BBR and a standard radiation thermometer shall be calibrated with a radiance temperature traceable to national standards and the International Temperature Scale (the ITS-90) by the calibration laboratory[4].

8.8.2 The correction to the readings of the BBR's own thermometer to be calibrated (verified) in the low temperature range $-50 \le T/°C \le +300$ is determined by comparing it with a standard BBR by a pyrometer-comparator working in a full radiation or in a spectral interval $8 \le \lambda/\mu m \le 14$, or by direct measurement of its radiance temperature with a standard radiation thermometer working in such a spectral interval[5].

8.8.3 The BBR to be calibrated (verified) is placed on a test bench connected to the power supply and adjusted to the specified lower stationary temperature mode.

8.8.4 Comparisons are performed by means of a comparator using the equal signals method[6]. With this method, the comparator is placed in such a way that its optical axis lies in the axis of the standard BBR and passes through the center of its radiating aperture.

8.8.5 Then the comparator is directed at the tested BBR. The temperature of the tested BBR is selected in such a way that the comparator signal is equal to the signal of the standard BBR. The standard BBR temperature and the readings of the calibrated (verified) BBR's own thermometer are recorded. The measurements shall be repeated 10 times. The average values of temperatures of the standard BBR and of the BBR's own thermometer to be calibrated (verified) are calculated.

8.8.6 The correction to the readings of the BBR's own thermometer to be calibrated (verified) is determined as the difference between the average temperature values of the standard and calibrated (verified) BBRs.

8.8.7 In the calibration of the variable temperature BBR, the standard BBR and the BBR to be calibrated (verified) are entered into the next stationary temperature mode and operations are carried out according to 8.8.3–8.8.6. These operations are repeated at all temperature modes of the BBR specified in the TD (or required by the customer).

8.8.8 The number of specified temperature modes during the verification of the variable temperature BBR may be reduced to three (including minimal and maximal temperatures).

8.8.9 The correction values obtained during the calibration are specified in the calibration certificate, if they exceed half the value of the expanded (permissible) uncertainty of the BBR temperature.

8.8.10 If the correction value obtained during the verification differs from the correction value given in the TD by more than half the value of the permissible expanded uncertainty of the BBR temperature at one temperature mode, the correction shall be revised at all specified temperature modes of the BBR. The obtained new correction values shall be specified in the TD of the BBR in the same way as during the calibration.

---

[4] Calibration laboratories must be accredited according to state legislation.

[5] The numerical ranges of temperature and wavelength in 8.8.2, 8.8.12 and 8.8.14 are given as an informative example.

[6] Method in which the comparator signals received from the test and standard BBRs are equal.

8.8.11 If the corrections are determined by means of a standard pyrometer, they are calculated as a difference of the average readings of the standard pyrometer and the BBR's own thermometer to be calibrated (verified).

8.8.12 The correction to the readings of the BBR's own thermometer to be calibrated (verified) in the mid temperature range ($300 \le T/°C \le 1000$) is determined by comparing it with a standard BBR by means of pyrometer-comparators with the partial spectral range, or standard pyrometers with two or three partial spectral ranges, e.g. with the ranges $2 \le \lambda/\mu m \le 5$ and $8 \le \lambda/\mu m \le 14$. The operations described in 8.8.3–8.8.11 are carried out for each spectral interval[7].

8.8.13 If the corrections obtained with a different spectral interval (within one temperature mode) do not agree with each other within a half value of the permissible expanded uncertainty U_{pBB}, they shall be averaged over all spectral intervals and the temperature uncertainty component, $\boldsymbol{u}_{\text{si}}$ (one standard uncertainty), shall be taken to be the maximum deviation of the correction from its average value. This yields $u_{\text{si}} = U_{\text{pBB}}$.

8.8.14 The corrections to the readings of the BBR's own thermometer to be calibrated (verified) at the temperature $T \ge 800\,°C$ can be determined by comparing it with a standard BBR by means of a spectral comparator with a narrow spectral band depending on the purpose of the BBR to be calibrated (verified). During the verification, it is permitted to use a pyrometer-comparator, or a standard radiation thermometer with a partial spectral interval instead of a spectral comparator[8].

8.8.15 When the BBR to be calibrated (verified) is intended for calibration of radiation thermometers of a special type, it is possible to calibrate (verify) the BBR by means of the same calibrated radiation thermometer type, if it meets the requirements in Table 1, irrespective of the temperature range.

8.8.16 If the BBR to be calibrated (verified) is intended to be applicable for calibration of radiation thermometers with wide-angle lenses the dependence of correction on the viewing angle[9] shall be determined. To achieve this, the operations in 8.8.2–8.8.15 are carried out for each viewing angle depending on the temperature mode. The average correction value is determined for all viewing angles. If the correction obtained is higher than half the value of the permissible expanded uncertainty, the maximum deviation of the corrections from the average value by all the viewing angles is taken into account as the uncertainty component u_{va}. These yields $u_{\text{va}} = U_{\text{pBB}}$.

8.8.17 The dependence of the correction on the radiating surface's non-uniformity of the radiance temperature T_i shall be determined only for BBRs with an extended radiating surface. To achieve this, the average correction value is determined as the maximum difference between the radiance temperature values T_i from 5 points of the surface (in the center and on the periphery) and their average value. This is taken into account as the uncertainty component: $u_{\text{rs}} = \max_{1 \le i \le 5}\left(\left|T_i - \frac{1}{5}\sum_{j=1}^{5} T_j\right|\right)$.

These measurements are made according to 8.8.2–8.8.13. In this case the dependence of the correction on the viewing angle is not determined. Such a correction, as a rule of practice, is most powerful at temperature $T \le 300\,°C$.

---

7 See footnote to 8.8.2

8 See footnote to 8.8.2.

9 The viewing angle is the angle between the line of observation and the normal line to the radiating area.

8.9 Evaluation of the uncertainty of the BBR temperature

8.9.1 The basic components of the uncertainty budget in the calibration (verification) of a BBR temperature are listed in Annex A and are grouped for the two methods:

a) for the method of calibration (verification) option by direct measurement of the tested BBR temperature using the reference pyrometer:
- uncertainty of the temperature related to the reference pyrometer (the standard radiation thermometer);

b) for the method of calibration (verification) option by comparison with a standard BBR as a reference using a pyrometer-comparator:

- uncertainty of temperature relating to the standard BBR as a reference;

- uncertainty due to the pyrometer-comparator;

8.9.2 The expanded uncertainty of the temperature value of the BBR to be verified which is obtained by the method described in Annex A shall not exceed the corresponding uncertainty specified in the TD.

8.9.3 The calibration interval usually lasts for one or two years in the case of BBRs with permanent jointed thermometers or in the case of BBRs with demountable thermometers, respectively, unless otherwise specified in the TD.

8.10 Expression of the results

8.10.1 The calibration and verification results are entered into the protocols, the forms for which are given in Annex B.

8.10.2 When verification or calibration results are favorable, a verification or calibration document (certificate, report) is issued. When verification or calibration results are unfavorable, a verification or calibration document (certificate, report) that clearly states the unserviceability of the instrument and the reasons identified is issued.

8.10.3 The legal metrological control system on a BBR is significantly different in each Member State. Accordingly, the practical procedure which is used to report the result of verification or calibration and to grant permission to use the instrument by issuing a certificate or a verification mark, is specified by the national authority in each Member State.

8.10.4 If appropriate, the following data and parameters shall be specified in the calibration or verification certificates:

a) radiating area dimensions of the BBR forming the effective geometric extent (emissivity, area and solid angle, cavity dimensions in case of the cavity BBR);

b) warm-up time of the BBR;

c) transition time for the BBR to pass from one stationary mode to another;

d) temperature drift of the BBR;

e) temperature control instability of the BBR at the specified stationary mode;

f) correction to the BBR’s own thermometer indication;

g) expanded uncertainty of the BBR temperature value;

h) positions of the temperature control device (if given) of the BBR unit depending on temperature (in table form);

i) indication about using the BBR as a reference;

j) period of validity of the BBR verification (only for the verification);

k) if appropriate, the following data and parameters shall be specified in the calibration or verification certificates:

   i. the working temperature range/sub-ranges of the BBR;

   ii. the temperature range/sub-ranges in which the BBR is calibrated/verified /certified.

Annex A – Evaluation of the BBR temperature uncertainty

(Informative)

A.1 Uncertainty contribution due to the reading of the BBR's own thermometer

The uncertainty contribution from the reading of the BBR's own thermometer is independent of the method of calibration (verification).

The uncertainty contribution from the readings Y_b of the BBR's own thermometer is determined as the maximum from either resolution $\pm\delta Y_b$ or the empirical standard deviation $\sigma(Y_b)$ of a number n of independent readings:

$$u(Y_b) = \max\left(\delta Y_b / \sqrt{3}, \sigma(Y_b)/\sqrt{n}\right) \quad (4)$$

where:

$u(Y_b)$	standard uncertainty of the BBR's own thermometer reading;
δY_b	resolution of the BBR's own thermometer;
$\sigma(Y_b)$	empirical standard deviation of the reading;
n	number of independent readings.

The readings are modified by a possible difference $\Delta T_{a,b} = T_{a,b} - T_{a,\mathrm{b},0}$ between the actual value $T_{a,b}$ of the ambient temperature and the value $T_{a,\mathrm{b},0}$ stated in the certificate. The small correction $|\alpha_b \cdot \Delta T_{a,b}| << 1$ is the product of the ambient temperature difference $\Delta T_{a,b}$ and the relative temperature coefficient α_b. In the TD of the BBR the value α_b is given with associated expanded uncertainty $U(\alpha_b)$ and coverage factor $k(p)$. Thus, the standard uncertainty $u(\alpha_b) = U(\alpha_b)/k(p)$ can be calculated. The corrected readings $Y_b \cdot (1 + \alpha_b \cdot \Delta T_{a,b})$ are the product with a correction factor:

$$u_b = c \cdot u\left(Y_b \cdot (1 + \alpha_b \cdot \Delta T_{a,b})\right) = c \cdot \sqrt{u^2(Y_b) + Y_b^2 \cdot \left(u^2(Y_b) \cdot \Delta T_{a,b}^2 + \left[\alpha_b^2 + u^2(\alpha_b)\right] \cdot u^2(\Delta T_{a,b})\right)} \quad (5)$$

where:

u_b	standard uncertainty of the BBR's temperature by its own thermometer;
$c \equiv 1$	sensitivity coefficient;
Y_b	reading of the BBR's own thermometer;
α_b	relative temperature coefficient;
$\Delta T_{a,b}$	ambient temperature difference.

Provided that the ambient temperature difference is less than the associated uncertainty $|\Delta T_{a,b}| < u(\Delta T_{a,b})$, then the higher order term in brackets has to be used.

A.2 Uncertainty contribution of standard measuring instruments

A.2.1 Calibration (verification) option by comparison with a standard BBR as a reference using a pyrometer-comparator and described by the following model of evaluation:

$$\Delta Y_b = T_{\mathrm{sb}} / c - Y_b + \Delta Y_p(T_b)$$
$$u(\Delta Y_b) = \sqrt{\frac{1}{c^2} u^2(T_{\mathrm{sb}}) + u^2(Y_b) + u^2\left(\Delta Y_p(T_b)\right)} \quad (6)$$

where:

Y_b , ΔY_b	reading, correction value of the BBR's own thermometer;
T_{sb}	temperature of the standard BBR;
$c \equiv 1$	sensitivity coefficient;
$u(Y_b)$	standard uncertainty associated with Y_b ;
$\Delta Y_p(T_b)$	difference of indications from the external pyrometer-comparator.

A.2.2 Uncertainty of temperature relating to the standard BBR as a reference

$u_{sb} = u(T_{sb})$ – includes the uncertainty of its calibration, its instability, its uncertainty due to its positioning against the optical axis of the comparator, the uncertainty of the measuring instruments used to maintain the conditions of its operation, and the uncertainty due to the effect of the ambient conditions.

It is evaluated using the following models:

The temperature T_{sb} of the standard BBR is evaluated from the reading Y_{sb} and the correction value ΔY_{sb} modified for small effects of ambient temperature $(1+\alpha_{sb}\cdot\Delta T_{a,sb})$ and ageing $(1+\beta_{sb}\cdot\Delta t_{sb})$, respectively.

$$T_{sb} \Rightarrow c\cdot\left(Y_{sb}\cdot\left(1+\alpha_{sb}\cdot\Delta T_{a,\,sb}\right)+\Delta Y_{sb}\cdot\left(1+\beta_{sb}\cdot\Delta t_{sb}\right)\right) \quad \text{with} \quad \begin{cases}\left|\alpha_{sb}\cdot\Delta T_{a,\,sb}\right| << 1\\ \left|\beta_{sb}\cdot\Delta t_{sb}\right| << 1\end{cases}$$

$$u_{sb} = u(T_{sb}) = c\cdot\sqrt{\begin{aligned}&u^2(\Delta Y_{sb})+\Delta Y_{sb}^2\cdot\left(\Delta t_{sb}^2\cdot u^2(\beta_{sb})+\beta_{sb}^2\cdot u^2(\Delta t_{sb})\right)+\\&u^2(Y_{sb})+Y_{sb}^2\cdot\left(\Delta T_{a,\,sb}^2\cdot u^2(\alpha_{sb})+\left[\alpha_{sb}^2+u^2(\alpha_{sb})\right]\cdot u^2(\Delta T_{a,\,sb})\right)\end{aligned}} \tag{7}$$

where:

T_{sb}	temperature of the standard BBR;
Y_{sb}	reading of the standard BBR;
$c\equiv 1$	sensitivity coefficient;
ΔY_{sb}	correction value of the standard BBR;
α_{sb}	relative temperature coefficient of the standard BBR;
$\Delta T_{a,sb}$	ambient temperature difference;
β_{sb}	relative ageing coefficient of the standard BBR;
Δt_{sb}	time since calibration, standard uncertainty.

$u(\Delta Y_{sb}) = U(\Delta Y_{sb})/k(p)$ is the uncertainty associated with the correction value of the standard BBR from calibration, certified as the expanded uncertainty $U(\Delta Y_{sb})$ with a coverage factor $k(p)$. For long-term stability the uncertainty contribution $\Delta Y_{sb}^2\cdot\left(\Delta t_{sb}^2\cdot u^2(\beta_{sb})+\beta_{sb}^2\cdot u^2(\Delta t_{sb})\right)$ is evaluated from the relative ageing coefficient β_{sb} with associated uncertainty $u(\beta_{sb}) = U(\beta_{sb})/k(p)$ and coverage factor $k(p)$ given in the TD. The period of time Δt_{sb} since the last calibration is determined from the certificate and usually the associated uncertainty $u(\Delta t_{sb})$ is negligible.

$u(Y_{sb}) = \max\left(\delta Y_{sb}/\sqrt{3}, \sigma(Y_{sb})/\sqrt{n}\right)$ is the uncertainty from the readings of the standard BBR's own thermometer. It is determined as the maximum from either resolution $\pm\delta Y_{sb}$ or the empirical standard deviation $\sigma(Y_{\mathrm{sb}})$ of a number n of independent readings.

The uncertainty contribution from ambient conditions e.g. the ambient temperature $Y_{\mathrm{sb}}^2 \cdot \left(\Delta T_{\mathrm{a,sb}}^{\mathbf{2}} \cdot u^2(\alpha_{\mathrm{sb}}) + \left[\alpha_{\mathrm{sb}}^2 + u^2(\alpha_{\mathrm{sb}})\right] \cdot u^2(\Delta T_{\mathrm{a,sb}})\right)$ is determined from the difference $\Delta T_{a,\mathrm{sb}} = T_{a,\mathrm{sb}} - T_{a,\mathrm{sb0}}$ between the actual ambient temperature $T_{a,\mathrm{sb}}$ near the standard BBR and the value $T_{a,\mathrm{sb0}}$ defined for its operation. Provided the temperature difference $\Delta T_{a,\mathrm{sb}}$ is less than the uncertainty $u(\Delta T_{a,\mathrm{sb}})$, then the higher order term (in brackets) has to be considered. The relative temperature coefficient α_{sb} with associated uncertainty $u(\alpha_{\mathrm{sb}}) = U(\alpha_{\mathrm{sb}})/k$ and coverage factor k is given in the TD.

The nominal effective geometric extent $G_{\mathrm{sb}} = \varepsilon_{\mathrm{sb}} \cdot A_{\mathrm{sb}} \cdot \Omega_{\mathrm{sb}}$ of the standard BBR has to be stated in the certificate of the standard BBR with individual values of emittance $\varepsilon_{\mathrm{sb}}$ of the radiating area A_{sb}, the size and location of this area and the solid angle Ω_{sb} to be collected. During the measurement with a radiation thermometer a geometric extent $G_{\mathrm{p,sb}} = \varepsilon_{\mathrm{p,sb}} \cdot A_{\mathrm{p,sb}} \cdot \Omega_{\mathrm{p,sb}}$ is used and the reading has to be corrected by a factor $(1 + \gamma_p \cdot \Delta G_{\mathrm{p,sb}})$. It is combined from the imperfect match $\Delta G_{\mathrm{p,sb}} = G_{\mathrm{p,sb}} - G_{\mathrm{sb}}$ between the effective geometric extents and a relative weighting coefficient γ_p. The value γ_p and associated standard uncertainty $u(\gamma_p) = U(\gamma_p)/k(p)$ are found in the TD or the latter is determined from the expanded uncertainty $U(\gamma_p)$ and the related coverage factor $k(p)$.

$u_{\mathrm{sb}} = u(T_{\mathrm{sb}})$ is the uncertainty associated with the temperature of the standard BBR and modeled in equation (7) and shall be specified in the calibration certificate. The uncertainty shall be expressed in terms of expanded uncertainty with the confidence level of $p = 0{,}95$. If it is expressed as a standard uncertainty, its value should be adjusted to correspond to the expanded value by multiplying by the coverage factor $k(p = 0{,}95) = 2$ determined by this probability[10].

A.2.2.1 Uncertainty due to the pyrometer-comparator

For the pyrometer-comparator the model of evaluation with the sources of uncertainty shall be known. It contains the readings $Y_p(T_b), Y_p(T_{\mathrm{sb}})$ for the temperatures T_b, T_{sb} of the BBR and the standard BBR, respectively. In the case of fine adjustment their difference $|Y_p(T_b) - Y_p(T_{\mathrm{sb}})| << 1$ will be negligible and the associated uncertainty can be evaluated in a simplified formula.

The readings have to be corrected for fluctuations in ambient temperature $\Delta T_{a,p} = \Delta T_{a,\mathrm{p},b} - \Delta T_{a,\mathrm{p,sb}}$, possible effects of ageing $\Delta t_p = \Delta t_{\mathrm{p},b} - \Delta t_{\mathrm{p,sb}}$ (usually negligible), and differences in the effective geometric extent $\Delta G_{\mathrm{p,b,sb}} = \Delta G_{\mathrm{p,b}} - \Delta G_{\mathrm{p,sb}}$. All these corrections are small and determined as products with relative coefficients for temperature α_p, ageing β_p and geometry γ_p.

$$\begin{aligned} \Delta Y_p(T_b) &= Y_p(T_b) \cdot \left(1 + \alpha_p \cdot \Delta T_{a,\mathrm{p},b} + \beta_p \cdot \Delta t_{\mathrm{p},b} + \gamma_p \cdot \Delta G_{\mathrm{p,b}}\right) \mathit{with} \; \{|Y_p(T_b) - Y_p(T_{\mathrm{sb}})| << 1 \\ &- Y_p(T_{\mathrm{sb}}) \cdot \left(1 + \alpha_p \cdot \Delta T_{a,\mathrm{p,sb}} + \beta_p \cdot \Delta t_{\mathrm{p,sb}} + \gamma_p \cdot \Delta G_{\mathrm{p,sb}}\right) \\ u(\Delta Y_p(T_b)) &= \sqrt{u^2(Y_p(T_b)) + u^2(Y_p(T_{\mathrm{sb}})) + u^2(\alpha_p \cdot \Delta T_{\mathrm{a,p}}) + u^2(\beta_p \cdot \Delta t_p) + u^2(\gamma_p \cdot \Delta G_{\mathrm{p,b,sb}})} \end{aligned} \quad (8)$$

where:

[10] Sources of uncertainties that were not considered in the calibration certificate shall be estimated separately by the user of the reference standard BBR, especially if it concerns uncertainty due to the difference in the dimensions of the compared BBRs.

$\Delta Y_p(T_b)$	difference in indications of the pyrometer-comparator for the BBR temperature;
T_b , T_{sb}	BBR temperature, standard BBR temperature;
$Y_p(T_b)$	pyrometer-comparator indication for the BBR temperature;
$Y_p(T_{\text{sb}})$	pyrometer-comparator indication for the standard BBR temperature;
α_p , β_p , γ_p	relative coefficients for ambient temperature, ageing, geometry;
$\Delta T_{\text{a,p}}$, Δt_p , $\Delta G_{\text{p, b, sb}}$	fluctuation in ambient temperature, time since calibration, difference in geometry;
$u_1 = u(\alpha_p \cdot \Delta T_{\text{a,p}})$	uncertainty component caused by the effect of ambient temperature fluctuations during the calibration. The tested BBR and the standard BBR are measured sequentially by the radiation thermometer. In between the radiation thermometer ambient temperature fluctuates from $T_{\text{a, p, b}}$ to $T_{\text{a, p, sb}}$;

$u_1 = \sqrt{Y_p^2(T_b) \cdot \left(u^2\left(\alpha_p \cdot \Delta T_{a,\text{p},b}\right)\right) + Y_p^2(T_{\text{sb}}) \cdot \left(u^2\left(\alpha_p \cdot \Delta T_{a,\text{p,sb}}\right)\right)}$ is the relative uncertainty and a part of equation (7) with differences $\Delta T_{a,\text{p,b}} = T_{a,\text{p,b}} - T_{a,\text{p0}}$ and $\Delta T_{a,\text{p,sb}} = T_{a,\text{sp,b}} - T_{a,\text{p0}}$.

Provided that the adjustment of the BBR is such that differences between the comparator readings $|Y_p(T_b) - Y_p(T_{\text{sb}})| << 1$ are negligible, then the simplification

$u_1 = Y_p(T_b) \cdot u\left(\alpha_p \cdot \left(T_{a,\text{p},b} - T_{a,\text{p},sb}\right)\right)$ is valid, and with the higher order term in brackets yields:

$$u_1 \approx Y_p(T_b) \cdot \sqrt{u^2(\alpha_p) \cdot \left(T_{a,\text{p},b} - T_{a,\text{p},sb}\right)^2 + \left[\alpha_p^2 + u^2(\alpha_p)\right] \cdot u^2\left(T_{a,\text{p},b} - T_{a,\text{p},sb}\right)} \quad (9)$$

where:

$Y_p(T_b)$	pyrometer-comparator indication for the BBR temperature;
α_p	relative temperature coefficient pyrometer;
$T_{a,\text{p},b}$, $T_{a,\text{p},sb}$	ambient temperature for the pyrometer when measuring the tested BBR, the standard BBR;
$u\left(T_{a,\text{p},b} - T_{a,\text{p},sb}\right)$	standard uncertainty of the ambient temperature difference.

The values α_p of the relative temperature coefficient with the associated uncertainty $u(\alpha_p) = U(\alpha_p)/k(p)$ and coverage factor $k(p)$ are given in the TD of the pyrometer-comparator. The ambient temperatures $T_{a,\text{p},b}$ and $T_{a,\text{p,sb}}$ are measured with a thermometer that is not necessarily certified. The uncertainty of the ambient temperature readings is found from either the resolution $\pm \delta T_{\text{a, p}}$ or the empirical standard deviation $\sigma(T_{\text{a},p})$. The latter is not affected by the type of BBR and one obtains:

$u\left(T_{a,\text{p},b} - T_{a,\text{p,sb}}\right) = \sqrt{2} \cdot \max\left(\delta T_{\text{a},p} / \sqrt{3}, \sigma\left(T_{\text{a},p}\right) / \sqrt{n}\right)$.

$u_2 = u(\beta_p \cdot \Delta t_p)$ is the uncertainty component due to the instability of the measurement transducer efficiency. The stability of the pyrometer between the sequential measurements is also part of equation (7) and with comparator readings $|Y_p(T_b) - Y_p(T_{\text{sb}})| << 1$ one obtains:

$$u_2 = u(\beta_p \cdot \Delta t_p) = Y_p(T_b) \cdot \sqrt{u^2(\beta_p) \cdot (t_{\text{p},b} - t_{\text{p,sb}})^2 + \beta_p^2 \cdot u^2(t_{\text{p},b} - t_{\text{p,sb}})} \quad (10)$$

where:

$Y_p(T_b)$ pyrometer-comparator indication for the BBR temperature;

β_p relative ageing coefficient of the pyrometer;

$t_{\text{p},b}$, $t_{\text{p,sb}}$ time since the calibration of the pyrometer when measuring the tested BBR, the standard BBR;

$u(t_{\text{p},b} - t_{\text{p,sb}})$ standard uncertainty of the difference in ambient times;

$u_3 = u(Y_p(T_b) - Y_p(T_{\text{sb}}))$ uncertainty component due to the resolution δY_p of the instrument measuring the comparator output signal and the empirical standard deviations $\sigma(Y_p(T_b))$ and $\sigma(Y_p(T_{\text{sb}}))$ for a number of *n* readings for the BBR $Y_p(T_b)$ and for the standard BBR $Y_p(T_{\text{sb}})$, respectively:

$$u_3 = u(Y_p(T_b) - Y_p(T_{\text{sb}})) = \sqrt{\max(\delta Y_p^2/3, \sigma^2(Y_p(T_b))/n) + \max(\delta Y_p^2/3, \sigma^2(Y_p(T_{\text{sb}}))/n)} \quad (11)$$

where:

$Y_p(T_b)$, $Y_p(T_{\text{sb}})$ pyrometer-comparator indications for the BBR temperature;

T_b, T_{sb} tested BBR temperature, standard BBR temperature;

δY_p resolution of the indication of the pyrometer-comparator;

$\sigma(Y_p(T_b))$, $\sigma(Y_p(T_{\text{sb}}))$ empirical standard deviation of the pyrometer indication;

$u_4 = u(\gamma_p \cdot \Delta G_{\text{p,b,sb}})$ uncertainty component due to the difference in the dimensions of the reference radiation source A_{sb} and the radiation source under calibration A_b (size-of-source effect)[11]. Their emittance $\varepsilon_{\text{sb}}, \varepsilon_b$ and solid angles $\Omega_{\text{sb}}, \Omega_b$ forming the differences in the effective geometric extents measured by the pyrometer-comparator have to be regarded, additionally $u(\gamma_p \cdot \Delta G_{\text{p,b,sb}}) = Y_p(T_b) \cdot (1 + \gamma_p \cdot \Delta G_{\text{p,b}}) - Y_p(T_{\text{sb}}) \cdot (1 + \gamma_p \cdot \Delta G_{\text{p,sb}})$. If the adjustment of the tested BBR is such, that $|Y_p(T_b) - Y_p(T_{\text{sb}})| << 1$ the comparator readings are (nearly) equal, then simplification $\Delta Y_p(T_b) = Y_p(T_b) \cdot (1 + \gamma_p \cdot (\varepsilon_b \cdot A_b \cdot \Omega_b - \varepsilon_{\text{sb}} \cdot A_{\text{sb}} \cdot \Omega_{\text{sb}}))$ is valid and one obtains:

$$u_4 = u(\gamma_p \cdot \Delta G_{\text{p,b,sb}}) = Y_p(T_b) \cdot \sqrt{u^2(Y_p(T_b)) + u^2(\gamma_p) + \gamma_p^2 \cdot (u^2(\varepsilon_b \cdot A_b \cdot \Omega_b) + u^2(\varepsilon_{\text{sb}} \cdot A_{\text{sb}} \cdot \Omega_{\text{sb}}))} \quad (12)$$

[11] Usually, in the process of calibration in laboratory conditions the fluctuations in the ambient temperature are negligibly small; the requirements for instability and resolution of the instrument measuring the output signal of the comparator given in Table 1 also allow these uncertainty components to be ignored. What it is important to take into account is the uncertainty due to the difference in the dimensions of the compared BBRs. According to the estimates of [4] and [5] the normal standard value of this uncertainty in the case of different dimensions of the compared BBRs varies between 0.1 and 0.2 %. If it is necessary to calibrate BBRs with an uncertainty below 0.5 %, one shall be guided by the rules and estimates given in [3–5].

where:

$Y_p(T_b)$ pyrometer-comparator indication for the BBR temperature;

γ_p relative geometry coefficient of the pyrometer;

T_b , T_{sb} tested BBR temperature, standard BBR temperature;

$\Delta G_{p,b,sb}$ effective geometric extents, tested BBR minus the standard BBR;

$\sigma(Y_p(T_b)), \sigma(Y_p(T_{sb}))$ empirical standard deviation of the pyrometer indication.

The combined uncertainty $\boldsymbol{u}_{st}$ for the temperature is compiled from the contributions of equation (4) to equation (11) of the standard measuring instruments and shall be calculated by the formula:

$$u_{st} = \sqrt{u_{sb}^2 + u_b^2 + c^2 \cdot \left(u_1^2 + u_2^2 + u_3^2 + u_4^2\right)} \qquad (13)$$

A.2.2.2 The calibration (verification) option by direct measurement of the tested BBR temperature using the reference pyrometer is described by the following model:

$$\begin{aligned} \Delta Y_b &= Y_{sp}(T_b) - Y_b + \Delta Y_{sp} \\ u(\Delta Y_b) &= \sqrt{u^2\left(Y_{sp}(T_b)\right) + u^2(Y_b) + u^2(\Delta Y_{sp})} \end{aligned} \qquad (14)$$

where:

Y_b reading of the BBR's own thermometer;

ΔY_b correction value for the tested BBR;

$Y_{sp}(T_b)$ reading of the standard pyrometer;

ΔY_{sp} correction value of the standard pyrometer.

A.2.2.3 Uncertainty of temperature related to the reference pyrometer (the standard radiation thermometer)

u_{sp} is the uncertainty of a BBR temperature T_b indicated by a standard pyrometer used as a reference. It includes the uncertainty of its calibration, its instability, the uncertainty due to its positioning against the optical axis of the BBR, and the uncertainty due to the effect of ambient conditions.

The temperature $\boldsymbol{T_b}$ of a BBR is evaluated from the reading $Y_{sp}(T_b)$ of the standard pyrometer corrected by a factor $\left(1 + \alpha_{sp} \cdot \Delta T_{a,sp} + \gamma_{sp} \cdot \Delta G_{sp,b}\right)$ for effects of ambient temperature $\Delta T_{a,sp}$ and effective geometric extent $\Delta G_{sp,b}$ and from the correction value ΔY_{sp} modified by a correction factor $\left(1 + \beta_{sp} \cdot \Delta t_{sp}\right)$ for ageing during the period of time Δt_{sp} since calibration. The small corrections are products of variations in the ambient temperature $\Delta T_{a,sp}$, differences in effective geometric extents $\Delta G_{sp,b}$ and due to ageing time $\Delta t_{a,sp}$ with the related relative coefficients $\alpha_{sp}, \beta_{sp}, \gamma_{sp}$.

$$\begin{aligned} T_b &= c \cdot \left(Y_{sp}(T_b) \cdot \left(1 + \alpha_{sp} \cdot \Delta T_{a,sp} + \gamma_{sp} \cdot \Delta G_{sp,b}\right) + \Delta Y_{sp} \cdot \left(1 + \beta_{sp} \cdot \Delta t_{sp}\right)\right) \\ u_{sp} = u(T_b) &= c \cdot \sqrt{\begin{aligned} & u^2(\Delta Y_{sp}) + \Delta Y_{sp}^2 \cdot \left(\Delta t_{sp}^2 \cdot u^2(\beta_{sp}) + \beta_{sp}^2 \cdot u^2(\Delta t_{sp})\right) + \\ & u^2\left(Y_{sp}(T_b)\right) + Y_{sp}^2(T_b) \cdot \begin{pmatrix} \Delta T_{a,sp}^2 \cdot u^2(\alpha_{sp}) + \left[\alpha_{sp}^2 + u^2(\alpha_{sp})\right] \cdot u^2(\Delta T_{a,sp}) + \\ \Delta G_{sp,b}^2 \cdot u^2(\gamma_{sp}) + \left[\gamma_{sp}^2 + u^2(\gamma_{sp})\right] \cdot u^2(\Delta G_{sp,b}) \end{pmatrix} \end{aligned}} \end{aligned} \qquad (15)$$

where:

T_b	indication of the tested BBR temperature;
$Y_{sp}(T_b)$	reading of the standard pyrometer;
ΔY_{sp}	correction value of the standard pyrometer;
$\alpha_{sp}, \beta_{sp}, \gamma_{sp}$	relative coefficients of the standard pyrometer for temperature, ageing and geometry.

$u(\Delta Y_{sp}) = U(\Delta Y_{sp})/k(p)$ is the uncertainty of the pyrometer correction value assigned by the calibration of the pyrometer, and certified as the expanded uncertainty $U(\Delta Y_{sp})$ with a coverage factor $k(p)$.

For long term stability the uncertainty contribution $\Delta Y_{sp}^2 \cdot \left(\Delta t_{sp}^2 \cdot u^2(\beta_{sp}) + \beta_{sp}^2 \cdot u^2(\Delta t_{sp})\right)$ is evaluated from the relative ageing coefficient β_{sp} with the associated uncertainty $u(\beta_{sp}) = U(\beta_{sp})/k(p)$ and a coverage factor $k(p)$ given in the TD for the standard pyrometer. The period of time Δt_{sp} since the last calibration is determined from the certificate and usually the uncertainty $u(\Delta t_{sp})$ is negligible.

$u(Y_{sp}(T_b)) = \max\left(\delta Y_{sp}/\sqrt{3}, \sigma(Y_{sp})/\sqrt{n}\right)$ from the readings is determined as the maximum from either resolution $\pm \delta Y_{sp}(T_b)$ or the empirical standard deviation $\sigma(Y_{sp}(T_b))$ of a number n of independent readings.

The uncertainty contribution $Y_{sp}^2(T_b) \cdot \left(\Delta T_{a,sp}^2 \cdot u^2(\alpha_{sp}) + \left[\alpha_{sp}^2 + u^2(\alpha_{sp})\right] \cdot u^2(\Delta T_{a,sp})\right)$ from the ambient conditions, e.g. the variation of the ambient temperature, is determined from the difference $\Delta T_{a,sp} = T_{a,sp} - T_{a,sp0}$ between the actual ambient temperature $T_{a,sp}$ near the standard pyrometer and the value $T_{a,sp0}$ defined for its operation. Provided the temperature difference $\Delta T_{a,sp}$ is negligible, then the higher order term (in brackets) has to be considered. The relative temperature coefficient α_{sp} with associated uncertainty $u(\alpha_{sp}) = U(\alpha_{sp})/k(p)$ and coverage factor $k(p)$ is given in the TD of the standard pyrometer.

A.2.2.4 Uncertainty of temperature related to geometric differences

The effective geometric extent $G_{b,0} = \varepsilon_{b,0} \cdot A_{b,0} \cdot \Omega_{b,0}$ for the tested BBR is stated in the certificate with nominal values of emittance $\varepsilon_{b,0}$ of the radiating area $A_{b,0}$, the size and location of this area and the collected solid angle $\Omega_{b,0}$. It is compared with the measured geometric extent $G_{sp,b} = \varepsilon_{sp,b} \cdot A_{sp,b} \cdot \Omega_{sp,b}$ of the standard pyrometer with individual values of emittance $\varepsilon_{sp,b}$ of the radiating area $A_{sp,b}$, the size and location of this area and the collected solid angle $\Omega_{sp,b}$. The correction factor $(1 + \gamma_{sp} \cdot \Delta G_{sp,b})$ is a product of the relative coefficient γ_{sp} and the difference $\Delta G_{sp,b} = G_{sp,0} - G_{b,0}$.

The uncertainty contribution $\Delta G_{sp,b}^2 \cdot u^2(\gamma_{sp}) + \left[\gamma_{sp}^2 + u^2(\gamma_{sp})\right] \cdot u^2(\Delta G_{sp,b})$ during the calibration of the tested BBR due to an imperfect match between these effective geometric extents has to be accounted for.

The uncertainty u_{sp} of the standard pyrometer shall be specified in its calibration certificate. In the same way as mentioned in the previous section, this uncertainty shall be expressed in terms of the expanded uncertainty with the probability level of $p = 0.95$. If it is expressed as a standard uncertainty ($k = 1$), its value shall be adjusted to correspond to the expanded value by multiplying by the coverage factor $k(p = 0{,}95) = 2$ determined by this probability.

The uncertainty due to the difference between (dimensions) the effective geometric extent of the BBR used in calibration of the reference pyrometer and the dimensions of the BBR to be calibrated is explained in Note 2 (see 2.1.2) and taken into account in equation (15). In this case the uncertainty of the standard measuring instruments u_{st} from equation (13) shall be equal to u_{sp}.

A.2.2.5 Incertitude type de température

L'incertitude type estimée par les lectures répétées est obtenue conformément au point 8.7.2.

A.3 Uncertainty in the calibration of the tested BBR

A.3.1 Tested BBR temperature

The tested BBR temperature is determined from the average Y_b of repeated readings of the tested BBR's own thermometer obtained in accordance with 8.7.2 and the correction value ΔY_b evaluated either from equation (7) or equation (15) and stated in the certificate as expanded uncertainty $U(\Delta Y_b) = k(p) \cdot u(\Delta Y_b)$ with the specified coverage factor $k(p)$. The related standard uncertainties are determined from equation (4) and either equation (7) or equation (15).

$$T_b \Rightarrow c \cdot (Y_b + \Delta Y_b) \quad (16)$$

where:

T_b	tested BBR temperature;
$c \equiv 1$	sensitivity coefficient;
Y_b	reading of the tested BBR's own thermometer;
ΔY_b	correction value for the tested BBR's own thermometer.

A.3.2 Maximum standard uncertainty of the tested BBR

The maximum standard uncertainty of the tested BBR temperature for verification is calculated using the correction value from equation (7) or equation (15) and the limiting intervals (rectangular probability distribution) in the TD estimated by Type B – $u(T_b)$ – is calculated by the formula:

$$u(T_b) = \sqrt{u_{\mathrm{st}}^2 + (u_{\mathrm{ci}}^2 + u_{si}^2 + u_{va}^2 + u_{rs}^2)/3} \quad (17)$$

where:

T_b	tested BBR temperature;
$c \equiv 1$	sensitivity coefficient;
u_{st}	standard uncertainty from equation (7) or equation (15);
u_{ci}	standard interval from the instability of the tested BBR's own thermometer given as limits in the TD;
u_{si}	standard interval from the calibration (verification) for spectral intervals, limits of uncertainty according to 8.8.15;
u_{va}	standard interval from calibration (verification) for viewing angle limits of uncertainty according to 8.8.16;
u_{rs}	standard interval from calibration (verification) for inhomogeneous radiating surface, limits of uncertainty according to 8.8.16.

All the components of the budget have to be expressed as standard uncertainties determined from the limits of permissible values taking into account the recommended coverage factor.

A.3.3 The combined standard uncertainty of a temperature measurement of a BBR to be calibrated (verified) – $u_\Sigma(T)$ – is calculated by the formula:

$$u_\Sigma(T) = \sqrt{c^2 \cdot u^2(Y_b) + u^2(T_b)} \qquad (18)$$

where:

$u_\Sigma(T)$	measured temperature of a BBR;
$c \equiv 1$	sensitivity coefficient;
$u(Y_b)$	standard uncertainty from equation (4);
$u(T_b)$	standard uncertainty from equation (17).

A.3.4 The expanded uncertainty of the temperature value of the tested BBR is determined by the coverage factor $k(p)$ depending on the confidence probability p ($k(p = 0{,}95) = 2$, $k(p = 0{,}99) = 3$) and is calculated by the formula:

$$U = k(p) \cdot u_\Sigma(T) \qquad (19)$$

Annex B – Typical forms for calibration and verification certificates

(Mandatory)

B.1 Results of the evaluation of the blackbody radiator cavity geometry

Aperture diameter, mm		**Distance from the aperture to the back wall of the BB model, mm**	
Permissible value	Measured value	Permissible value	Measured value

B.2 Results of the evaluation of the warm-up time, temperature drift and transition time for the blackbody radiator to pass from one stationary mode to another

Temperature t_{90}, °C	Readings of the BBR's own thermometer to be calibrated (verified), °C	Average temperature values at time intervals t_1, t_2, t_3, °C			Maximum difference of the average temperature values at time intervals t, t_2, t_3, °C	
		t_1 (0–5 min)	t_2 (5–10 min)	t_3 (10–15 min)	Permissible value	Value calculated by the measurement data

B.3 Results of the evaluation of the blackbody radiator temperature control uncertainty

Temperature t_{90}, °C	Readings of the thermometer of a BBR to be calibrated (verified), °C	Average temperature value, °C	Maximum deviation from the average temperature value, °C	
			Permissible value	Value calculated by the measurement data

B.4 Results of the correction evaluation during sighting along the blackbody radiator axis

B.4.1 Results of the correction evaluation using full radiation comparators

Temperature t_{90}, °C	Thermometer readings of a BBR to be calibrated (verified), °C	Radiance temperature of a standard BBR, °C	Difference between the radiance temperature of a standard BBR and thermometer readings of a BBR to be calibrated (verified), °C

B.4.2 Results of the correction evaluation using pyrometer-comparators with a partial spectral range

Temperature t_{90}, °C	Spectral range, µm	Thermometer readings of a BBR to be calibrated (verified), °C	Radiance temperature of a standard BBR, °C	Difference between the radiance temperature of a standard BBR and thermometer readings of a BBR to be calibrated (verified), °C

Average temperature difference for all spectral ranges, … °C

Maximum deviation from the average temperature difference, … °C

B.4.3 Results of the correction evaluation depending on the viewing angle of a BBR to be calibrated (verified)

The table is filled in for each viewing angle according to 4.2. Then the results are summarized in the following table:

Temperature t_{90}, °C	Viewing angle, α_i, $1 \le i \le m$, grad	Differences between the standard BBR temperature and the temperature indicated by the thermometer of the calibrated (verified) BBR thermometer for $1 \le j \le n$ spectral bands, °C		Uncertainty of correction for each band and angle, °C	Average value of the temperature correction for all spectral ranges and angles, °C
		The j-th band	Average by all angles		

Maximum deviation from the average temperature correction for all spectral ranges and angles, … °C

B.4.4 Results of the correction evaluation depending on the viewing location at a BBR to be calibrated (verified)

Temperature t_{90}, °C	Thermometer readings of a standard BBR, °C	Coordinates of the location of view, mm	BBR's own thermometer readings, °C	Difference between the thermometer readings of a standard BBR and a BBR to be calibrated (verified), °C

NB: ***T*** is the temperature set measured by the BBR's own thermometer to be calibrated (verified).

Average temperature difference for all sighting locations, … °C

Maximum deviation from the average temperature difference, … °C

Annex C – References

(Informative)

[1] ISO/IEC 17000:2004

[2] OIML V2-200:2012 International Vocabulary of Metrology - Basic and General Concepts and Associated Terms (VIM). 3rd Edition (Bilingual E/F)

[3] OIML G 1-100:2008 Evaluation of measurement data - Guide to the expression of uncertainty in measurement

[4] J. Fischer et al., “CCT-WG5 on radiation thermometry, Uncertainty budgets for realization of scales by radiation thermometry”, 2003, CIPM, CCT/03-03. Summary in Temperature, Its Measurement and Control in Science and Industry, 2003 vol.7, D.C. Ripple ed., Melville, New York, pp.631-638

[5] J. Fischer et al., “CCT-WG5 on radiation thermometry, Uncertainty budgets for calibration of radiation thermometers below the silver point”, Ver. 1.71, CIPM, CCT-WG5/docs-03-2008, (http://www.bipm.org/wg/AllowedDocuments.jsp?wg=CCT-WG5)

[6] P. Saunders et al., “Uncertainty budgets for calibration of radiation thermometers below the silver point”, 2008, Int J Thermophys vol. 29, pp1066–1083; DOI 10.1007/s10765-008-0385-1