10th IMEKO TC7 International Symposium
June 30 - July 2, 2004, Saint-Petersburg, Russia

UNCERTAINTY OF OCCUPATIONAL HEALTH MEASUREMENTS

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Abstract – Occupational health measurements have considerable importance to safeguard the health of personnel in the working environment. Assurance of healthy conditions is prescribed in legal acts and if those requirements are not fulfilled can entrepreneur have considerable economical losses trough the authorities sanctions and charges for the damaged personnel. To have correct conformity estimation against legal limit values evaluator must have the reliable result of measurement and the truthful uncertainty estimation. Uncertainty estimation of occupational health measurements have some special particularities. Sound way to assure the best measurement capability is the interlaboratory comparison.

Keywords: occupational health measurements, uncertainty, proficiency testing.

1. INTRODUCTION

In this work is handled uncertainty estimation of working area environment measurements, also named as occupational health measurements. Such measurements have considerable importance to safeguard the health of personnel in the working environment. Such requirements are prescribed in legal acts and if those requirements are not fulfilled can entrepreneur have considerable economical losses trough the authorities sanctions.

In the occupational health area more used are next measurements: light density, noise parameters, EM radiation, particles and dust in air and air temperature, humidity and velocity of air.

Exact uncertainty shall be founded to have possibility to give the correct conformity estimation of conditions, taking account the legal limits of hazardous parameters.

The best measurement capability can be assessed suitably using interlaboratory comparison schemes.

Above problems were ground of this study work.

2. MEASUREMENT PROBLEM

Occupational health measurements are carried out based on the large amount of methods and procedures. Some methods are used through long years and they based on regional requirements and some on ISO standards. As general case, in the methods and procedures is not handled uncertainty estimation as given in GUM [1].

Also accreditation process in Estonia showed that laboratories did not used uncertainty estimation in practice and used was errors simplified estimation using different accuracy parameters.

For the accuracy estimation was involved mainly only the measurements instruments accuracy parameters which were given by producers and often the competent traceability was forgotten. Mainly the measuring instrument verification was carried out.

For the accreditation those problems shall be corrected. To correct above problem, help was given through this work results.

3. UNCERTAINTY ESTIMATION

3.1 *General principles*

Occupational health measurements are complicated, they have individual particularities and influence have plenty of various factors. Some influence factors cause asymmetric distribution of results. Uncertainty components have various sensitivity coefficients.

For the uncertainty estimation of occupational health measurements can be follow GUM principles. Uncertainty calculation shall be carried out on the level of standard uncertainty using sensitivity coefficients giving final result on measurement unit which is typical for the given measurement.

Shall be taken account standard uncertainty components which can be calculated using statistical techniques, A-type components, and standard uncertainty components found by others methods, B-type components.

Combined standard uncertainty can be found by equation:

$$u = \sqrt{u_\mathrm{A}^2 + u_\mathrm{B}^2}\ . \qquad (1)$$

Standard uncertainty component u_A is suitable to calculate in the most cases through well-known equation, presuming that repetitions are more than 10 and they are non correlated:

$$u_\mathrm{A} = \sqrt{\frac{1}{n(n-1)}\sum (x_i - \bar{x})^2}\ , \qquad (2)$$

where n is repetitions quantity, x_i value of measurement and $\bar{x}$ is arithmetical mean of measurement results.

Combined standard uncertainty u_B is formed from the influence of measuring instruments, measurement object, method and environment and if possible it can include the pooled uncertainty.

Combined standard uncertainty from the measuring instrument u_{MI} includes next components:
- combined uncertainty estimated through calibration of measuring instrument;
- possible drift;
- various parts connection and its mutual influence and cooperation;
- reading of indication.

Uncertainty of the measuring instrument u_{MI} can be estimated using values of the permissible error limits Δ by verification or the expanded uncertainty U (or combined uncertainty u) given in the calibration certificate of the measuring instruments. For the verification permissible error Δ values, it is presumed that by verifications the result had normal distribution and confidence level is 2 standard deviations, then $u_{MI} = = \Delta_{\max} / 2$. For the calibration, as a rule, coverage factor $k = 2$ is applied and then $u_{\mathrm{MI}} = U / 2$.

Uncertainty component from the various parts connection and its mutual influence and co-operation. Shall be used producers values or experimental data.

Uncertainty component from the indication u_{RE} includes uncertainty from parallax and instrument resolution by the single measurement. The component u_{RE} values estimation shall be based on the minimal scale interval (*SI*) for the analogue indication and on smallest difference of the extreme right numbers (*DI*) for the digital indication. Assuming rectangular distribution of values, the uncertainty is given by:

$$u_{RE} = \frac{VJ}{\sqrt{3}} \text{ or} \tag{3}$$

$$u_{RE} = \frac{SJ}{2\sqrt{3}}\,. \tag{4}$$

Combined standard uncertainty from the measurement object u_{OBJ} includes next components:
- large dimensional parameters of the site;
- accuracy of the determination of measurement actual place;
- object parameters dependence from the various influence quantities like nearby situated powerful items and sources, electricity field parameters and s.o.;
- distance between measured object and measuring instrument;
- object shape and specific characteristics.

For example for the light density measurement importance has spectral quantity of the lamp, where exists correction factor K_{V} and corrected measurement result uncertainty value u_{Kv} is calculated by equation:

$$u_{\mathrm{Kv}} = \sqrt{E_i^2 u_{Kvp}^2 + K_V^2 u_{Ei}^2}\,, \tag{5}$$

where u_{Kvp} is uncertainty of correction factor K_{V} and E_{i} is the measurement result before correction and u_{Ei} is its summary standard uncertainty.

Combined standard uncertainty from the environment influences u_{EN} includes next main components:
- natural level;
- industrial disturbances and “noises”;
- sudden change of conditions and its non-stability;
- object unstable power supply and its deviations.

The uncertainty caused by power supply consists of voltage value calculation to the standardised value, from the voltage non-stability and from the measurement of voltage.

For example, for the light density measurement the uncertainty of corrected result is calculated using equation:

$$u_{\mathrm{KU}} = \sqrt{E_i^2 u_{KvU}^2 + K_U^2 u_{Ei}^2}\,, \tag{6}$$

where K_{U} is the correction factor for voltage influence with uncertainty u_{KU} and E_{M} is the measurement result before correction.

As rule those components has minor importance if conditions parameters values are near to the normal, but can rapidly grow even by the small deviations.

Uncertainty component from the method u_{M} includes next components:
- pooled uncertainty;
- influence of specific requirements which demand exact set up of the measurement;
- influence from the calculation of the result to the other conditions.

Pooled uncertainty u_{SP}. A good measurement plan uses replication, as well as repetition, in the measurements. Since replications are independent estimates of the same measured value, their data represents separate data samples that can be combined to provide a better statistical estimate of a measured variable than are obtained from a single sample. Samples that are grouped in such a manner as to determine a common set of statistics, are said to be pooled. Consider M replicates of a measurement of variable x, each of N repeated readings so as to yield the data x_{ij}, where $i = 1, 2, \ldots,\ M$. The pooled mean of x is defined by equation:

$$\bar{x} = \frac{1}{MN} \sum_{j=1}^{M} \sum_{i=1}^{N} x_{ij}\,. \tag{7}$$

If pooled uncertainty is not known, then the uncertainty component u_R should be found in few repeated measurements, which characterises measurement process non-stability and shall be estimated if the repeated measurements are less than 5 ÷ 9 by using variation limits $x_t = x_{\max} - x_{\min}$, where $x_{\max}$ is the maximum value and $x_{\min}$ is the minimum value in the results batch. Assuming results rectangular distribution uncertainty is given by:

$$u_R = \frac{x_t}{2\sqrt{3}}\,. \tag{8}$$

Occupational health measurement combined uncertainty u is calculated by an equation:

$$u = \sqrt{u_{\mathrm{MI}}^2 + u_{\mathrm{M}}^2 + u_{\mathrm{ENV}}^2 + u_{\mathrm{OBJ}}^2}\,, \tag{9}$$

where all components are expressed in same measurement units, this mean sensitivity coefficients are equal to 1.

Expanded uncertainty U has coverage factor $k = 2$ and this gives the level of confidence approximately 95 %.

Statistical techniques shall be used to detect extraneous data points as outliers, in the repeated set, which increases the precision estimate. Outliers measured values fall outside the probable range of values for a measurand. If detected, a decision as to be made whether to remove the data points from the data set. Prior to their removal, one is strongly cautioned to be certain that these extraordinary deviations from central tendency are truly spurious and not a unique physical tendency of the measurand. The simplest way for outliers detection would be to calculate the data set statistics and to label all points that lie outside the range of 99,8 % probability of occurrence, $\bar{x} \pm t_{v,99,8} S_x$ and carry out some specific outliers test as Cochran test or Stubbs test or other.

For uncertainty components must be analysed that they have well behaving probability distribution, such as normal or rectangular, and one component with an unknown probability distribution does not dominate. For example for occupational health measurements this can take place in noise parameters measurements where some outer industrial frequency causes more systematic behaviour of the measurement conditions.

Occupational health measurement input quantities can be in some cases correlated i.e. they are dependent on each other in one way or the other. The measured variable is usually a function of one or more independent variables, which are controlled during the measurement. When the measured variable is sampled, these variables are controlled to the extent possible, as are all the other operating conditions. Following the sample, one of these variables is changed and the sample is made under the new operating conditions. This is the procedure used to document the relationship, i.e. correlation between the measured variable and an independent process variable. The correlation exists mainly due to the fact that measured value of the object was obtained using the same measuring instrument, the same method and the same surrounding conditions.

Correlation coefficient is calculated by an well-known equation:

$$r(x_i, x_j) = \frac{u(x_i, x_j)}{u(x_i)u(x_j)}. \tag{9}$$

3.2 *Specific moments for light density measurements*

Specific moments of the uncertainty estimation of the light density measurements are: the measurement position shall be pointed exactly, the object illumination characteristics and the dependence from power supply of lamps.

An average level of the uncertainty of light density measurement can be achieved as shows next example. Given are uncertainty components:

- from the light density meter: $u_{\mathrm{MI}} = \Delta/2 = 10\,\% \cdot E\,/\,2 = 0{,}1 \cdot 160\,/\,2 = 8$ lx, where Δ is the measuring instrument error limit and E is the measurement result (for example 160 lx);
- from the reading: $u_{\mathrm{r}} = JV/\sqrt{3} = 1/\sqrt{3} = 0{,}6$ lx;
- from the variation of measurement results by repeated measurement: $u_{\mathrm{v}} = (E_{\max} - E_{\min})\,/\,2\sqrt{3} = 2\,/\,2\sqrt{3} = 0{,}6$ lx, where $E_{\max}$ and $E_{\min}$ are results limit values;
- from the variation of the power supply of lamps and voltage measurement: $u_{\mathrm{e}} = (E_{\mathrm{Umax}} - E_{\mathrm{Umin}})\,/\,2\sqrt{3}$, where E_{Umax} and E_{Umin} are the light density limit values depending on the maximum and minimum voltage of power supply of lamps, $u_{\mathrm{v}} = (166{,}4 - 155{,}2)\,/\,2\sqrt{3} = 3{,}2$ lx (voltage maximum 222 V and minimum 218 V, class 1 voltage meter, indication interval 1 V, variation of voltage during measurement 1 V;
- from the correction factor of the lamps spectral characteristic and its influence to light density meter: $u_{\mathrm{s}} = E_{\mathrm{s}}/\sqrt{3}$, where E_{s} is correction factor limit value given in lx. Depending on type of lamp this has value can be 0 up to 2 lx by 1000 lx.

Realistic is to have the combined standard uncertainty for the light density measurement for general lightning conditions summarising above values:

$$u = \sqrt{u_{\mathrm{mi}}^2 + u_{\mathrm{r}}^2 + u_{\mathrm{v}}^2 + u_{\mathrm{e}}^2 + u_{\mathrm{s}}^2} =$$

$$= \sqrt{8{,}0^2 + 0{,}6^2 + 0{,}6^2 + 3{,}2^2 + 0} = 8{,}6 \text{ lx}$$

or as relative value 5,4 % for 160 lx.

Similarly for spot lightning:

$u = \sqrt{21{,}0^2 + 0{,}6^2 + 1{,}8^2 + 7{,}2^2 + 0} = 22{,}2$ lx or as relative value 5,2 % for 410 lx.

Expanded uncertainties by coverage factor $k = 2$ are $U_{\mathrm{com}} = 10{,}8$ % and $U_{\mathrm{spot}} = 10{,}4$ %.

3.3 *Specific moments for noise measurements*

Noise parameters measurement has wide area of specific requirements [2]. The uncertainty estimation for noise parameters measurements shall include at least next components: measuring instrument and transducers co-operation, measuring device calibration before measuring; measuring object form and specific characteristics, industrial noise level and measurement set up.

Components of uncertainties of the simple noise measurement process can be as follows:

- from the noise measurement device: $u_{\mathrm{mi}} = 0{,}5$ %;
- from the reading: $u_{\mathrm{r}} = 0{,}5$ %;
- from the variation of measurement results by repeated measurement $u_{\mathrm{v}} = 0{,}3$ %;
- sum of the specific components: $u_{\mathrm{v}} = 1{,}0$ %.

Realistic is to have combined standard uncertainty u for simple noise measurement up to (1,5 ÷ 2) % from the measurement result.

3.4 *Specific moments for other measurements*

Given in art 3.1 all principles are valid and additionally shall be taken account next particularities.

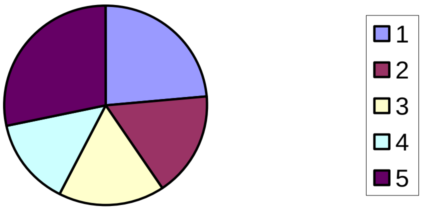
Measurement of the air velocity is very dependent on the position, where measuring instrument is placed because the air flow is different in various places. Dust quantity measurement in air is dependent on the sampling method and its quality. For air temperature and humidity measurement shall be pointed out the exact set up of the measurement. Air humidity measuring instrument shall have the suitable maintenance and the preparation procedure. For EM radiation measurement have influence various natural and industrial disturbances.

3.5 *Components influence to combined uncertainty*

Occupational health measurement uncertainty components influence to combined uncertainty in percentages (coarse estimation) can be express as next relation:

uncertainty of the measuring instrument ÷ uncertainty caused by the resolutions of readings; ÷ uncertainty from the object influence ÷ uncertainty from the natural level and uncertainty of the other influence factors = (25÷30) % + (15÷20) % + (10÷20) % + (10÷20) % +ca 30 %.

This relationship is illustrated on Fig.1.



Components from: 1 – measuring instrument; 2 – readings; 3 – object; 4 – natural level; 5 – others.

Fig.1 Uncertainty components influence to combined uncertainty in percentages (coarse estimation)

3.6 *Correction factors*

Almost for all occupational health measurements exist some systematic influence quantity (see art. 3.1) and this shall be corrected using correction factors. Correction factor estimation is as rule not very exact and this cause need to estimate its uncertainty correctly.

3.7 *Specific statistical aspects for occupational measurements uncertainty*

For the occupational health measurements influence quantity have mainly non-normal distribution and in extreme it has the rectangular distribution. But the convolution of even as few as three rectangular distributions is more or less normal, if they have equal width. More better is situation when components are more than three and this is the case for occupational health measurements. Central Limit Theorem allows [3], if the combined standard uncertainty is not dominated by a standard uncertainty component obtained from a type A evaluation based on just a few observations or by a standard uncertainty component obtained from a type B evaluation based on an assumed rectangular distribution, a reasonable first approximation to calculating an expanded uncertainty, that provides an interval level of confidence p is to use for k_p a value from the normal distribution.

For the occupational health measurements influence quantities may have asymmetric distribution and then conditions for the central limit theorem is not completed.

If the exact asymmetry factor cant be found then is better to find new corrected mean value which is suitable for the application of a simple distribution, for example as triangular distribution.

In some cases distribution of initial data can be over estimated using other statistical values like median or weighed mean and giving them a simple distribution.

Of cause, uncertainty of results shall be also over calculated for the both cases.

3.7 *Coverage factor*

For the occupational health measurements the GUM principles are valid for the coverage factor establishment. To obtain the value of the coverage factor k that produces an interval corresponding to a specified level of confidence p requires detailed knowledge of the probability distribution characterised by the measurement result and its combined standard uncertainty. Because the parameters characterising the probability distributions of input quantities are estimates and because it is unrealistic to expect that the level of confidence to be associated with a given interval can known with a great deal of exactness and because of the complexity of convolving probability distributions, such convolutions are rarely implemented when intervals having specified levels of confidence need to be calculated.

For the occupational health measurements is common to assume to have probability level of 95,45 which allows to use coverage factor $k = 2$. The ground for this assume is, that measurement process include more than four components of the influence quantities.

4. PRACTICAL ASSURANCE OF MEASUREMENTS UNCERTAINTY BY INTERLABORATORY COMPARISONS.

4.1 *General*

Uncertainty estimation is connected with verification of the best measurements capability of laboratory. For this purpose, one of the most suitable is interlaboratory comparison.

For Estonian laboratories are carried out 2 comparisons schemes in the occupational health measurement area. In 1999, for the light density measurements and in 2002 for the measurement of the noise parameters in the working place.

Particularly difficult for those comparisons schemes was to assure the similarity and stability of the measurement object for all participants.

4.2 *Light density measurement.*

Simultaneously by participants the light density produced by standard was measured.

Determined was spot light density and general light density. Comparison main data are given in Table 1 and Table 2. On the ground of measurement results was calculated the arithmetical mean of participants results using equation:

TABLE 1. Comparisons general data of light density measurements

Quantity of participants	Arithm. mean: general lightning	Arithm. mean: spot lightning
17	158,2 lx u = 11,3	417,4 lx u=29,9

$$E_a = \frac{\sum_{i=1}^{n} E_i}{n}, \qquad (10)$$

where E_i is the laboratory measurement results and n is the quantity of laboratory.

Standard deviation of average of results was calculated by equation:

$$s = \sqrt{\frac{1}{n(n-1)}\sum_{i=1}^{n}(E_i - E_a)^2}\ . \qquad (11)$$

TABLE 2. Comparisons results of light density measurements

Parti-cipant	Results		Z-score		Deviation from mean value	
	1	2	1	2	1	2
	lx	lx			%	%
1	141	350	-1,5	-2,3	-12,2	-19,3
2	154	395	-0,4	-0,8	-3,0	-5,4
3	170	413	1,0	-0,1	7,5	-1,1
4	168	435	0,9	0,6	6,2	4,2
5	139	380	-1,7	-1,3	-12,1	-9,0
6	162	417	0,3	0	2,4	-0,1
7	166	436	0,7	0,6	4,9	4,3
8	145	425	-1,2	0,3	-8,3	1,8
9	148	393	-0,9	-0,8	-6,5	-5,9
10	160	465	0,2	1,6	1,1	11,4
11	180	480	1,9	2,1	13,8	15,0
12	149	419	-0,8	0,1	-5,8	0,4
13	156	427	-0,2	0,3	-1,4	2,3
14	165	429	0,6	0,4	4,3	2,8
15	170	410	1,0	-0,2	7,5	-1,8
16	162	408	0,3	-0,3	2,4	-2,3
17	155	415	-0,3	-0,1	-2,0	-0,6

Laboratory's result relative deviation from the mean value was calculated by equation:

$$E_{ri} = \frac{E_i - E_a}{100\,E_a}\ \%. \qquad (12)$$

Reference value was not used because concrete criteria can't be determined.

Laboratory Z-value was calculated by equation:

$$Z = \frac{E_i - E_a}{s}\ . \qquad (13)$$

Participant result by ISO Guide 43:1 [4] is good if Z-value is less than 1 and satisfactory if Z-value is less than 2. In this case Z-value was over 2 for 4 measurement results of 3 laboratory, and for laboratory No 10 twice. Result deviation to one side from the mean value had laboratories No 1, 5, 10 and 11. This shows possibility to have systematic influence quantity.

4.3 *Noise parameters measurement*

Simultaneously by participants the noise parameters produced by standard noise source was measured.

Determined was sound pressure level by various dB. Comparison main data are given in Table 3 and Table 4. Formulas given in 4.2 were used similarly for the calculation of values.

TABLE 3. Comparisons general data of noise measurements

Quantity of participants	Mean value for 125 Hz	Mean value for 4000 Hz
12	77,3 dB u = 0,33 dB	80,5 dB u = 0,28 dB

TABLE 4. Comparisons results of noise measurements (given are data only for one level)

Participants	Sound pressure		Z-score		Deviation from mean value, %	
	125 Hz	4000 Hz	125 Hz	4000 Hz	125 Hz	4000 Hz
	dB	dB			%	%
1	76	81	-1,6	0,6	-3,8	1,7
2	79	81	2,3	0,6	5,3	1,7
3	76,6	80,0	-0,9	-0,6	-2,0	-1,9
4	76,4	79,3	-1,1	-1,5	-2,6	-4,4
5	77,1	81,0	-0,2	0,6	-0,5	1,7
6	77,4	80,5	0,2	0	0,4	-0,1
7	77,2	80,9	-0,1	0,5	-0,2	1,4
8	76,4	81,5	-1,1	1,2	-2,6	3,6
9	79,0	81,5	2,3	1,2	5,3	3,6
10	79,0	81,5	2,3	1,2	5,3	3,6
11	76	79	-1,6	-1,9	-3,8	-5,5
12	77	79	-0,3	-1,9	-0,8	-5,5

4.4 *Best measurement capability*

The relative deviation from the mean value allows to estimate Estonian laboratories mean best measurement capability.

For light density measurements this is ca 7 % and for noise measurements ca 3 %.

5. USE OF QUALITY SYSTEMS TO ASSURE PROPER MEASUREMENTS

To become aware of the critical points of measurements, especially taking account estimation of the uncertainties, in occupational health measurement area were analysed findings of the accreditation process of 36 Estonian laboratories. Accreditation assessments were carried out during 1999 up to 2004.

In Estonia were up to 01.04.2004 accredited 19 laboratories which perform measurements various parameters of working area environment and 17 more laboratories perform only light density measurement.

Quality system shall give more stability to laboratories measurements. More common is to built up quality assurance system on ISO 17025 or ISO 9001 standards requirements. First is more suitable and specific for the testing, including measurements, laboratories and second for the measurement service.

Practical accreditations carried out by Estonian Accreditation Centre [5] showed the articles which are difficult to complete by laboratories in context of uncertainties are as follows.

- weakly were evaluated environment conditions influence to the measurement result;
- uncertainty of measuring instrument was often taken as measurement uncertainty;
- measuring instrument was not inspected in period between two calibration;
- exact data for describing measurement conditions and measurement set up were not documented;
- the uncertainty of measurement result was weakly taken account by conformity decision;
- analyse of results of comparisons were not properly carried out.

5. CONCLUSION

Novelty of this work includes next moments for the occupational health measurements:

- given is concrete list of uncertainty components;
- through interlaboratory comparisons are estimated and validated best measurement capability and given are validation data.
- interlaboratory comparisons show that laboratories can carry out measurement of light density and noise parameters with declared best measurement capability.

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