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INGREDIENT MASS MEASUREMENT AND UNCERTAINTY

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Abstract. To compose a material or a solution in required quantities, it is necessary to measure ingredient mass or volume. The paper analyses the weighing procedures taking into account specific conditions in Estonia. An analysis of the assurance of the traceability of the mass measurement unit in Estonian calibration and testing laboratories is presented. Calculation of the uncertainties by weighing is considered. An overview of the results of the first proficiency testing of Estonian mass calibration laboratories is given.

Key words: reference material, ingredient mass, weighing, uncertainty, quality assurance.

1. INTRODUCTION

In materials research, it is often needed to determine the percentage composition of the ingredients to obtain a required solution or a reference material. Frequently, the composition is determined on the basis of ingredient masses, and therefore exact mass measurement is required. Another widespread method is the determination of the moisture content in a material. In this case, high accuracy is ensured by measuring an object's mass before and after drying. Ingredient mass measurement is essential in reference material production. The certificate of the reference material specifies the characteristic parameters with estimated uncertainty.

Though mass measurement has been widely used throughout centuries, estimation of the accuracy based on contemporary principles, i.e., using a detailed estimation of uncertainty components, is not yet widely spread in materials research. If by various objects mass measurement is made with the same weighing instrument, influence of the correlation must be taken into

account. Such influence can add an important component to the uncertainty and, if neglected, it may lead to an inadmissible composition of the material or solution.

A reliable measurement result with an estimated uncertainty presumes also that the weighing procedure is conducted and the weighing instrument and the weights are calibrated in a competent way and the measurement unit is traceable to the highest international standard or a reference material.

This study analyses the procedures and the conditions of weighing in Estonia. Particularly, it gives calculation principles of the uncertainties of weighing and covers mass measurement unit traceability assurance in Estonia, the competence of Estonian calibration laboratories, and proficiency testing results. The influence of correlation on the accuracy of the weighing procedure is analysed and calculated.

2. MASS MEASUREMENT

On the Earth, downward force G is given by

$$G = C_{\mathrm{M}} \frac{mM_{\mathrm{E}}}{R^2}, \tag{1}$$

where C_{M} is the gravity constant, m is the object mass, M_{E} is the Earth mass and R is the distance of the weighed object from the central point of the Earth.

Replacing $g = C_{\mathrm{M}} M_{\mathrm{E}} / R^2$, where g is local acceleration due to gravity, the downward force for a permanent point can be expressed as

$$G = mg. \tag{2}$$

Due to gravity, local acceleration depends on the centrifugal force of Earth's rotation. This means that g depends on the latitude φ and on the height of the weighing place. The nominal value of the acceleration due to gravity is equal to the value that exists at the latitude 45° on the sea level. Each meter above the sea level diminishes the nominal value of acceleration for 3×10^{-6} m s^{-2} [1].

In general, weighing is performed in ambient conditions. Each object is subjected not only to the gravitational downward force but also to the air buoyancy, i.e., to an upward force which is proportional to the mass of the volume of air it displaces. This value is taken into account as a correction factor if the weight(s) density used in balance calibration, verification, or weighing is different from the density of the weighed object.

The resultant downward force F is expressed as

$$F = mg - V_{\mathrm{o}} \rho_{\mathrm{a}} g, \tag{3}$$

where V_{o} is the volume of the weighed object and ρ_{a} is air density.

The weighing instrument indication is corrected by a factor which is expressed as

$$K_a = (V_o - V_w)\rho_a, \tag{4}$$

where V_w is the volume of the weight(s) which gives equilibrium to the weighed object on the weighing instrument. For less exact weighing, an air density value $\rho_a = 1.2$ kg m^{-3} may be used. Air density is affected by barometric pressure and air temperature, humidity, and composition. For exact weighing, ρ_a is determined by using the accurate values of the above air parameters.

The correction factor K_a is added to the indication if the volume of the weighed object exceeds the volume of the used weights and subtracted in the opposite case. For example, if the volume of the steel weights is 1.0 l (7.8 kg) and that of the weighed object is 10.0 l (light petroleum product, 7.8 kg), then the correction factor is K_a = 10.8 g or 0.14% of the indication. Such correction will be taken into account by medium or higher accuracy weighing.

3. MASS MEASUREMENT METHODS

The accuracy of mass measurement depends on the parameters of the weighing instrument and on the weighing method. By weighing, the downward force is balanced by the reaction produced by the weighing instrument. According to this reaction, weighing instruments are classified as balanced by gravitation, elasticity, or electrical force. Weighing instruments balanced by the gravity force are widely used because they are highly accurate, simple to maintain and have a relatively low price. Low efficiency and difficulties in the automation of the measurement process are their disadvantages. The mechanical beam balance is an example of such weighing instruments.

In the weighing instruments balanced by the elasticity force, the reaction is produced by elastic elements like springs, hydraulic, or pneumatic devices. Such weighing instruments are simple in construction but they have a low accuracy.

Today the weighing instruments balanced by electrical force are widely spread. They are characterized by high accuracy and electrical output signal generation which can easily be used for automatic data processing.

Weighing methods can be divided into two general categories: a) the comparison method where an unknown weight and the calibrated weight are compared, thus giving a measure of small difference in their values, b) the direct reading method where the measured value is displayed via a mechanical and/or electronic indicator.

The comparison method can be divided into two subcategories. First, standard weights substitute the item to be weighed on the same pan and the measured mass is expressed by

$$mg = g\sum_{i=1}^{n} m_i + Q_w, \tag{5}$$

where m_i is the weight mass and Q_w is the reaction force of the moving system of the weighing instrument. Equation (5) can be transformed for the case of mechanical beam balance with equal arms (mass comparator) for weighing in the air

$$L_{\mathrm{L}}(m_1 g - V_1 \rho_{\mathrm{a}} g) = L_{\mathrm{R}}(m_2 g - V_2 \rho_{\mathrm{a}} g), \tag{6}$$

where m_i and V_i are the mass and the volume of the object on different arms, L_{L} and L_{R} are the effective lengths of the lever arms. If $V_1 = m_1/\rho_1$ and $V_2 = m_2/\rho_2$, then $m_1(1-\rho_{\mathrm{a}}/\rho_1) = m_2(1-\rho_{\mathrm{a}}/\rho_2)$.

This equation shows that for high precision measurements, it is necessary also to take into account concrete densities of the weights and the object, and the air buoyancy.

In the second method, the weights are placed on the opposite pans, for single or double weighing. In the single weighing, the item to be weighed is placed on one pan and balanced against the known weights placed on the other pan. In the double weighing, ascribed to Gauss, the ordinary single weighing is repeated with the loads interchanged on the pans, the object being to minimize the combined errors due to the inequality of the arms of the balance beam and the inequality of temperature distribution within a balance case.

Direct reading is expressed by a simple equation

$$m = Q_{\mathrm{w}}/g. \tag{7}$$

4. TRACEABILITY, STANDARDS, AND EQUIPMENT

A reliable and acceptable weighing result has an unbroken traceability chain to the highest international mass reference standard. Such traceability is obtained through the competent calibration laboratory of the reference standards. Competent means here accreditation according to the international requirements or in exceptional cases through good results on international scale during many years and implementation of the quality assurance system.

Mass measurement traceability scheme for Estonia is shown in Table 1. The initial point for mass standard is an international kilogram standard, maintained in Bureau Internationale des Mesures et Poids (BIMP), France. Such traceability scheme allows the calibration of the standardized highest accuracy weights by the international classification which are class E1 weights by OIML R111. Class E1 weights facilitate the calibration of weighing instruments with the highest accuracy parameters, which are class I balances by OIML R76.

Table 1. Traceability scheme of mass measurement

Standard	Place	Accuracy parameters
International kilogram standard	BIMP	1 kg, has change in value (from 1889 until 1954 minus 0.0034 mg [2])
BIMP reference standards (prototype)	BIMP	1 kg
Copies of the kilogram prototype	In different countries (originally 42 copies [3]): Russia – copy No. 12, UK – No. 18, Finland – No. 23, etc., Estonia – none	±0.002 mg [2]
National reference standards	Almost in all countries	Various values 1 kg ±0.01 mg
Working standards of national metrology centres	If appropriate	Various values
Reference standards of leading calibration laboratories	If appropriate Estonia – Metrosert Ltd Estonia – Tartu SMK	Various values 1 kg ±0.1 mg 1 kg ±0.2 mg
Standards of companies, test and secondary regional calibration laboratories	In Estonia up to 150 laboratories	Various values 1 kg ±0.5 mg or less accurate

The official national mass reference standard has not yet been established in Estonia. Up to the beginning of 2000, Metrosert Ltd has the best mass laboratory standard and its competence has been confirmed by Finnish accreditation body FINAS in 1999.

Table 2 gives examples of weights and Table 3 examples of weighing instruments with accuracy parameters widely used in measurements; *d* is actual scale interval.

Table 2. Accuracy parameters of weights

Nominal mass of weights, g	Permissible errors according to OIML R111, ± mg			
	Class E1	Class E2	Class F1	Class F2
1000	0.5	1.5	5.0	15.0
100	0.05	0.15	0.5	1.5
10	0.02	0.06	0.20	0.6

Table 3. Accuracy parameters of weighing instruments

Weighing instrument	Measurement range	Permissible errors
Equal arm balances	Up to 20 g, $d = 0.005$ mg	Up to 5 g ±0.05 mg From 5 to 20 g ±0.1 mg
I class	200 g, $d = 0.05$ mg	Up to 50 g ±0.5 mg From 50 to 200 g ±1.0 mg
	1 kg, $d = 10$ mg	±10 mg
Electronic weighing instruments	Various, for example 20 g, $d = 0.1$ mg	±0.2 mg

5. COMPETENCE OF CALIBRATION LABORATORIES

A calibration laboratory is recognized as competent when it has an accreditation according to the requirements of ISO/IEC 17025. If no such calibration laboratory exists, then all the results of the testing laboratories or bodies performing measurements and using the not competently calibrated standards, are considered as unreliable. The first Estonian accredited (January, 1999) laboratory which calibrates mass standards is Metrosert Ltd with its best measurement capability ±0.1 mg by 1 kg.

To some extent, competence can be estimated by comparisons of calibration laboratories. In this case, the reference laboratory must have good results in international interlaboratory comparisons. Such an approach helps to avoid possible systematic deviations related to the closed area. Up to 2000, three Estonian leading calibration laboratories have participated in intercalibration between European calibration laboratories. The results have proved satisfactory.

The first proficiency testing between Estonian calibration laboratories for weighing instruments was held on 14 to 16 October, 1997. The calibration object was an electronic weighing instrument with a measurement range from 40 g to 15 kg, situated in Saue. Seven laboratories took part in the proficiency testing (Kaalukoda A.A. Ltd, Metrosert Ltd, Metrex Mõõtelabor Ltd, Juveel Mõõtelabor Ltd, Virumaa Metroloog Ltd, Reiw-Elektroonika Ltd, and Silmet Ltd).

Summarized results are shown in Figs. 1 (increasing load) and 2 (decreasing load). These figures illustrate deviations from the standard value and the expanded uncertainty for every measurement point. Calibration laboratories are shown only by the identification number according to the rules of confidentiality.

The result of proficiency testing shows that Estonian calibration laboratories are capable of calibrating weighing instruments. In none of the laboratories the permissible errors were overpassed.

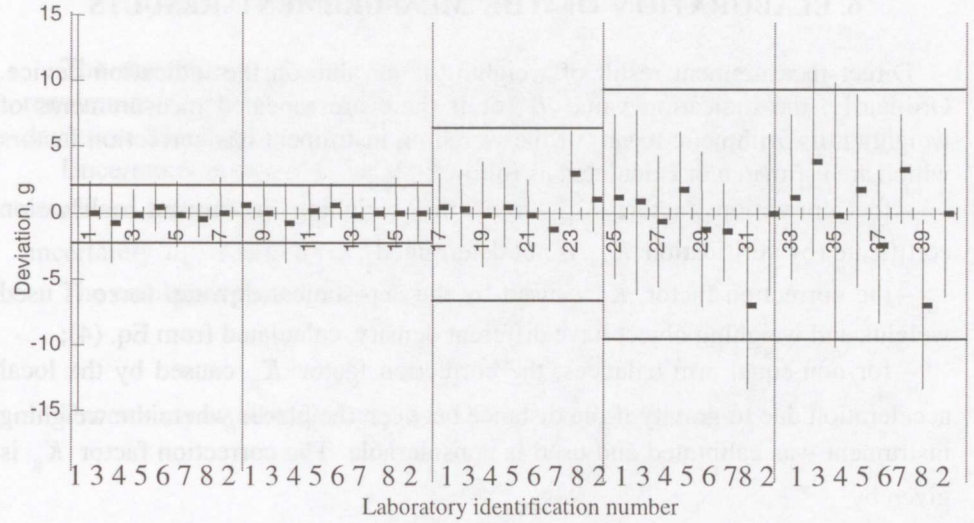

Fig. 1. Deviations from the standard value and expanded uncertainty by increasing load, —— permissible errors.

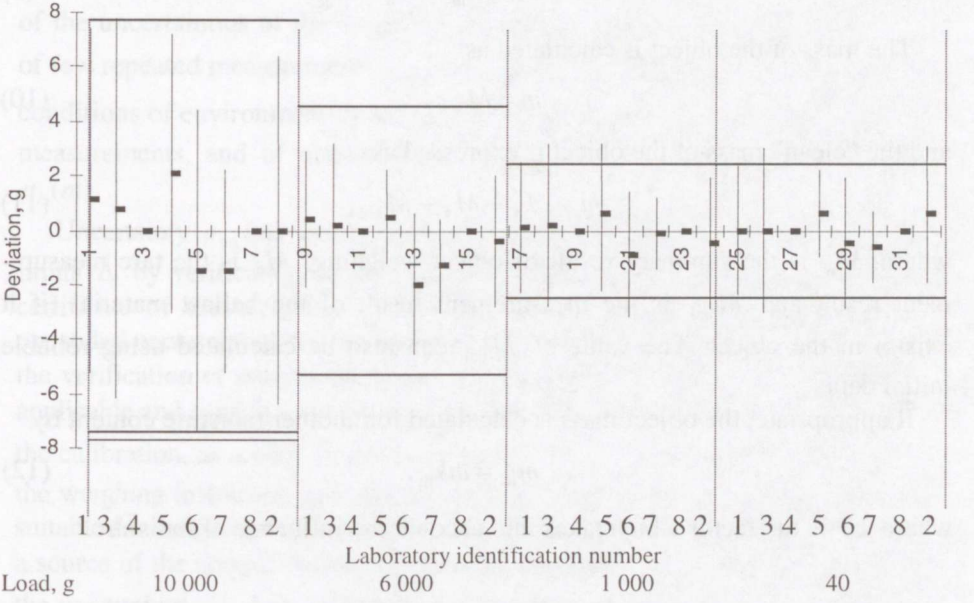

Fig. 2. Deviations from the standard value and expanded uncertainty by decreasing load, —— permissible errors.

6. ELABORATION OF THE MEASUREMENT RESULTS

Direct measurement result of weighing is a value on the indication device. Ordinarily, the indication value L (or if there are repeated measurements of weighing, its arithmetic mean) of the weighing instrument has correction factors which are estimated or calculated as follows:

– the correction factor K_{mi} from the weighing instrument calibration certificate (by verification K_{mi} is not determined);

– the correction factor K_a caused by the aerostatical downup force if used weights and weighing object have different density, calculated from Eq. (4);

– for non-equal arm balances, the correction factor K_g caused by the local acceleration due to gravity if the distance between the places where the weighing instrument was calibrated and used is considerable. The correction factor K_g is given by

$$K_g = M(1 - g_T / g_V), \tag{8}$$

where g_T is the local acceleration due to gravity at the weighing instrument calibration place and g_V is the same at the place where the weighing instrument was used. Taking into account all correction factors, the measurement result M is given by

$$M = L + K_{mi} + K_a + K_g. \tag{9}$$

The mass of the object is calculated as

$$m = M, \tag{10}$$

and the "clean" mass of the object is expressed as

$$m = M_o - M_t - M_{bal}, \tag{11}$$

where M_o is the summary result of object weighing, M_t is the tare measurement result and M_{bal} is the measurement result of the ballast material (if it exists) in the object. The value of M_{bal} can also be calculated using reliable initial data.

If appropriate, the object mass is calculated for another moisture content by

$$m_m = mk_m, \tag{12}$$

where k_m is the factor which takes into account the influence of moisture.

7. UNCERTAINTY OF MEASUREMENT

The uncertainty of the measurement is calculated according to the basic requirements of the document EA-4/02:1997 [4] on the level of the standard deviation. The latter is expressed in mass measurement units.

Uncertainty is expressed as the combined uncertainty u, which consists of the combined uncertainty u_A, calculated by statistical methods and of the combined uncertainty u_B, found by other methods [4].

The combined uncertainty u is calculated as

$$u = \sqrt{u_A^2 + u_B^2}. \tag{13}$$

Uncertainty u_A is calculated using the well-known equation

$$u_A = \sqrt{\frac{1}{n(n-1)} \sum_{i=1}^{n} (x_i - \bar{x})^2}, \tag{14}$$

where n is the number of statistically independent repeated measurements, x_i is the statistically independent measurement result in the set, and $\bar{x}$ is the arithmetic mean of the individual measurement results of the set. When the number n of repeated measurements is small ($n<10$), the reliability of uncertainty, as expressed by Eq. (14), has to be considered.

Measuring mass by weighing, the combined uncertainty $u_B = u(m)$ consists of the uncertainties of the weighing instrument $u_{mi}(m)$, of the readings $u_r(m)$, of few repeated measurements $u_{rep}(m)$, of the measurement object $u_o(m)$, of the conditions of environment by the measurement $u_e(m)$, of technical conditions of measurements, and of non-sufficient maintenance of the weighing instrument $u_c(m)$.

Uncertainty $u_{mi}(m)$ can be estimated using the values of the permissible error limits Δ by verification or the expanded uncertainty U given in the calibration certificate of the weighing instruments. Values of the error limits Δ or the expanded uncertainties U are transferred to the level of the standard deviation. For the verification of permissible errors Δ it is presumed that normal distribution is applicable and confidence level is two standard deviations; then $u_{mi}(m) = \Delta/2$. For the calibration, as a rule, the coverage factor $k = 2$ is used; then $u_{mi}(m) = U/2$. If the weighing instrument is calibrated only in some points and these points are not suitable for weighing of the object, a calibration curve will be formed. This may be a source of the complementary uncertainty component $u_{mic}(m)$. The true value of the uncertainty $u_{mic}(m)$ is difficult to estimate and appropriate procedures for its calculation are under development. A possible description of uncertainty calculation of the calibration curve is given in [5].

If equilibrium is achieved by using various weights, the combined uncertainty is calculated as

$$u_{\mathrm{mi}}(m) = \sqrt{\sum_{i=1}^{N} u_{\mathrm{w},i}^2(m)}, \tag{15}$$

where $u_{\mathrm{w},i}$ is the uncertainty of one weight.

Equation (15) can be used if no correlation exists between the weights. The correlation between the used weights exists if these weights are calibrated by one laboratory using the same comparator, the same or partly the same reference standards, and the same conditions. If a complete correlation exists between the used weights, then uncertainty can be expressed by

$$u_{\mathrm{mi}}(m) = \sqrt{\left(\sum_{i=1}^{N} u_{\mathrm{w},i}^2(m)\right)^2 + \sum_{i=1}^{N-1} u_{\mathrm{wn},i}^2}, \tag{16}$$

where $u_{\mathrm{w},i}$ are the combined uncertainty components of the weights which correlate entirely and $u_{\mathrm{wn},i}$ are the combined uncertainty components which do not correlate. In practice, uncertainty has a medium value compared to those calculated by Eqs. (15) and (16).

Uncertainty $u_{\mathrm{r}}(m)$ (includes uncertainty from parallax and instrument resolution) for a single measurement is estimated using the minimal scale interval value of the analogue indication or the smallest difference of the extreme right numbers of the digital indication. Assuming rectangular distribution of values, the uncertainty is given for the analogue indication as

$$u_{\mathrm{r}}(m) = \frac{\text{scale interval}}{2\sqrt{3}},$$

or

$$u_{\mathrm{r}}(m) = \frac{\text{the smallest difference of extreme right numbers}}{\sqrt{3}}$$

for the digital indication, if rounding criterion for the indication device is not known.

The uncertainty $u_{\mathrm{r}}(m)$ is not calculated independently if it was taken into account in the calculation of $u_{\mathrm{mi}}(m)$.

For few repeated measurements, uncertainty component $u_{\mathrm{rep}}(m)$ characterizes the non-stability of the measurement process and is estimated if the number of measurements is less than 5 to 9 by using variation limits $m_v = M_{\max} - M_{\min}$, where $M_{\max}$ is the maximum and $M_{\min}$ is the minimum value in the batch. Assuming that repeated measurement results have rectangular distribution, uncertainty is given by

$$u_{\mathrm{rep}}(m) = m_{\mathrm{v}} / 2\sqrt{3}. \tag{17}$$

Uncertainty $u_{\mathrm{o}}(m)$ is caused by the calculation errors of the correction factors of the ballast material, by the object moisture content, and by the aerostatic upward force. Uncertainty is given by

$$u_{\mathrm{o}}(m) = \sqrt{u^2(M_{\mathrm{bal}}) + u^2(k_{\mathrm{m}}) + u^2(K_{\mathrm{a}})}, \tag{18}$$

where $u(M_{\mathrm{bal}})$ is the standard uncertainty of the determination of the ballast, $u(k_{\mathrm{m}})$ is the standard uncertainty of the calculation of the moisture factor expressed in mass units, and $u(K_{\mathrm{a}})$ is the standard uncertainty of the calculation of the aerostatic correction factor K_{a}, calculated using Eq. (4). Then $u(K_{\mathrm{a}})$ is expressed by

$$u(K_{\mathrm{a}}) = \sqrt{\left(\frac{\partial K_{\mathrm{g}}}{\partial \rho_{\mathrm{a}}}\right)^2 u^2(\rho_{\mathrm{a}}) + \left[\frac{\partial K_{\mathrm{a}}}{\partial (V_{\mathrm{o}} - V_{\mathrm{w}})}\right]^2 u(V_{\mathrm{o}} - V_{\mathrm{w}})}. \tag{19}$$

Uncertainty $u_{\mathrm{e}}(m)$ consists of the uncertainty components caused by the environment conditions. It is influenced by the calculation accuracy of the local acceleration due to gravity correction factor and, if the air density is calculated with high accuracy, by temperature, humidity, pressure, and air composition. All uncertainty components are expressed on the level of the standard deviation as mass units. Uncertainty is given by

$$u_{\mathrm{e}}(m) = \sqrt{u^2(K_{\vartheta}) + u^2(K_{\mathrm{ah}}) + u^2(K_{\mathrm{ap}}) + u^2(K_{\mathrm{ac}}) + u^2(K_{\mathrm{g}})}, \tag{20}$$

where $u(K_{\vartheta})$, $u(K_{\mathrm{ah}})$, $u(K_{\mathrm{ap}})$, and $u(K_{\mathrm{ac}})$ are the uncertainties caused by correction calculations of the environment temperature, air humidity, atmospheric pressure and air composition, and $u(K_{\mathrm{g}})$ is the uncertainty of calculation of the correction from the local acceleration due to gravity. The uncertainty $u(K_{\mathrm{g}})$ can be calculated as

$$u(K_{\mathrm{g}}) = \sqrt{\left(\frac{\partial K_{\mathrm{g}}}{\partial M_{\mathrm{o}}}\right)^2 u^2(M_{\mathrm{o}}) + \left[\frac{\partial K_{\mathrm{g}}}{\partial (g_{\mathrm{T}}/g_{\mathrm{V}})}\right]^2 u(g_{\mathrm{T}}/g_{\mathrm{V}})}, \tag{21}$$

where $u(M_{\mathrm{o}})$ is the combined uncertainty of total mass measurement and $u(g_{\mathrm{T}}/g_{\mathrm{V}})$ has maximum value about 0.5×10^{-5} on the territory of Estonia. Uncertainty $u(K_{\mathrm{g}})$ has a significant value only when a non-equal arm weighing instrument is used and its calibration or verification place was distant from the

place where it was used. If the conditions are normal and the weighing process has medium accuracy, uncertainty $u_e(m)$ influence is minor.

Uncertainty $u_c(m)$ is caused by vibration, wind, local magnetic field, electricity quality, weighing instrument tilting and static electricity. When all uncertainty components are expressed on the level of the standard deviation as mass units, then uncertainty is given by

$$u_c(m) = \sqrt{\sum_{i=1}^{N} u_{c,i}^2(m)}, \tag{22}$$

where $u_{c,i}(m)$ are different component uncertainties in mass units. If conditions are normal and the weighing process is on a medium accuracy level, $u_c(m)$ influence is minor, but in the case of unfavourable conditions it may have a significant value.

The combined uncertainty $u(m)$ of mass measurement calculated by Eq. (10) is for a single measurement

$$u(m) = \sqrt{u_{mi}^2(m) + u_r^2(m) + u_o^2(m) + u_e^2(m) + u_c^2(m)}, \tag{23}$$

and for a few repeated measurements

$$u(m) = \sqrt{u_{mi}^2(m) + u_r^2(m) + u_{rep}^2 + u_o^2(m) + u_e^2(m) + u_c^2(m)}. \tag{24}$$

If the output values M_o and M_t are obtained using different weighing instruments, the combined uncertainty $u'(m)$ of mass measurement is given by

$$u'(m) = \sqrt{u^2(m_o) + u^2(m_t)}, \tag{25}$$

where $u(m_o)$ and $u(m_t)$ are the combined uncertainties of object weighing and tare measurement; they are calculated using Eq. (23) or (24).

8. CORRELATION INFLUENCE

Weighing input quantities are often correlated, i.e., they depend on each other in one way or another. The correlation exists because: a) the net mass of the object was obtained by subtracting the tare mass from the complete mass and these masses were weighed using the same weighing instrument, the same method, and the same surrounding conditions, or b) by the weighing process where the weights were used, which were calibrated, the same comparator and the same standards or the same method were used.

When the uncertainty components are correlated, they can be written as

$$u^2(m) = \sum_{i=1}^{N} c_i^2 u^2(m_i) + 2 \sum_{i=k}^{N-1} \sum_{k=i+1}^{N} c_i c_k u(m_i, m_k), \quad (26)$$

where c_i and c_k are the sensitivity coefficients of the correlated input quantities which brings them to the equal level.

Sensitivity coefficients are calculated, taking partial derivatives by x_i or x_k from the dependence function f

$$c_i = \partial f / \partial x_i, \quad c_k = \partial f / \partial x_k . \quad (27)$$

In practice, it is often difficult to find values of c_i, c_k, and $u(m_i, m_k)$. In the worst case, if the same weighing instrument and the same conditions are used, the uncertainty can be calculated as

$$u(m) = \sqrt{[u'(m_o) + u'(m_t)]^2 + u_o^2(m) + u_e^2(m) + u_c^2(m)}, \quad (28)$$

where $u'(m_o)$ and $u'(m_t)$ are combined uncertainties which are expressed for a single measurement as

$$u'(m_o) = \sqrt{u_{mi}^2(m) + u_r^2(m)}, \quad (29)$$

or

$$u'(m_t) = \sqrt{u_{mi}^2(m) + u_r^2(m)}, \quad (30)$$

and for a few repeated measurements as

$$u'(m_o) = \sqrt{u_{mi}^2(m) + u_r^2(m) + u_{rep}^2(m)}, \quad (31)$$

or

$$u'(m_t) = \sqrt{u_{mi}^2(m) + u_r^2(m) + u_{rep}^2(m)}. \quad (32)$$

9. NUMERICAL EXAMPLE SHOWING THE CORRELATION INFLUENCE

Single weighing results were: $M_t = 56.2$ kg, $M_o = 247.2$ kg. Weighing took place in Valga with the weighing instrument calibrated in Tallinn with no weights used. A calculated "clean" mass was $m = 191.0$ kg. The correction factor due to aerostatic upwards force was $K_a = 198$ g and from local acceleration due to gravity $K_g = -5$ g (may be neglected as a minor). The calculated uncertainty component values were: $u_{mi}(m) = 58$ g, $u_r(m) = 115$ g, $u_o(m) = 6$ g, and $u_c(m) = 4$ g.

If the correlation is neglected, the combined uncertainty is $u(m) = \sqrt{58^2 + 115^2 + 6^2 + 4^2} = 129$ g. Taking into account the correlation, we have $u'(m) = \sqrt{(58+115)^2 + 6^2 + 4^2} = 173$ g. The values show a considerable difference.

10. EXPANDED UNCERTAINTY

Expanded uncertainty U is given by

$$U = ku(m), \tag{33}$$

where the coverage factor $k = 2$ gives the probability level 95%, assuming normal distribution.

Weighing result is expressed as

$$m \pm U \tag{34}$$

or

$$m_{\mathrm{m}} \pm U_{\mathrm{m}}. \tag{35}$$

11. CONCLUSIONS

The analysis of the weighing procedures and given elaboration principles of weighing results and uncertainties of material ingredients mass allows for the composition of powder material ingredients. This, in its turn, promotes the quality of the produced test samples. In addition, the procedure above gives the possibility to compose reference materials with prescribed uncertainty parameters which can be used by the measuring instrument calibration.

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SEGU KOMPONENTIDE MASSI MÕÕTMISVIGADEST

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Etteantud koostisega materjalide või etalonsegude valmistamisel mõõdetakse nende komponentide mass selleks, et saada materjali või segu vajalik koostis ning etalonsegude hinnatud määramatus. Töös on analüüsitud komponentide massi mõõtmise protseduuri ja määramatuse hindamist arvestades Eesti spetsiifilisi tingimusi ning käsitletud korrelatsiooni mõju täpsushinnangule, mis võib mõõtemääramatust oluliselt suurendada. On toodud andmed massi mõõteühiku jälgitavuse tagamisest Eestis ning esitatud Eesti massimõõtevahendite kalibreerimislaborite võrdlev analüüs. Töö tulemused võimaldavad usaldusväärselt valmistada vajaliku koostisega pulbermaterjale ning etteantud määramatusega etalonaineid mõõtevahendite kalibreerimiseks arvestades kohapealseid olusid.