Organization Internationale de Mitrologie Legale

OIML

International Recommendation

BLACKBODY RADIATORS FOR THE TEMPERATURE RANGE FROM - 50 TO + 2500 °C

Calibration and Verification Procedure

Contents

Explanatory Note

This Draft Recommendation deals with the metrological control in manufacturing and operating cavity blackbody radiators in the OIML member-states. It can be a basis for verification, calibration and certification of these instruments.

At present, more than a half of manufactured pyrometers are verified and calibrated against blackbody radiators, and this proportion is constantly increasing. With the growth of the number of pyrometers, also grows the number of manufactured blackbody radiators. However, no international documents describing calibration and verification of these blackbody radiators are available. Therefore the present Recommendation is quite important.

1. Scope

The present Recommendation applies to blackbody radiators (hereinafter referred to as BB radiators) intended for calibration, verification and engineering work in production, maintenance and adjustment of reference and working pyrometers, thermographic instruments and radiometers in the temperature range from -50 ^{o}C to +2500 ^{o}C; it sets up methods and procedures for their calibration and verification.

2. Terms and Definitions

The Recommendation uses the following terms and definitions:

2.1 **BB radiator** – radiator with an effective emissivity ε close to one ($\varepsilon \geq 0{,}95$).

2.2 **Temperature keeping instability** – instability of the BB radiator temperature keeping in a specified stationary temperature mode, i.e. standard deviation of the BB radiator temperature values measured every 10-15 seconds during 15-20 minutes with reference to their average value during the same period.

2.3 **Temperature drift** – temperature drift of the BB radiator during its operation in a specified stationary temperature mode, which is equal to the maximum difference of average temperature values determined every five minutes (measurements being taken every 10-15 seconds) during fifteen minutes.

2.4 **Warm-up time** – time elapsed from the moment of turning on the BB radiator till it reaches the specified working stationary temperature mode when it is allowed to determine the metrological characteristics of the BB radiator.

2.5 **Demountable contact sensors** – thermometers, which can be removed from the BB radiator without its dismantling for the purpose of calibration and/or verification.

2.6 **Permanent jointed contact sensors** – thermometers that cannot be removed from the BB radiator without the dismantling of the latter.

2.7 **Permissible uncertainty** – Uncertainty value specified in the technical documentation, at which the blackbody radiator is considered fit for its intended use.

Celsius degrees or kelvins are used as the unit of temperature in this Recommendation.

3. Technical Requirements for BB Radiators

3.1 Types of BB radiators

3.1.1 The BB radiators are subdivided with respect to the method of cavity temperature measurement into the following types:

- BB radiators with demountable contact sensors;
- BB radiators with permanent jointed contact sensors that are either included into the automatic temperature adjustment system, or that are operating off-line;
- BB radiators with non-contact sensors that are either included into the automatic temperature adjustment system, or that are operating off-line.

3.1.2 The BB radiators can be both portable and stationary.

3.1.3 Requirements to the design of BB radiators.

The BB radiator shall be equipped with an automatic temperature adjustment system.

4. Metrological requirements for BB radiators. tested characteristics of BB radiators

In the process of testing (calibration, verification) the following metrological characteristics of the BB radiator shall be determined:

4.1 Dimensions of the BB radiator cavity.

4.2 Warm-up time required for the BB radiator to reach the specified stationary mode at the lower and upper levels of the working temperature range of the BB radiator.

4.3 Transition time required for the BB radiator to pass from one stationary mode to another.

4.4 Temperature drift during the operation in specified stationary modes.

4.5 Instability of temperature keeping at a specified level.

4.6 Uncertainty of the BB radiator temperature .

4.7 Corrections to the readings of the BB radiator temperature sensor.

4.8 Expanded uncertainty of the BB radiator temperature at a specified confidence level (0,95 or 0,99).

5. Calibration and verification conditions

5.1 The process of verification and calibration should be carried out in a stable indoor environment within a temperature range from 20 ºC to 22 ºC and with the relative humidity range of 40% to 80 %, unless the other conditions are specified in the certificate of a blackbody radiator. A blackbody radiator should not be affected by shocks, vibrations, external electromagnetic fields, extraneous radiation sources influencing the readings of measuring instruments;

6. Methods for calibration and verification of BB radiators. Form of the report.

6.1 Operations and means for calibration and verification of BB radiators

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

Table 1

No.	Operation	Item in the Recommendation	Verification instruments and their characteristics	Obligation of procedure	
				Initial verification	Periodical verification
1	2	3	4	5	6
1	External examination	6.2		Yes	Yes
2	Testing	6.3		Yes	Yes
3	Determination of the BB radiator cavity geometry	6.4	Linear measuring instrument with the scale factor of 1 mm.	Yes	No

4	Determination of the warm-up time, temperature drift and transition time of BB radiator from one stationary mode to another	6.5	Watches Universal digital voltmeters, voltage comparators with a scale factor in the last discharge being 0,1 μV, pyrometers-spectrocomparators, radiometers-comparators	Yes	
5	Determination of the BB radiator temperature keeping instability	6.6	Equipment from item 4 in the given Table	Yes	
6	Determination of the correction to the readings of the sensor of the BB radiator to be calibrated (verified)	6.7	Standard BB radiators with variable temperature and temperatures of the fixed points, pyrometers-spectrocomparators, radiometers-comparators		
7	Determination of the expanded uncertainty of the BB radiator temperature value	6.8	-		

6.1.2 All measuring instruments specified in Table 1 shall be provided with the corresponding legal documents about their verification or calibration.

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

6.1.4 Demountable contact and non-contact thermometers measuring the temperature of the BB radiator to be calibrated shall have valid calibration certificates.

6.1.5 Experts qualified for performance of verification and calibration in the field of temperature and radiometric measurements, are admitted to verification and calibration

6.2 External examination

6.2.1 During external examination the following points shall be checked:

6.2.2 Correspondence of the completeness of BB radiator set to the requirements of its valid documentation;

6.2.3 Correspondence of the BB radiator to the safety requirements specified in its technical documentation (hereinafter referred to as TD);

6.2.4 Absence of external damage of the calibrated (verified) BB radiator set that may adversely affect its metrological performance and main functions.

6.2.5 BB radiator that does not comply with the requirements of item 6.2.4 is not subject to calibration or verification.

6.3 Testing

6.3.1 The BB radiator is connected to a power supply and its serviceability is tested in compliance with the valid documentation.

6.3.2 A BB radiator in which a defect was found during the testing is not subject to calibration (verification).

6.4 Determination of the BB radiator cavity geometry

6.4.1 The outlet diameter of the BB radiator and the cavity depth shall be measured once

by means of a measuring rule. The difference between the measured values and the values specified in the TD with reference to the values specified in the TD and expressed as percentage, shall not exceed +5 %.

6.4.2 If relative differences calculated according to 6.4.1 exceed the limits ±5 %, the calibration (verification) certificate shall specify actual dimensions and the recommendation to the user to amend the TD.

6.5 Determination of the warm-up time, temperature drift and transition time for the BB radiator to pass from one stationary mode to another

6.5.1 The warm-up time of the BB radiator is interrelated with its temperature drift. Therefore these parameters shall be determined simultaneously.

6.5.2 The warm-up time of the BB radiator at the lower temperature limit is determined by setting the value corresponding to the lower temperature limit on the temperature control device of the BB radiator control unit. The BB radiator is turned on and entered in the specified stationary mode in compliance with the valid documentation. After the time that is specified in the TD as the BB radiator warm-up time (τ_W) expires, the BB radiator temperature drift is measured.

6.5.3 When the BB radiator reaches the stationary mode after the time τ_W, the temperature value is determined every 10-15 seconds during fifteen minutes by the readings of the temperature measuring device having a resolution better than 1 ^oC.

6.5.4 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.

6.5.5 If the maximum difference between the average temperature values of the BB radiator is bigger than the drift value, the BB radiator is rejected as defective. In the process of calibration the warm-up time of the BB radiator is determined with more precision through additional measurements.

6.5.6 With this purpose, the operations in items 6.5.2 – 6.5.3 are repeated until the measured temperature drift becomes equal to the value specified in the TD. If the measured drift value agrees with the value specified in the TD, the BB radiator warm-up time being less than $2\tau_W$, a new value of the BB radiator warm-up time is indicated in the TD.

6.5.7 If the measured drift value exceeds the value specified in the TD, the BB radiator warm-up time being equal to $2\tau_W$, the BB radiator is rejected as defective.

6.5.8 The BB radiator transition time from one stationary mode to another (τ_t) is determined by setting, on the temperature setter of the BB radiator control unit, the value corresponding to the next temperature mode of the BB radiator, and, after the time specified in the TD as the transition time from one stationary mode to another expires, the operations mentioned in items 6.5.2 – 6.5.6 are repeated.

6.5.9 The transition time of the BB radiator to the stationary mode at the upper temperature limit is determined after disconnecting the BB radiator from the power supply and cooling down to the room temperature. Then the value corresponding to the upper temperature limit is set on the temperature setter of the BB radiator control unit. The BB radiator is turned on again and, when the transition time of the BB radiator to the stationary mode at the upper temperature limit (τ_{W2}) expires, the operations in items 6.5.2 – 6.5.6 are repeated, and the values τ_{W2} and $2\tau_{W2}$ substitute the values τ_W and $2\tau_W$.

6.6 Determination of the the temperature keeping instability of the BB radiator

6.6.1 The value corresponding to the lower temperature limit is set on the temperature setter of the BB radiator control unit and then the BB radiator is adjusted to this

temperature value according to the operation manual.

6.6.2 When the BB radiator reaches the stationary mode, the temperature value T_i is measured every 10-15 seconds during 15…20 minutes by the readings of the temperature measuring device with a resolution better than 0,1 °C.

The average temperature value during the period t = 15 … 20 min $\overline{T}$ and the experimental standard deviation of the current temperature value $u(T_i)$ are calculated using the formulae:

$$\overline{T} = \frac{\sum_{i=1}^{n} T_i}{n} \; ; \qquad u(T_i) = \sqrt{\frac{\sum_{i=1}^{n} (T_i - \overline{T})^2}{n-1}} \; , \qquad (1)$$

where T_i is the i-th temperature measurement result.

6.6.3 The expanded uncertainty with the confidence probability P = 0,95 equal to the double value of standard deviation value shall not exceed the temperature keeping instability specified in the TD.

6.6.4 If the double value of standard deviation exceeds the temperature keeping instability value specified in the TD, the BB radiator shall be rejected as defective.

6.6.5 The operations in items 6.6.1 – 6.6.4 are repeated at the average and maximum temperature values in the working range of the BB radiator.

6.7 Determination of the correction to apply to the readings of the built-in BB radiator thermometer

6.7.1 The correction to the readings of the measuring thermometer of a BB radiator to be calibrated (verified) in the temperature range from -50 °C to +300°C is determined by comparing it with a standard BB radiator by means of a radiometer or a full radiation pyrometer-comparator, or by measuring its temperature using a standard radiation pyrometer. The uncertainty of the standard pyrometer and the standard BB radiator should be specified according to the uncertainty of the BB radiator to be calibrated (verified).

6.7.2 A BB radiator to be calibrated (verified) is placed on a test bench connected to the power supply and adjusted to the specified lower stationary temperature mode.

6.7.3 Comparisons are performed by means of a comparator using the equal signals method. With this purpose, the comparator is placed in such a way that its optical axis lies in the axis of the BB radiator and passes through the centre of its radiating aperture. The operation is carried out using a measuring rule, a crosshair stop inserted into the radiating aperture, and a comparator viewfinder. The comparator is turned on and its output signal (voltage, current) is measured.

6.7.4 Then the comparator is directed at the standard BB radiator. The temperature of the standard BB radiator is selected in such a way that the comparator signal were equal to the signal from the BB radiator to be calibrated (verified). The standard BB radiator temperature and the readings of the calibrated (verified) BB radiator thermometer are specified. The measurements shall be repeated ten times. The average temperature values of the standard BB radiator and the thermometer of the BB radiator to be calibrated (verified) are calculated.

6.7.5 The correction to the readings of the thermometer of the BB radiator to be calibrated (verified) is determined as a difference of the average temperature values of the standard and calibrated (verified) BB radiators.

6.7.6 If the standard BB radiator temperature cannot be changed (e.g., in case of the fixed point temperature), the temperature of the BB radiator to be calibrated (verified) (6.7.4) shall be changed to receive equal signals from this BB radiator and the standard one. Then the correction is determined as a temperature difference of the BB radiator to be calibrated (verified) after equalizing the signal and prior to that

when its thermometer readings agree with the standard BB radiator temperature.

6.7.7 The BB radiator to be calibrated (verified) is entered in the next stationary temperature mode and operations are carried out according to items 6.7.3 – 6.7.6. During calibration of the BB radiator these operations are repeated at all specified temperature modes of the BB radiator. During verification the number of specified temperature modes may be reduced to three (including minimal and maximal temperatures).

6.7.8 The correction values obtained during calibration should be specified into the calibration certificate, if it exceed a half value of the permissible expanded uncertainty of the BB radiator.

6.7.9 If during the verification the obtained correction exceeds the correction value given in the TD by more than a half value of the permissible expanded uncertainty of the BB radiator temperature even at one temperature mode, the correction is applied at all specified temperature modes of the BB radiator. The obtained new correction values are specified in the TD of the BB radiator in the same way as during the calibration.

6.7.10 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 measuring thermometer of the BB radiator to be calibrated (verified).

6.7.11 If during the verification the obtained correction value exceeds more than two times the expanded uncertainty value of the BB radiator, the BB radiator is rejected as defective.

6.7.12 The correction to the readings of the thermometer of a BB radiator to be calibrated (verified) in the temperature range from 300 ^{o}C to 1000 ^{o}C is determined by comparing it with a standard BB radiator by means of radiometers or pyrometer-comparators with the partial spectral range, or standard pyrometers with two or three partial spectral ranges, e.g., with the ranges 2 – 5 and 8 – 14 μm. The operations described in items 6.7.2 – 6.7.11 are carried out for each spectral range.

6.7.13 If the correction obtained with different spectral ranges (within one temperature mode) do not agree with each other, they shall be averaged over all spectral ranges. The maximum deviation of the correction from its average value shall be taken into account as the total standard uncertainty component of temperature $\mathbf{u_5'}$.

6.7.14 The corrections to the readings of the thermometer of a BB radiator to be calibrated (verified) at the temperature 1000^{o}C and higher are determined by comparing it with a standard BB radiator by means of a spectrocomparator with spectral ranges depending on the purpose of the BB radiator to be calibrated (verified). The corrections are determined according to items 6.7.12 – 6.7.13. During the verification it is allowed to use radiometers or the pyrometers-comparators, or the standard pyrometers with the partial spectral range instead of the spectrocomparator.

6.7.15 It is possible to calibrate (verify) the BB radiator according to one of the above methods, irrespective of the temperature range, if the TD of the BB radiator specifies the pyrometer types, for which calibration this BB radiator is designed.

6.7.16 If the BB radiator to be calibrated (verified) is applied for calibration of pyrometers with wide-angle objectives, the dependence of correction on sight angle shall be determined. With this purpose, the operations from items 6.7.1 - 6.7.15 are carried out for each sight angle depending on the temperature mode. The average correction value is determined by all sight angles. The maximum deviation of the corrections from their average value by all sight angles is taken into account as the expanded uncertainty component $\mathbf{u_4}$. The average value of the expanded uncertainty component $\mathbf{u_4}$ is also determined by all sight angles. The uncertainty value $\mathbf{u_4}$ is taken into account as a expanded uncertainty component instead of the

uncertainty component **u_3**.

6.7.17 At temperatures lower than 300 °C the dependence of correction on sighting location shall be determined for BB radiators with extensional radiating surfaces. With this purpose, the average correction value is determined by the surface and the maximum deviation of corrections by the surface from their average value is taken into account as the expanded uncertainty component **u_5**. These measurements are made according to items 6.7.1 – 6.7.11. In this case the dependence of correction on the sight angle is not determined.

6.8 Determination of the expanded uncertainty of the BB radiator temperature

6.8.1 The expanded uncertainty of the temperature value of the BB radiator to be calibrated (verified) is calculated by the formula:

$$U = k \cdot u_{\Sigma}(T), \qquad (2)$$

where: k is the coverage factor depending on the confidence probability P; at P = 0,95 k = 2, at P = 0,99 k = 3;

$u_{\Sigma}(T)$ is the total standard uncertainty of temperature measurement of a BB radiator to be calibrated (verified).

The total standard uncertainty (u_{Σ}) includes a standard uncertainty estimated by Type A (u_A) and by Type B (u_B); it is calculated by the formula:

$$u_{\Sigma} = \sqrt{u_A^2 + u_B^2}, \qquad (3)$$

The standard uncertainty estimated by Type A, represents the standard deviation of the measurement result obtained in determining the correction to the calibrated BB radiator thermometer readings; it is calculated by the formula:

$$u_A(T) = \sqrt{\sum_{i=1}^{n} \frac{(T_i - \overline{T})^2}{n(n-1)}}, \qquad (4)$$

where: T_i is the i-th result of temperature measurement;

$\overline{T}$ is the average temperature measurement result;

n is the number of measurements.

The total standard uncertainty of the BB radiator temperature estimated by Type B, is calculated by the formula:

$$u_B = \sqrt{\frac{1}{3}(u_1^2 + u_2^2 + u_3^2 + u_4^2 + u_5^2)}, \qquad (5)$$

where: u_1 is the temperature uncertainty component of the standard BB radiator estimated by Type B;

u_2 is the instability of the temperature readings of the built-in thermometer of the BB radiator to be calibrated (verified) during the calibration interval, the limits of which are given in the TD of the thermometer;

u_3 is the uncertainty due to the difference between the corrections to the thermometer readings of the BB radiator to be calibrated (verified) in different spectral ranges and at different sight angles; it depends on the calibration (verification) limits according to 6.7.16;

u_4 is the uncertainty due to the difference between the corrections to the thermometer readings of the BB radiator to be calibrated (verified) at different sight angles, which depends on the calibration (verification) limits according to 6.7.16;

u_5 is the uncertainty due to the difference between the temperatures by the radiating surface of the BB radiator to be calibrated (verified), which depends on the calibration (verification) limits according to 6.7.16.

6.8.2 During calibration (verification) of the BB radiator in the temperature range from -50 °C to +300°C the uncertainty u_3 in Eq.(5) is eliminated, and if there are no BB

radiator temperature variations due to the sight angle or sighting location, the uncertainties u_4 or u_5 are eliminated, respectively. In the temperature range over 300 ^{o}C u_5 is eliminated from Eq.(5), and if the BB radiator temperature variations due to the sight angle u_3 are absent, u_4 is substituted by u_5' determined according to 6.7.13.

6.8.3 The expanded uncertainty of the temperature value of the BB radiator to be calibrated (verified) with the confidence probability P determined by the factor k, is calculated by the formula:

$$U = k\sqrt{u_A^2 + \frac{1}{3}(u_1^2 + u_2^2 + u_3^2 + u_4^2 + u_5^2)}\,, \qquad (6)$$

(k = 2 for P = 0,95, and k = 3 for P = 0,99.)

6.8.4 The obtained expanded uncertainty value of the BB radiator to be calibrated (verified) shall not exceed the corresponding uncertainty specified in the TD.

6.9 Drawing up the results

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

6.9.2 A verification or calibration certificate is issued if the verification or calibration results are favorable. If the verification or calibration results are unfavorable, a notice on unserviceability of the instrument is issued, the reasons being identified.

6.9.3 The following data and parameters shall be specified in calibration or verification certificates:

1) cavity dimensions of the BB radiator (during the calibration);
2) warm-up time of the BB radiator;
3) radiation transition time for the BB radiator to pass from one stationary mode to another;
4) temperature drift of the BB radiator;
5) temperature keeping instability of the BB radiator at the specified stationary mode;
6) correction to the thermometer readings;
7) expanded uncertainty of the BB radiator temperature value;
8) positions of the temperature setter of the BB radiator control unit depending on temperature (in the table form);
9) indication about using the BB radiator as a reference one;
10) calibration interval of the BB radiator.

7. Annex

Forms of the calibration and verification certificates for the BB radiator**s**

1. Results of the determination of the BB radiator cavity geometry

Outlet diameter, mm		Distance from the outlet to the back wall of the BB model, mm	
Permissible value	Measured value	Permissible value	Measured value

2. Results of the determination of the warm-up time, temperature drift and transition time for the BB radiator to pass from a stationary mode to another

Temperature T, °C*	Readings of the thermometer of a BB radiator to be calibrated (verified), °C	Average temperature values at the time intervals τ_1, τ_2, τ_3, °C			Maximum difference of the average temperature values at the time intervals τ_1, τ_2, τ_3,	
		τ_1 (0–5 min)	τ_2 (5-10 min)	τ_3 (10-15 min)	Permissible value	Value calculated by the measurement data

3. Results of the determination of the BB radiator temperature keeping uncertainty

Temperature T, °C	Readings of the thermometer of a BB radiator 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

4. Results of the correction determination during sighting along the BB radiator axis

4.1 Results of the correction determination using full radiation comparators

Temperature T, °C	Thermometer readings of a BB radiator to be calibrated (verified), °C	Thermometer readings of a standard BB radiator, °C	Difference between the thermometer readings in a BB radiator to be calibrated (verified), °C

4.2 Results of the correction determination using pyrometers-comparators with a partial spectral range

Temperature T, °C	Spectral range, μm	Thermometer readings of a BB radiator to be calibrated (verified), °C	Thermometer readings of a standard BB radiator, °C	Difference between the thermometer readings of a standard BB radiator and a BB radiator to be calibrated (verified), °C

The average temperature difference for all spectral ranges, °C…
The maximum deviation from the average temperature difference, °C…

4.3 Results of the correction determination depending on the sight angle of a BB radiator to be calibrated (verified)

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

Temperature T, °C	Sight angle, α_i, i=1…m, grad	Differences between the standard BB radiator temperature and readings of the calibrated (verified) BB radiator thermometer for j=1…n spectral		Uncertainty of correction for each sight angle, °C	Average value of the temperature correction for all spectral ranges and angles, °C
		j-th	Average		

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

4.4 Results of the correction determination depending on the location of sighting at a BB radiator to be calibrated (verified)

Temperature T, °C[1]	Thermometer readings of a standard BB radiator, °C	Coordinates of the location of sighting at a BB radiator to be calibrated (verified), mm	Thermometer readings of a BB radiator to be calibrated (verified), °C	Difference between the thermometer readings of a standard BB radiator and a BB radiator to be calibrated (verified), °C

The average temperature difference for all sighting locations, °C…

The maximum deviation from the average temperature difference, °C…

[1] T is the temperature set according to the temperature adjustment device of a radiator to be calibrated (verified)