The object of this study is the assessment of total uncertainty during calibration in terms of assessing the component due to the competence of the personnel. The problems addressed here related to the lack of regulatorily-defined decision criteria regarding the materiality of the impact of the study component; improvement of existing statistics that would minimize errors of the first and second kinds to make a decision on the impact of personnel competence on uncertainty during calibration. A brief interpretation of the results obtained regarding errors of the first and second kinds and insufficient power of E_n, the statistics, which are most often used by calibration laboratories, alternative statistics are explained by violation of the conditions of their use. The proposed method based on the modified E_n-statistics shows the power of more than 95 % and the absence of parcels of the first and second kinds. This is due to the developed modification, which makes it possible to take into consideration the maximum permissible uncertainty. The peculiarity is the flexibility of the formula since the maximum permissible uncertainty is chosen according to metrological rules for the selection of standards. It differs for various measuring instruments; a specialist can be allowed to calibrate a less accurate measuring equipment tools and is not allowed to have high-precision ones. The scope of use of the obtained results can be certified calibration laboratories. This procedure will make it possible to obtain reliable data to devise internal methods for assessing uncertainty during calibration. The conditions for the practical use of the proposed method of assessing the impact of personnel based on the modified E_n-statistics in calibration laboratories are the presence of calibration methods that largely depend on the competence of the personnel, such as measurement of linear and mechanical quantities

Keywords: calibration laboratories, uncertainty assessment, staff competence, reliability of results, evaluation criteria

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ANALYSIS OF THE IMPACT OF PERSONNEL COMPETENCY ON UNCERTAINTY DURING CALIBRATION

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1. Introduction

Calibration of measuring instruments is one of the mandatory ways to establish and maintain metrological traceability of measurement results to the appropriate basis. To ensure competitiveness in the calibration services market, certified calibration laboratories primarily improve the reference base, which makes it possible to expand the scope of accreditation. Another equally important opportunity for improvement is the involvement of competent personnel who are able to perform calibration according to the approved methodology. However, for testing laboratories, the most important indicator when choosing a calibration laboratory is the accuracy of assessing the extended uncertainty of measurement during calibration.

Evaluation of calibration uncertainty by a certified calibration laboratory involves taking into consideration all significant components. Calibration laboratories mistakenly assume that the establishment and compliance with the requirements of the standard [1] to the competence of personnel make it possible not to take into consideration the component of uncertainty caused by competence (subjective component). However, the decision to reject one of the components of the total uncertainty should be statistically justified.

The recommendations given in the EuroLab federation document [2] on the personnel competence management process are generalized, suitable for laboratories regardless of their profile, but do not contain criteria for assessing the competence of a quantitative nature.

For many types of calibrations, especially linear and mechanical quantities, the impact of personnel on the calibration result is significant. There are no uniform regulated rules for obtaining reliable assessments of the component of uncertainty caused by personnel. Therefore, research aimed at improving existing methods of deciding to exclude or take into consideration this component of uncertainty should be considered relevant.

2. Literature review and problem statement

The principles and requirements on which the measurement uncertainty assessment is based when calibrated in the European Cooperation on EA accreditation are regulated primarily by document [3]. The document was developed in accordance with the ILAC policy regarding uncertainty during calibration [4]. The peculiarity of the documents is that their provisions are presented in a general form and the issues of a quantitative assessment of competence have not been considered. This will cover all areas of calibration but needs to be supplemented, using detailed recommendations. Calibration laboratories are also guided by these documents and instructions for presenting uncertainty in measurement measurements [5]. However, [5] also lacks decision-making criteria for assessing the impact of personnel competence on uncertainty during calibration.

The number of components of total uncertainty is determined by the developers of the calibration procedure while the component caused by the personnel is almost always not taken into consideration, considering the competence of the staff sufficient.

Ensuring the proper competence of the personnel of certified calibration laboratories is determined by the direct requirement of the international standard ISO/IEC 17025:2017 [1], namely obtaining technically reliable calibration results. The calibration laboratory «shall ensure that personnel has the appropriate competence to carry out their activities in the calibration process». Monitoring the competence of personnel is another direct requirement of standard [1]. In addition, regulated methods for ensuring the reliability of results involve duplication of calibrations using the same methods and re-calibration of samples stored [1].

It should be noted that in [5] the criteria for neglecting the uncertainty component are not considered in sufficient detail: the components of the assessment of total uncertainty are demonstrated and specified which of the components are insignificant without specifying the criterion of smallness.

An important practical value for metrologists who develop calibration procedures is manual [6]. It states that with a small number of components of uncertainty, those of them, which are less than one-third of the largest component, can be excluded from consideration. At the same time, a preliminary assessment of the contribution of components that will be excluded from the total uncertainty is mandatory.

Work [7] analyzes the requirements for the competence of laboratory personnel and how to evaluate them but the proposed methods do not take into consideration the specificity of calibration laboratories and do not contain decision criteria. Paper [8] considers the competence of personnel as a component of the quality of service and contains a comparative character for certified laboratories in accordance with ISO/IEC 17025:2017, without highlighting a separate component in the calibration uncertainty. Works [9, 10] deal with critical factors that can be used to compare best practices in certified calibration laboratories, in particular, the competence of personnel but do not distinguish its contribution. Study [11] describes the general measures required by laboratory personnel to conduct testing and calibration and obtain ISO/IEC 17025:2017 accreditation in terms of the quality of electromedical equipment. Paper [12] defines the needs and directions of staff training without methods of assessing their competence. Article [13] looks at the reliability of the results of testing and the technical competence of the chemical laboratory on the part of the management and audits but does not consider the competence of the personnel. Works [14, 15] make it possible to check the laboratory readiness to meet the ISO/IEC 17025:2017 requirements. The descriptive statistics in them are used for the development of radar diagrams and empirical methods of studies; however, however, the resulting improvement planning did not contain a statistical description of the impact of staff competence.

This means that the lack of documented evidence based on which the component of uncertainty caused by personnel was excluded is a non-compliance with the requirements [1]. The risks caused by this discrepancy can also be classified as significant as they lead to loss of reliability, and loss of customers. The unreliable result obtained by the calibration laboratory negates the chain of traceability of the results, multiplies and spreads in the results of its customers. Customers have inconsistencies that can be classified as significant and lead to the suspension of the laboratory.

Paper [16] states that as a criterion for deciding on the competence of personnel, E_n-statistics is often used [17], which is directly used to analyze the results of rounds of interlaboratory comparisons:

$$E_n = \frac{X_1 - X_2}{\sqrt{U_1^2 + U_2^2}}, \tag{1}$$

where X_1, X_2 are the measurement results obtained during calibration by the first and second specialists; U_1, U_2 – extended uncertainties of calibration results, respectively, which contain all components, including a component due to the competence of personnel.

If the value is $-1 \leq E_n \leq 1$, the result of such assessment is considered satisfactory and the staff competent.

Despite the seeming versatility and ease of application of these statistics, it has limitations because it is only correct for independent data. It is obvious that E_n-statistics are a characteristic of the functioning of the laboratory and are used to compare the results of two laboratories or the result of the laboratory and the average result obtained in several laboratories. To confirm the possibility of using E_n-statistics in order to make a decision on leveling the component of uncertainty due to the competence of the staff, no relevant studies were conducted.

ISO 5725-6:1994/COR 1:2001 [18] proposes a criterion for assessing the difference between two groups of measurements (similar to the Student criterion for independent data) obtained in the same laboratory under the conditions of repeatability. The module of the difference between the average values $\left|\bar{X}_1 - \bar{X}_2\right|$ should not exceed the critical value:

$$CD = 2.8\sigma_r \sqrt{\frac{1}{2n_1} + \frac{1}{2n_2}}, \tag{2}$$

where σ_r is the standard deviation of repeatability, which should be known in advance, for example, from the results of validation of the calibration procedure. In addition, for the value of σ_r, it is advisable to choose the value of the random component of the maximum permissible calibration uncertainty.

In the case when it is impossible to get the value σ_r, (2) will take the form:

$$CD = 2.8 s_r \sqrt{\frac{1}{2n_1} + \frac{1}{2n_2}}, \tag{3}$$

where s_r is the standard repeatability deviation estimated by calibration results.

The criteria calculated for (2), (3) can be considered an alternative for assessing the results of specialists. However, there is no study of their power to assess the impact of staff competence on uncertainty during calibration.

The contribution of the component due to the competence of the personnel in the combined uncertainty u_c of calibration result can be represented by the formula [16]:

$$u_c^2 = u_{we}^2 + u_{ec}^2 + u_p^2 + u_{MM}^2 + u_\xi^2, \tag{4}$$

where u_{we} is the standard uncertainty caused by working standard; u_{ec} – standard uncertainty due to calibration conditions, environmental parameters, etc.; u_p – standard uncertainty, subjective, due to the competence of personnel, intermediate indicator of precision; u_{MM} – standard uncertainty is due to the characteristics of measuring equipment tool (MET), which is calibrated, in particular its stability, unit of junior bit, features of operation, etc.; u_ξ – the component of uncertainty is due to unaccounted factors, as a rule, random. This model is not complete and can be expanded depending on the calibration object and the components of the process.

Paper [16] shows that the subjective component of uncertainty u_p can be calculated using the formula [18]:

$$u_p = \frac{\max|X_1 - X_2|}{2.8}, \tag{5}$$

where $\max|X_1-X_2|$ is the maximum value of the difference in the results of specialists, which can be regarded as a boundary of intralaboratory reproducibility, or as a component of intermediate precision.

However, it is noted that under the condition $U=U_1=U_2$, the maximum permissible difference between the results of specialists tends to the value of $\sqrt{2}U$, then the impact of the competence of the staff will be half of the extended uncertainty and must be taken into consideration. The analysis conducted in [16] showed the imperfection of E_n-statistics but did not contain recommendations for its improvement, the above methods of taking into consideration the correlation were not investigated.

Therefore, there are reasons to believe that the lack of regulated criteria and methods for assessing the component of calibration uncertainty due to the competence of personnel, insufficient research of alternative methods, and the need to make reliable decisions about the competence of personnel predetermine the feasibility of conducting research in this area.

3. The aim and objectives of the study

The purpose of this study is to analyze the peculiarities of the impact of staff competence on the assessment of total uncertainty. This will enable calibration laboratories to reduce the risks associated with assessing uncertainty during calibration.

To achieve the set aim, the following tasks have been solved:

– to experimentally examine the classic E_n-statistics;

– to modify E_n-statistics and develop a methodology for assessing the competence of personnel on its basis, give an example of calculation;

– to conduct a comparative analysis of the classical, modified, and alternative statistics for assessing the impact of personnel competence on uncertainty during calibration to determine statistics that minimize errors of the first and second kinds.

4. The study materials and methods

Our experiment for the purpose of examining the E_n-statistics was carried out at the installation for calibration of torque keys UMPC-2000 (Ukraine), (Fig. 1). As a calibration object, we used the dynamometric key ANDRMAX 1/2′ DR 210 N–M (PRC).

Fig. 1. General view of the installation for calibrating torque keys

Influential factors on which calibration uncertainty depends were the point of application of effort and the load mode of the key (Fig. 2).

We studied alternative methods using an example of calibration of pyrometers. The installation for calibration Tensor «Vlant-28» (Ukraine) consists of several completely black bodies (CBB) (Fig. 3), which makes it possible to calibrate industrial pyrometers in the range from minus 20 °C to 250 °C.

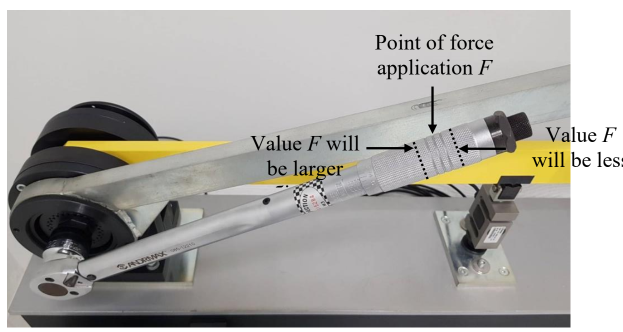

Fig. 2. Installation for calibration of torque keys, points of application of force to the dynamometric key

Fig. 3. General view of the installation for calibration of pyrometers

As a calibration object, we used the industrial pyrometer Benetech GM910 (PRC). Calibration was performed at a temperature of 40 °C. The maximum uncertainty of the pyrometer according to the passport for this temperature is 1.5 %, which in absolute form is 0.6 °C. The maximum permissible calibration uncertainty should be 0.2 °C. The influential factors on which the calibration uncertainty depends were the positioning of the pyrometer relative to CBB, for which two experiments were conducted. In the first experiment, the positioning of the pyrometer was carried out manually, without the use of a special holder, in the second experiment, the pyrometer was fixed in the holder (Fig. 4). The study was carried out at a temperature of 40 °C. The extended uncertainty of working standard is 0.1 °C, respectively, and the component u_{MP}=0.087 °C.

Fig. 4. Installation for calibration of pyrometers, positioning of a pyrometer

The main hypothesis of our study assumed that decision-making based on generally accepted statistics leads to the emergence of unmanageable risks in the laboratory associated with calibration uncertainty. Improvement of procedures with the use of improved statistics will minimize such risks.

During the study, methods of probability theory and mathematical statistics, simulation modeling, and methods for assessing the uncertainty of measurements during calibration, regulated by the European Association, were used.

We studied the E_n-statistics by the Monte Carlo method [19]. According to the results of the simulation, reliability calculations were carried out (P, %) identifying the difference in the results of specialists $\Delta=|X_1-X_2|$. The result of each specialist was modeled as a sample of 1000 values following the Gaussian distribution law. The mathematical expectation for the first specialist is $\mu_1=0$, and for the second – $\mu_2=\Delta$. The values of parameters σ_1 and σ_2 were the same for both samples in the first experiment and were equal to $0.5U$, respectively, it was assumed that the value U was determined only by a random component evaluated by the results of the simulation. In the second and third experiments, the σ_1 and σ_2 values were different. The values Δ were chosen proportional to the value of the extended uncertainty U.

Our experimental studies were carried out at a calibration laboratory certified by the National Accreditation Agency of Ukraine. This allowed us in practice to check the adequacy of the proposed concepts and procedures.

5. Results of studies on the impact of personnel competence on uncertainty during calibration

5. 1. Experimental investigation of classical E_n-statistics

In order for the contribution of laboratory staff u_p to the uncertainty of calibration results (4) to be accepted irrelevant on the basis that the personnel is competent, the laboratory must provide auditors with statistically sound evidence.

We have analyzed the results of measurements obtained during the calibration of the dynamometric key at the installation in Fig. 1.

Table 1 gives the initial records based on the results of the calibration of the dynamometric key at the installation (Fig. 1) and the calculated value of E_n-statistics for two experiments.

Table 1

Results of calibration of dynamometric torque keys

No.	Force momentum F, Nm			
	Experiment 1		Experiment 2	
	Specialist 1	Specialist 2	Specialist 1	Specialist 2
1	101	105	105	109
2	102	106	101	105
3	101	105	101	105
4	100	104	97	101
5	101	105	101	105
Mean value	101	105	101	105
U	1.7		5.7	
E_n (from formula (2))	–1.6		–0.5	
E_n (from formula (4))	–2.1		–1.1	

It is necessary to note a slight variation in the impressions of each of the specialists during the first experiment and a significant variation in impressions during the second experiment, as well as the obtained values of E_n-statistics for both experiments. The variation is directly affected by the place of application, speed, and uniformity (without jerks) of effort application, which are components of the competence of the staff.

Table 2 gives the results of the calculation of the reliability of the detection of the difference in the results of specialists for classical E_n-statistics (1). Evaluation of the reliability of the results is a direct requirement of the requirements of standard [1].

Table 2

Reliability of detecting the difference in the results of specialists

Δ/U, relative unit	P, % $\sigma_1=\sigma_2=0.5U$	P, % $\sigma_1=0.5U$, $\sigma_2=0.75U$	P, % $\sigma_1=0.5U$, $\sigma_2=0.25U$
1	11	8	27
1.5	60	40	82
2	97	80	98
2.5	100	95	100
3	100	100	100

In the results, attention should be paid to the values of the ratio Δ/U at which the probability of detection is greater than 95 %.

5. 2. Devising a methodology for assessing the impact of personnel competence on uncertainty during calibration

In order to avoid second-kind errors in determining the impact of staff competence, we propose to modify (1) to the following form:

$$E_n = \frac{X_1 - X_2}{\sqrt{2}U_{MP}}, \tag{6}$$

where U_{MP} is the maximum permissible uncertainty, which is chosen according to metrological rules for the selection of standards, it should be at least three times less than the maximum permissible uncertainty of the MET, which is calibrated.

The proposed modification is based on the fact that the maximum permissible uncertainty (or its random component) is an important characteristic that depends on the ratio of the accuracy of the working standard and MET. This characteristic should be taken into consideration when assessing the competence of staff.

Statistics according to (1) do not take into consideration the correlation of the results of specialists, although its presence is not in doubt, since during calibration specialists use the same equipment under the same conditions and for the same calibration points.

It is possible to involve the correlation of the results of specialists in calculations using (1), which is implied for processing the metrological reconciliations of standards, according to [19]:

$$E_n = \frac{X_1 - X_2}{2\sqrt{u_1^2 + u_2^2 - 2\operatorname{cov}(X_1, X_2)}}, \tag{7}$$

where u_1, u_2 are the standard uncertainties of calibration results; $\operatorname{cov}(X_1, X_2)$ is the evaluation of covariance of specialists' results.

It should be noted that in order to obtain a statistically reliable assessment of the value of covariance for the results of two specialists in practice, one needs to get a significant amount of data and, accordingly, spend time. Therefore, we propose, taking into consideration recommendations [20], that the value of $\operatorname{cov}(X_1, X_2)$ should be replaced with the standard uncertainty of calibration of working standards u_{we}, which is more effective for practical application:

$$E_p = \frac{X_1 - X_2}{2\sqrt{u_1^2 + u_2^2 - 2u_{we}^2}}. \tag{8}$$

It should also be noted that (7) requires conscious use since, unlike (8), it still contains the above disadvantages.

We propose to conduct an assessment of competence according to the methodology, which involves the following:

1. Determine the maximum permissible calibration uncertainty. To assess competence, it is advisable to choose, if possible, the most accurate MET, which has a minimum value of the limit of permissible error, or extended uncertainty U_{MM}. For the maximum permissible uncertainty value, it is recommended to choose $U_{MP} \leq 1/3 U_{MM}$.

2. Conduct a series of calibration experiments at several points (at least three in each range or sub-range) for each specialist. For each point and specialist, calculate the average values of X_1, X_2 and the values of standard deviations s_1, s_2, which are part of the random component of calibration uncertainty.

3. Check the compliance of the random component of the calibration uncertainty with the maximum permissible uncertainty. To do this, from the U_{MP} value, it is necessary to exclude the permissible random component in the form of standard uncertainty u_{MP}:

$$u_{MP} = \sqrt{\left(\frac{U_{MP}}{2}\right)^2 - u_{we}^2}. \tag{9}$$

If the values s_1 and s_2 exceed u_{MP}, we use the Fisher criterion to compare variances [21]. If the criterion confirms the homogeneity of variances, use (6).

4. If the values obtained during calibration of the standard uncertainties of repeatability s_1 and s_2 are less than u_{MP}, proceed to check the value of the difference in the results of specialists.

We calculate the values of modified E_n-statistics:

$$E_n = \frac{X_1 - X_2}{2\sqrt{s_1^2 + s_2^2}}. \tag{10}$$

The decision-making criterion for E_n-statistics remains $1 \leq E_n \leq 1$.

In order to facilitate the use of the methodology that we devised in practice, below is an example of calculations according to the above methodology.

The MET was calibrated with maximum extended uncertainty $U_{MM}=0.5V$. A working reference with maximum extended uncertainty $U_{we}=0.1V$ was used, respectively, $u_{MP}=0.083V$ according to (9). The specialists received ten results of observations, for which $\bar{X}_1 = 10.16V$, $\bar{X}_2 = 10.31V$. The extended uncertainty of the calibration result obtained by the first and second specialists was, respectively, $U_1=0.109V$, $U_2=0.110V$. The value of the coefficient $E_n=-0.97$, according to (1), so the specialists were recognized as competent. The calibration uncertainty regardless of the specialist will be $U=0.110V$.

According to the proposed methodology, we evaluate the values of standard deviations: $\tilde{s}_1 = 0.70V$, $\tilde{s}_2 = 0.074V$. Values $s_1 = \tilde{s}_1/\sqrt{10} = 0.022B$, $s_2 = \tilde{s}_2/\sqrt{10} = 0.023B$ do not exceed the value of the maximum permissible standard uncertainty $u_{MP}=0.083B$. Calculated according to (10), the modified value is $E_n=-2.33$ therefore, we considered specialists incompetent. The use of (1) led to the second-kind error. The uncertainty of the personnel $u_p=0.05B$ is equal to the standard uncertainty of the working standard $u_{we}=0.1/2=0.05B$, it must be taken into consideration in the extended calibration uncertainty, the estimated reliable value of which will be $U=0.148B$.

5. 3. Comparative analysis of the classical, modified, and alternative statistics of personnel competence assessment

Conducting a comparative analysis on the example of calibrating an industrial pyrometer is explained by a significant dependence of calibration accuracy on the competence of personnel. The accuracy is determined by the coaxiality of the optical axis of the pyrometer and CBB, the distance between them, and the perpendicularity of the optical axis of the pyrometer and the CBB plane.

The primary records obtained during calibration and calculations are given in Table 3. The E_p-statistics values were calculated using formulas (1), (6), and (8). The values of CD statistics (2) were determined under the condition $\sigma_r=u_{MP}$ (9) and by the values of repeatability s_r. Table 3 gives two indicators $CD\ \sigma_r$ and $CD\ s_r$, respectively.

Table 3

Results of analysis of the difference in pyrometer calibration results

No.	Temperature, °C			
	Experiment 1 (manual positioning)		Experiment 2 (positioning with a holder)	
	Specialist 1	Specialist 2	Specialist 1	Specialist 2
1	40.0	40.5	40.0	40.2
2	40.0	40.4	40.1	40.1
3	40.2	40.4	39.8	40.1
4	40.3	40.6	40.1	39.9
5	40.0	40.2	39.9	40.0
6	40.2	40.6	40.0	40.1
7	40.1	40.2	39.9	40.0
8	40.2	40.5	40.0	39.9
9	39.7	40.8	39.9	40.1
10	40.0	40.2	40.1	40.2
Mean value	40.07	40.494	39.98	40.06
Δ	–0.371		–0.080	
s_{ri}	0.17	0.20	0.10	0.11
s_r	0.19		0.11	
U	0.58		0.25	
E_n (1)	–0.45	Competence is satisfactory	–0.23	Competence is satisfactory
E_n (6)	–1.30	Competence is not satisfactory	–0.28	Competence is satisfactory
E_n (8)	–0.36	Competence is satisfactory	–0.14	Competence is satisfactory
E_n (10)	–2.22	Competence is not satisfactory	–0.85	Competence is satisfactory
$CD\ \sigma_r$ (2)	0.077	Competence is not satisfactory (Δ>0.077)	0.077	Competence is not satisfactory (Δ>0.077)
$CD\ s_r$ (3)	0.165	Competence is not satisfactory (Δ>0.165)	0.093	Competence is satisfactory (Δ<0.093)

In Table 3, it should be noted that in the first experiment there is a difference between specialists that indicates a lack of competence. However, the E_n-statistics values, calculated according to different formulas, differ, that is, the use of different formulas will lead to different decisions regarding the competence and form of the total calibration uncertainty.

6. Discussion of results of the impact of personnel competence on uncertainty during calibration

Unmanageable risks associated with simplification of the generalized model (4) are explained by the neglect of the component of uncertainty due to the competence of the staff.

The criterion with statistics (1), proposed in [17], was originally developed to analyze the results of interlaboratory comparisons, that is, the results obtained under the conditions of interlaboratory reproducibility. When assessing the competence of specialists, there are conditions for intralaboratory reproducibility.

If we calculate the uncertainty component from (5) under condition $U=U_1=U_2$, then in practice this will mean that the criterion using E_n-statistics will show that specialists are competent. That is, the component of competence can be neglected. In fact, the component will be 50 % of the total uncertainty, so the condition of insignificance is not met.

The calibration procedure using the installation for calibrating dynamometric keys (Fig. 1) demonstrates a significant dependence of calibration accuracy on the competence of the personnel (Table 1). However, due to violations of the terms of use, the E_n-statistics are insensitive to this. Thus, the worse the calibration personnel (the greater the calibration uncertainty), the lower the value of E_n-statistics, that is, the criterion will show that the personnel is competent and the component can be neglected.

The results of the first experiment, given in Table 1, are explained by the fact that each of the specialists faithfully conducted an experiment, an unknown variation in the impressions of each of the specialists indicates that he imposed the same force at the same point.

Comparing the results of specialists with each other, however, shows that each specialist has chosen a different point of application. As a result, there was a shift between the average measurement values, and the E_n-statistics values at the same time exceeded the limit values and the specialists were recognized as incompetent.

In the second experiment (Table 1), a significant variation in impressions is explained by the fact that each individual specialist performed a separate measurement with a different application force, changing the application point. In fact, such results indicate staff incompetence. However, mathematically, the variation of impressions led to an increase in the denominator in expression (1) and, in turn, a decrease in the value of E_n-statistics. As a result, according to the criterion with statistics (1), a conclusion was made about the competence of the staff, which has made it possible not to take into consideration the component of competence.

Taking into consideration the above, we consider the disadvantage of the criterion using E_n-statistics its main thesis: «the results of specialists are statistically indistinguishable», which leads to the adoption of erroneous decisions.

We believe that the main thesis on competence should be the following: «the difference between the results of specialists obtained during calibration should not affect the uncertainty of calibration».

To avoid errors of the second kind is possible by using our proposed modification (1) of the E_n-statistics. Unlike the classical E_n-statistics, its application is possible when the difference in the results of specialists is insignificant, at the level of uncertainty of calibration U, experts are recognized as competent but the uncertainty U itself may be greater than the maximum allowable, which will not be detected during such an assessment. On the other hand, the maximum permissible uncertainty is different for different METs and the specialist can be allowed to calibrate the less accurate MET and is not allowed to touch high-precision ones, which allows us to assert the flexibility of the proposed formula.

The results of modeling given in Table 2 show that the criterion based on E_n-statistics is not powerful enough. In the case of equal calibration uncertainties of both specialists, it reveals a difference of 1U in less than 11 % of cases. Such a difference indicates a different level of competence of the staff, that is, the component of uncertainty must be taken into consideration in the uncertainty of calibration.

The probability of detection of more than 95 % is achieved only for a difference of 2U or more. If one of the specialists shows greater individual uncertainty, this leads to a decrease in the likelihood of detecting an inadmissible difference in results, which indicates the insufficient capacity of the criterion using statistics (1).

Thus, the initial data when assessing the value and possible impact of the component from incompetence is, in our opinion, the maximum permissible calibration uncertainty.

Flexibility and making reliable decisions using modified formulas (9), (10) become possible due to the methodology for assessing the competence of personnel that we proposed. This makes it possible to close the outlined issues in terms of obtaining reliable assessments to make a decision on the impact of personnel competence on calibration uncertainty.

The considered alternative methods with statistics (2) and (3) make it possible to objectively make decisions on taking into consideration the contribution of personnel to the uncertainty of calibration at the maximum difference between the results of specialists no more than the maximum permissible uncertainty.

The advantages of our proposed methodology are given in Table 3. For the data of experiment 1, when there is a significant difference between specialists (Δ=–0.371 °C exceeds the permissible calibration uncertainty U=0.2 °C, and the subjective component of uncertainty cannot but be taken into consideration) the real value of this uncertainty was 0.58 °C. However, the correct result of the assessment of competence – «competence is unsatisfactory» can be obtained only according to the formula that we proposed (6) and using an alternative approach (2).

The results of experiment 2 (Table 3) showed that the use of the holder reduced the subjective component of uncertainty since the value of =–0.080 °C was half the permissible calibration uncertainty (U=0.2 C). Accordingly, the competence of specialists in experiment 2 can be recognized as not affecting the uncertainty of calibration. That was confirmed by all applicable criteria, except for the CD σ_r statistics. The CD σ_r result «competence is unsatisfactory» is neither really correct nor false. The value of Δ differs from the value of CD σ_r statistics only by 0.003 °C, so this difference compared to the maximum permissible uncertainty of the pyrometer is insignificant.

Therefore, an alternative approach with the use of (2) produces generally correct conclusions, although it is necessary to take into consideration the increased probability of a mistake of the first kind – the possibility of recognizing a competent specialist as incompetent.

This makes it possible to close a certain problem in terms of determining statistics, which minimizes errors of the first and second kinds. Such statistics are proposed by us (6).

The limitation of this seminal study is that the thresholds for the statistics in question stipulate that Gauss's law is the law of distributing calibration results. In the case of other laws, especially asymmetric (Raleigh, Exponential) or multimode (arcsine), the limit values of statistics must be determined for specific cases.

The disadvantages of this study include:

1. The methodology implies additional calibrations, respectively, time and resources.

2. Evaluation should be carried out for everything provided for by the scope of accreditation, calibration range, as well as for different classes of MET, which are calibrated, which is also not always possible for the calibration laboratory.

3. The procedure does not provide for determining the minimum required number of measurements during calibration, sufficient to ensure a reliable decision on the competence of personnel.

The development of this study can be considered the next modifications of E_n-statistics that will ensure resistance to the laws of distribution of calibration results, and limited sample volumes. Another area of development is to devise and approve of national regulatory documents containing the method that we proposed.

The findings can be used by calibration laboratory personnel as a precautionary measure to minimize the risks posed by the impact of staff competence on uncertainty during calibration.

7. Conclusions

1. It is established that the classical E_n-statistics are not regulated by any regulatory document for use to quantify the impact of staff competence. Violation of the terms of its use has been determined. The experimental study of the classical E_n-statistics showed insufficient power and significant errors of the second kind, which leads to uncontrolled risks for the calibration laboratory.

2. The modification of the E_n-statistics, which provides flexibility in decision-making due to the fact that it is based on the comparison of standard deviations of personnel calibration results with the maximum permissible calibration uncertainty, is proposed. The methodology for assessing the competence of personnel using the modified E_n-statistics has been developed. The methodology makes it possible to choose a formula for calculating the E_n-statistics depending on the intermediate indicator of personnel precision in the form of standard deviation s_1 and s_2. The result is to minimize the error of the first and second kinds.

An example of calculations of extended uncertainty during calibration based on the classical and modified E_n-statistics is given. The use of classical statistics led to an erroneous decision on competence and the exclusion of the component from the competence of the staff. Our calculations using the proposed methodology based on the modified E_n-statistics showed that the component of the competence of the staff should be taken into consideration. The error of calculating extended uncertainty based on the E_n-statistics was 35 % compared to the use of modified statistics in accordance with the developed procedure.

3. The comparative analysis of the classical, modified, and alternative statistics for assessing the impact of personnel competence on uncertainty during calibration based on the numerical assessments of E_n-statistics was carried out. It is shown that under the same conditions, the modification makes it possible to avoid errors of the second kind when making decisions.

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