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EURAMET CG-18 – A PRACTICAL APPROACH TO CALIBRATING NON-AUTOMATIC WEIGHING INSTRUMENTS

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Abstract – This paper presents the state-of-the-art calibration strategy for non-automatic weighing instruments (NAWI), based on the recently revised guideline EURAMET cg-18. Besides of the uncertainty at calibration, the document provides advice for the so-called uncertainty of a weighing result that describes the device performance during day-to-day use. The concept of minimum weight was added during a recent revision. The minimum weight is the smallest sample quantity that can be weighed on the device, still adhering to a predefined relative weighing tolerance requirement.

Keywords: calibration, non-automatic weighing instruments, minimum weight, harmonization, quality

1. INTRODUCTION

Calibration of non-automatic weighing instruments (NAWIs) is one of the key activities in quality control and in the production area that needs to be carried out rigorously in order to accomplish pre-defined quality attributes of a weighing process. As a matter of fact, many misconceptions and ambiguities with regards to efficient calibration of balances and scales have been prevalent in the industry for many decades. There are recent activities in the scientific community to address this issue by creating a harmonized approach for calibration of NAWIs that is based on an internationally recognized calibration guideline. This approach goes beyond traditional calibration as it addresses not only the performance of the instrument at calibration, but also provides guidance to estimate the uncertainty during day-to-day use. This approach has significant practical importance as it facilitates the assessment of the equipment's performance against user specific weighing tolerance requirements. One of the most important implications is the definition of the so-called minimum weight and the safe weighing range, which is derived from the uncertainty in use. Weighing quantities in the safe weighing range of the instrument ensures adherence to user-specific tolerance requirements and thus fosters compliance with the pre-defined quality attributes of a weighing process.

2. CALIBRATION, ADJUSTMENT AND VERIFICATION

Calibration is one of the key activities that must be performed periodically when instruments are used for quality relevant measurements. Internationally, there are many standards which stipulate this requirement, e.g. ISO9001, GMP regulations or standards concerned with food safety. Unfortunately, there is no common understanding on the definition, the implementation and the specific activities that comprise calibration. Let us therefore start by establishing a common platform on what calibration is.

Calibration is a set of activities carried out on a measurement instrument to understand its behavior by establishing a relationship between known values (measurement standards) and the associated measured values (indications). The relationship consists of a deviation and its associated uncertainty. The "International Vocabulary of Metrology" (VIM) [1] provides the official definition of calibration:

"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."

It is evident that the relation between the known and the measured values can only be established if the associated measurement uncertainties are derived. Basically, measurement uncertainty describes how far away from the true value a measurement result reasonably might be.

Besides calibrating, an instrument can also be adjusted. Adjustment is defined in the "International Vocabulary of Metrology" (VIM) as follows:

"Set of operations carried out on a measuring system so that it provides prescribed indications corresponding to given values of a quantity to be measured."

In other words, when adjusting an instrument, its indications are modified in a way so that they correspond – as far as possible – to the quantity values of the measurement standards applied. Unfortunately, many users apply the words calibration and adjustment interchangeably, incorrectly or even randomly. Quite often, they talk about calibrating a weighing instrument, however they mean adjusting it. The VIM also emphasizes this by stating:

"Adjustment of a measuring system should not be confused with calibration, which is a prerequisite for adjustment. After an adjustment of a measuring system, the measuring system must usually be recalibrated."

This statement highlights another important aspect of calibration: Before an instrument is adjusted, it must be first calibrated in order to understand – and document – its behavior. Equally after an adjustment, the instrument must usually be recalibrated. Quite often, users talk about an "as found" calibration, i.e. a calibration of the instrument before any modification (adjustment) is carried out, and about an "as left" calibration, i.e. a calibration of the instrument after any necessary adjustment and/or repair has been carried out.

Usually, instruments need to fulfill predefined requirements, quite frequently expressed as tolerances. While calibration only establishes the relationship between measurement standards and indications ("how well the instrument performs"), the assessment against tolerances provides a "pass" or a "fail" ("does the instrument perform well enough"). With respect to weighing instruments, the requirements can come from the manufacturer who specifies tolerances for each balance or scale model, international or national testing recommendations and handbooks for weighing instruments used for applications involving commercial transactions (like OIML R76-1 [2] or HB44 [3]) as well as industry specific regulations (like USP General Chapter 41 [4]). However, even more importantly, the user needs to specify weighing tolerances that assure that the instrument performs well enough to fulfill his specific process requirements. In view of the application of the weighing instruments, these tolerances are the most important ones as they have a direct impact on the quality of the final product.

3. CALIBRATION OF NON-AUTOMATIC WEIGHING INSTRUMENTS

In an effort to harmonize the requirements for the calibration of non-automatic weighing instruments (NAWI) on an international level, the guideline EURAMET cg-18 "Guidelines on the calibration of non-automatic weighing instruments" was developed by the leading European metrology institutes and is now widely applied by calibration laboratories in Europe [5]. The guide has been adopted by SIM (Sistema Interamericano de Metrología) and thus is formally recognized by the regional American metrology organizations [6]. There are recent activities in the US, triggered by ASTM, who are interested in taking over the methodology of cg-18 and transposing it into an ASTM standard, which could potentially serve as a future national calibration guide for the US.

4. CALIBRATION PROCEDURE OF EURAMET CG-18

Usually, a repeatability test, a test for errors of indication and an eccentricity test are performed to assess the performance of the weighing instrument. In respect to assessing the normal use of the instrument or evaluating the performance under special conditions of use, EURAMET cg-18 allows for a flexible execution of the tests; however adherence to specific minimum requirements of the tests is stipulated as explained in the following paragraphs.

4.1. Repeatability test

Usually, a test load of about 0.5·*Max* to *Max* is quite common (*Max* stands for the maximum capacity of the instrument). However, this is often reduced for instruments where the test load would amount to several 1000 kg. For multiple range and multi-interval instruments, a load below and close to the capacity of the range/interval with the smallest scale interval d may be sufficient. A special value for the test load may be agreed where this is justified in view of a specific application of the instrument. An example would be weighing standards or samples on analytical and micro balances where the typical quantity that is weighed is at the low end of the measurement range. Here, a small repeatability test load at the lower end of the weighing range may be agreed. The test load should, as far as possible, consist of one single body. A strict requirement is that the load has to be applied at least 5 times, and at least 3 times where the load is or exceeds 100 kg.

Repeatability is quantified by calculating the standard deviation of the repeated measurements:

$$s = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(I_i - \bar{I})^2} \qquad (1)$$

with n being the number of repeated weighings, I_i representing the individual indications and $\bar{I}$ being the mean value of the indications.

4.2. Test for errors of indication

This test requires at least five test points, distributed fairly evenly over the weighing range of the instrument. Note that zero is considered a test point. The reason is that a measurement uncertainty can also be allocated to zero. Consequently, an error of indication test with four physical test loads, plus the zero, fulfills the minimum requirements of EURAMET cg-18. The individual errors of indications E_j are calculated as:

$$E_j = I_j - m_{ref,j} \qquad (2)$$

Usually, the reference value of mass $m_{ref,j}$ of the test loads is approximated to its nominal value $m_{N,j}$ or its conventional value $m_{c,j}$. I_j represents the individual indications of the error of indication test points.

4.3. Eccentricity test

The test is carried out with a test load of about $Max/3$ or higher. Depending on the shape of the load receptor, the number of test points might vary. For rectangular and round platforms, usually four positions and the center are taken as test points. From the indications I_i obtained in the different positions, the differences $\Delta I_{ecc,i}$ are usually calculated as:

$$\Delta I_{ecc,i} = I_i - I_1 \qquad (3)$$

with I_i representing the indications at the different positions of the load outside the center, and I_1 normally being the center reading (if the load can be placed in the center of the platform). For estimation of the uncertainty the largest $\Delta I_{ecc,i}$ (as absolute value) will be taken into account, which will be abbreviated $\left|\Delta I_{ecc,i}\right|_{max}$.

5. STANDARD UNCERTAINTY FOR DISCRETE VALUES

The first calculation step is to derive the so-called standard uncertainty $u(E)$ for the error of indication E of the selected calibration points. The basic formula for that step defines the error of indication as the deviation of the indication from the reference value of mass:

$$E = I - m_{ref} \tag{4}$$

with the related variance:

$$u^2(E) = u^2(I) + u^2(m_{ref}) \tag{5}$$

Note that above formulas apply for every error of indication test point, including zero. This means that for every error of indication test point the associated standard uncertainty is derived individually. This is graphically indicated in Fig 1.

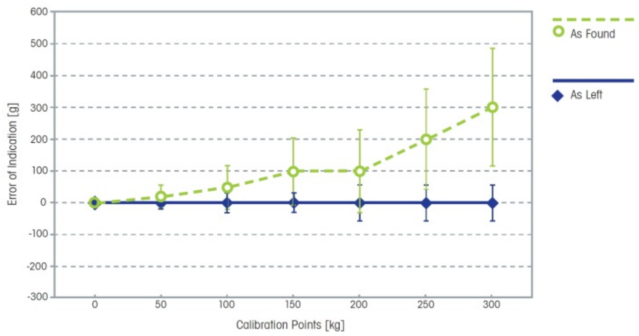

Fig. 1. Graphical indication of the error of indication test points with their respective standard uncertainties from a calibration certificate (green circles for as found, before adjustment, and blue rhombi for as left, after adjustment of the scale).

As can be seen from the above equation, the standard uncertainty for discrete values comprises of two main sources: $u(I)$, the standard uncertainty of the indication and $u(m_{ref})$, the standard uncertainty of the reference mass. This is also evident from the definition of calibration as per the VIM, which states that the quantity values provided by measurement standards as well as the corresponding indications are associated with measurement uncertainties.

5.1. Standard Uncertainty of the Indication

The standard uncertainty of the indication comprises of four individual contributions, which account for the rounding error of the no-load indication, the rounding error of the indication at load, the repeatability and the eccentricity of the weighing instrument. Note that the rounding error is taken into account twice as any indication I related to a test load is the difference of the indications I_L at load and I_0 at no-load. The standard uncertainty of the indication is obtained by the following formula:

$$u^2(I) = \frac{d_0^2}{12} + \frac{d_L^2}{12} + s^2(I) + u_{rel}^2(\delta I_{ecc}) I^2 \tag{6}$$

The variances of the rounding errors have been derived based on the assumption of a rectangular distribution of the unrounded (analogue) measurement values [1]. In other words, it was assumed that the probability of occurrence of any unrounded measurement value (which is not indicated on the instrument) is constant within the limits of $\pm\frac{d_0}{2}$ or $\pm\frac{d_L}{2}$, respectively. The standard deviation of a rectangular distribution is $\frac{d_0}{2\sqrt{3}} \approx 0.29 d_0$ or $\frac{d_L}{2\sqrt{3}} \approx 0.29 d_L$, leading to the variances indicated above in the formula. In case that the scale interval at no-load and at load is the same (abbreviated with d), the total uncertainty accounting for the rounding error of the indication would thus be derived as:

$$u_{rounding} = \frac{d}{\sqrt{6}} \approx 0.41 d \tag{7}$$

This value is also known from other regulations (e.g. USP General Chapter 41) and constitutes the lowest standard uncertainty of the indication that can be realized on a weighing instrument for the case that the standard deviation of the repeatability is zero and the uncertainty related to eccentricity is neglected.

With regards to repeatability, usually a single test is carried out during calibration. When estimating measurement uncertainty, the standard deviation s is considered as being representative for all indications of the instrument, and is taken as the uncertainty contribution of repeatability. In case that more than one repeatability test is carried out, EURAMET cg-18 describes specific rules how to apply the standard deviations within the weighing range(s) of the instrument.

The standard uncertainty accounting for eccentricity $u_{rel}(\delta I_{ecc}) I$ is approximated as a linear function of the indication I. The proportionality factor, the relative uncertainty $u_{rel}(\delta I_{ecc})$ is given by:

$$u_{rel}(\delta I_{ecc}) = \frac{|\Delta I_{ecc,j}|_{max}}{2 L_{ecc} \sqrt{3}} \tag{8}$$

with L_{ecc} being the test load applied.

5.2. Standard Uncertainty of the Reference Mass

The standard uncertainty of the reference mass usually comprises of four individual contributions, which account for the tolerance or the uncertainty of the reference mass, air buoyancy, a possible drift of the reference mass since its last calibration and convection effects due to potential temperature differences between the reference mass and the instrument.

$$u^2(m_{ref}) = u^2(\delta m_c) + u^2(\delta m_B) + u^2(\delta m_D) + u^2(\delta m_{conv}) \tag{9}$$

[1] A rectangular distribution is assumed for most of the contributions to measurement uncertainty. As the rectangular distribution is explained for the case of rounding, it will not be detailed individually anymore in the following chapters.

Whether the tolerance or the uncertainty of the reference mass is taken as a contribution to the above formula depends on whether the nominal or the conventional value is taken as reference mass for the calculation of the individual errors of indication. If the nominal value m_N is used, then the weight tolerance Tol is taken into account, leading to:

$$u(\delta m_c) = \frac{Tol}{\sqrt{3}} \tag{10}$$

Note that OIML R111-1 [7] and ASTM E617 [8] use the term "maximum permissible error" for the tolerance, for which quite frequently the abbreviation mpe is used.

If the conventional value m_c is applied, then the uncertainty U and the respective coverage factor k of the weight calibration certificate is taken into account, leading to:

$$u(\delta m_c) = \frac{U}{k} \tag{11}$$

It is evident that the contribution of $u(\delta m_c)$ can be minimized if the conventional value m_c instead of the nominal value m_N is applied. Where a test load consists of more than one standard weight, the standard uncertainties are added arithmetically not by sum of squares, to account for assumed correlations of the weights.

Further to the reference mass itself, buoyancy contributes to the standard uncertainty. In general, air buoyancy can be corrected if the density ρ of the reference mass and the air density ρ_a at the time of calibration of the weighing instrument are known. Normally, however, the air density is not measured during calibration of the weighing instrument, so that an air buoyancy correction is not carried out frequently in practice. In these cases, the (unknown) buoyancy correction is taken into account as an intrinsic part of the buoyancy uncertainty.

For this scenario, two cases have to be distinguished, one with the instrument being adjusted immediately before calibration, and the other with the instrument not being adjusted before calibration. If the instrument is adjusted immediately before calibration, the respective buoyancy uncertainty is minimized as a potential change in buoyancy due to different air densities at calibration and adjustment is removed. If the instrument is adjusted independent of the calibration, worst-case assumptions should be made in regards to the potential air density variation between adjustment and calibration. If conformity of the standard weights with OIML R111-1 is established, the following worst-case uncertainties can be derived [2]:

If the instrument is adjusted immediately before calibration:

$$u(\delta m_B) \approx \frac{mpe}{4\sqrt{3}} \tag{12}$$

[2] Recourse is taken to section 10 of OIML R111-1: The density of the material for weights shall be such that a deviation of 10% from the specified air density ($1.2\,\frac{kg}{m^3}$) does not produce an error exceeding one quarter of the maximum permissible error.

If the instrument is not adjusted before calibration (thereby assuming an air density variation of 10% of the reference density of air ρ_0 between adjustment and calibration):

$$u(\delta m_B) \approx (0.1\frac{\rho_0}{\rho_c} m_N + \frac{mpe}{4})/\sqrt{3} \tag{13}$$

The last formula is very conservative approach to estimating uncertainty due to buoyancy, and if there is evidence that air density variations are smaller than $0.1\rho_0$ this value should be substituted by a less conservative value.

A possible drift of the reference mass m_c since its last calibration can be assumed based on the difference in m_c evident from consecutive calibration certificates of the standard weights. The drift may be also estimated in view of the quality of the weights, and frequency and care of their use, to a multiple (expressed by a factor k_D) of their expanded uncertainty $U(\delta m_c)$. It is not advised to apply a correction to the reference mass, but include the potential drift in the uncertainty, which is given by:

$$u(\delta m_D) = \frac{k_D U(\delta m_c)}{\sqrt{3}} \tag{14}$$

The factor k_D is usually chosen between 1 and 3. For weights conforming to OIML R111-1 or ASTM E617, an upper limit $\frac{mpe}{\sqrt{3}}$ for the uncertainty contribution due to the drift of the reference mass can be applied, provided subsequent weight calibrations confirm that the mpe of the applicable weight class is adhered to.

Where weights have been transported to the calibration site they may not have the same temperature as the instrument and its environment. A temperature difference leads to a change of the apparent mass Δm_{conv} of the weights due to viscous friction at their surface induced by air flow originating from convection. This effect should be taken into account by either allowing the weights to acclimatize to the extent that the remaining change Δm_{conv} is negligible in view of the uncertainty of the calibration, or by considering the possible change of indication in the uncertainty budget. The effect may have to be considered for weights of high accuracy class as OIML E2 or F1 weights. It is not advised to apply a correction, but include the potential convection effects in the uncertainty, which is given by:

$$u(\delta m_{conv}) = \frac{\Delta m_{conv}}{\sqrt{3}} \tag{15}$$

Appendix F of EURAMET cg-18 provides further information and tables to derive Δm_{conv}.

5.3. Expanded Uncertainty at Calibration

After having derived the standard uncertainty at calibration for the individual calibration points, these uncertainty values must be expanded by the coverage factor k which is chosen in a way such that the expanded uncertainty of measurement *U(E)* has a coverage probability of 95.45 %, i.e. the expanded uncertainty shall ensure that the true value – which is not known – lies with a probability of at least 95.45 % within the interval 'measured value ± expanded measurement uncertainty'.

$$U(E) = ku(E) \tag{16}$$

6. UNCERTAINTY OF A WEIGHING RESULT

When the expanded uncertainty is calculated, the calibration itself is formally completed. However, the data derived so far is of reduced value for the user as three sources of interpretation are missing: (1) Behavior of the instrument in-between the selected error of indication test points, (2) estimation of the measurement uncertainty in normal usage and (3) assessment of the instrument against specific requirements such as weighing process tolerances or specifications.

6.1. *Interpretation of Calibration Data*

The calibration data offers a restricted set of information as they derive the measurement uncertainty only for a very limited amount of error of indication test points. Selecting more error of indication test points does not overcome this obstacle as this still constitutes a very limited picture of the real behavior and increases the time (and cost) for calibration. Furthermore, calibration only assesses the behavior of the instrument at the time of calibration, but not during normal usage. Any potential influence on the instrument that occurs before or after the calibration cannot be taken into account during the calibration itself. However, when assessing the instrument against specific requirements such as weighing process tolerances or specifications, the normal usage should – as far as possible – be taken into account.

EURAMET cg-18 offers detailed information on how to interpret calibration data, i.e. on how to derive the so-called standard uncertainty of a weighing result *u(W)*. The standard uncertainty of a weighing result takes into account the normal usage of the instrument and allows estimation of the measurement uncertainty for any quantity of material which is placed on the weighing instrument during normal use of the instrument. The uncertainty of a weighing result is frequently used for the assessment against weighing process requirements (tolerances) as e.g. in respect to minimum weight. This specific assessment is detailed later in this paper.

Note that the uncertainty of a weighing result is not covered by an accreditation as it is based on an interpretation of the calibration results and is not directly and exclusively derived from the measurement values of the instrument which were taken during calibration.

The contributions to $u(W)$ are usually constant over the measurement range or depend linearly on the reading of the instrument R, and thus may be grouped in two terms α_W^2 and β_W^2:

$$u^2(W) = \alpha_W^2 + \beta_W^2 R^2 \tag{17}$$

6.2. *Errors Included in Uncertainty – The "Global Uncertainty"*

It is common practice, even of utmost importance, to derive a "global uncertainty" $U_{gl}(W)$ which includes the errors of indication such that no correction has to be applied to the reading of a weighing result. In practice, applying corrections for the day-to-day work is inefficient and essentially almost impossible. In this case, the weighing result can be expressed as follows:

$$W = R \pm U_{gl}(W) \tag{18}$$

A common approach to calculate the global uncertainty is to add arithmetically the expanded uncertainty of a weighing result $U(W)$ and the absolute of the error of indication $E(R)$, reflecting possible correlations between these two terms. $E(R)$ is quite often approximated by a linear equation: $E(R) = a_1 R$, with a_1 being the linear regression coefficient, so that:

$$U_{gl}(W) = k\sqrt{\alpha_W^2 + \beta_W^2 R^2} + |a_1| R \tag{19}$$

In order to facilitate the understanding and the interpretation the result, $U(W) = k\sqrt{\alpha_W^2 + \beta_W^2 R^2}$, which is a rather complicated formula, is approximated by a linear equation, so that:

$$U_{gl}(W) \approx U(W=0) + \frac{U(W=Max) - U(W=0)}{Max} R + |a_1| R \tag{20}$$

Introducing the parameters α_{gl} and β_{gl}, the global uncertainty can be expressed as:

$$U_{gl}(W) = \alpha_{gl} + \beta_{gl} \cdot R \tag{21}$$

with the offset α_{gl}, i.e. the uncertainty without load, and the slope β_{gl}, i.e. the parameter describing the increase of the uncertainty when larger loads are applied on the instrument.

7. MINIMUM WEIGHT AND SAFE WEIGHING RANGE

It is general practice for users to define specific requirements for the performance of an instrument (User Requirement Specifications). Normally they define upper thresholds for measurement uncertainty values that are acceptable for a specific weighing application. Colloquially users refer to weighing process accuracy or weighing tolerance requirements. Typically these requirements are indicated as a relative value, e.g. adherence to a measurement uncertainty of 0.1%.

For a given tolerance requirement, *Req*, only weighings with a relative global uncertainty $U_{gl}(W)/R \leq Req$ fulfill the respective user requirement. The limit value R_{min}, i.e. the smallest weighing result that fulfills the user requirement is called “minimum weight”.

As measurement uncertainty of a weighing result and thus also the global uncertainty may be difficult to estimate due to specific environmental factors such as high levels of vibration, draughts, influences induced by the operator, etc., or due to specific influences of the weighing application such as electrostatically charged samples, magnetic stirrers, etc., a safety factor *SF*, is usually applied. The safety factor is a number larger than one, by which the user requirement *Req* is divided. The objective is to ensure that the relative global measurement uncertainty is smaller than or equal to the user requirement, divided by the safety factor. This ensures that environmental effects or effects due to the specific weighing application that have an important effect on the measurement and thus might temporarily increase the measurement uncertainty above a level estimated by the global uncertainty, still allow – with a high degree of insurance – that the user requirement is fulfilled.

$$\frac{U_{gl}(W)}{R} \leq \frac{Req}{SF} \tag{22}$$

Consequently, the minimum weight under consideration of the safety factor $R_{min,SF}$ can be calculated as follows:

$$R_{min,SF} = \frac{\alpha_{gl} \cdot SF}{Req - \beta_{gl} \cdot SF} \tag{23}$$

This leads to the definition of the safe weighing range: It is the range of the instrument, where the user can weigh safely, i.e. he fulfills the weighing tolerance requirement and adheres to the defined safety factor, see Fig. 2. The lower boundary of the safe weighing range is given by $R_{min,SF}$.

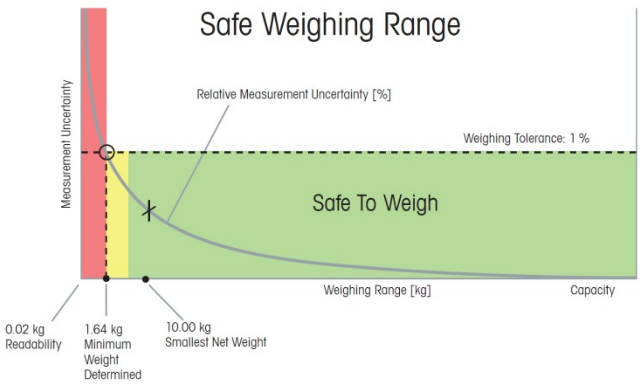

Fig. 2. Safe weighing range for an industrial floor scale, derived from the calibration data and presented in an annex to a calibration certificate.

Weighing quantities in the red region results in non-compliance with the tolerance requirement, while weighing quantities in the green region ensures the tolerance requirement is fulfilled (safe weighing range). Weighing quantities in the yellow area fulfills the user requirements; however the safety factor is not adhered to.

The minimum weight and the safe weighing range refer to the net (sample) weight which is weighed on the instrument, i.e. the tare vessel mass must not be considered to fulfill the user requirement *Req*. Therefore minimum weight is frequently called "minimum sample weight".

8. CONCLUSION

Calibration of measuring instruments is amongst the most important activities within any quality management system. Unfortunately, industry practices with respect to weighing instruments do not always appropriately reflect state-of-the-art concepts. The most evident shortcoming is the lack of a scientifically correct estimation of the measurement uncertainty, which is needed to assess whether the instrument under consideration fulfills predefined process tolerances. The EURAMET cg-18 calibration guideline is the most widespread reference document that details the methodology of deriving the measurement uncertainty of non-automatic weighing instruments. It not only includes information on the uncertainty at calibration, but also on the uncertainty of a weighing result which describes the performance of the instrument during day-to-day work and frequently serves as a basis for assessing the instrument against predefined tolerances. A critical consequence of calibration is the concept of the minimum weight. By determining the minimum weight the user can assure compliance with his weighing requirements by weighing a sufficiently higher quantity of material than the minimum weight, expressed quantitatively by the safety factor. The minimum weight under consideration of the safety factor defines the lower boundary of the safe weighing range, and weighing quantities of material within the safe weighing range guarantees compliance with the required weighing process tolerance. In simple words, calibration and the subsequent interpretation of its data establishes minimum weight and safe weighing range, and ensures the user meets applicable quality requirements.

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