Report of comparison

FINAL REPORT

Project EURAMET.EM-S29

Supplementary comparison

"Traceability of DC High Voltage Reference Measuring Systems up to 200 kV"

Report by: **Mr. Ricardo Martín (L.C.O.E. – Spain)**
Dr. Anders Bergman (SP – Sweden)
Dr. Jari Hällstrom (MIKES – Finland)

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1 Introduction

DC is an important quantity in testing of high voltage equipment. It is important to ensure the accuracy of measurement. One of the methods to check the metrological capabilities of the National Metrology Institutes (NMI) is by performing international comparisons, including supplementary comparisons.

This comparison was proposed in order to check the capabilities of the participating NMI in the area of high DC voltage. Measurement capabilities of DC voltage level were compared.

A Travelling Reference Measuring System (TRMS) circulated among the participants and they compared the high DC voltages obtained by their own measuring system with those obtained by the TRMS.

The measurement period of this comparison started in November 2007 and participants from eight European National Metrology Institutes took part including the "Laboratorio Central Oficial de Electrotecnia" (LCOE) from Spain as pilot laboratory and owner of the TRMS.

All the participants were asked to follow their usual measurement procedures corresponding to their best measurement capabilities.

The uncertainty of the calculated comparison reference values ranged from 7 to 34 ppm (k=2), depending on the voltage level.

2 Participants

The participants and their affiliation, the eight institutes involved, are listed in Table 1 in order of the TRMS circulation:

R. Martín / T. García	LCOE, Laboratorio Central Oficial De Electrotecnia, Madrid, Spain
E. Kroon / G. Rietveld	NMi, Nederlands Meetinstituut, Delft, The Netherlands
J. Hällström / Y. Chekurov	MIKES, Centre for Metrology and Accreditation, Helsinki, Finland
A. Bergman	SP, Technical Research Institute of Sweden, Borås, Sweden
A. Merev	UME, Ulusal Metroloji Enstitüsü, Gebze/Kocaeli, Turkey
P. Aladzhem	BIM, Bulgarian Institute of Metrology, Sofia, Bulgaria
M. Schmidt	PTB, Physikalisch-Technische Bundesanstalt, Braunschweig, Germany
V. Kiselev	VNIIMS, All-Russian Research Institute of Metrological Service, Moscow, Russia

Table 1. List of comparison participants.

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3 Equipment

3.1 Travelling standards

The Transfer Reference Measuring System (TRMS) consisted of a shielded resistive divider with fixed input and grounding leads, a coaxial cable with a 1 MΩ resistive termination, a digital multimeter and a computer with a printer. During the comparison measurements the divider had to be placed in the high voltage hall at least 24 hours before the measurements. The rest of the instrumentation had to be placed in the control room next to the high voltage hall, and the measuring instrument of the TRMS had to be powered and switched on at least 1 hour before the measurements. Estimated uncertainty of the TRMS is ± 100 ppm.

Detailed description of the TRMS:

H.V lead:	Description:	Copper tube (length = 2 m; Ǿ = 28 mm).
Divider:	Description:	Resistive divider.
	Manufacturer:	ROSS ENGINEERING.
	Type:	VD240-6Y-CBD-KC-BBC.
	Serial Nº:	930729-5.
	LCOE's Reference:	III-1-DT-003.
	Nominal DC voltage:	240 kV.
	Nominal ratio:	10 000.
Measuring cable:	Description:	Coaxial cable.
	Type:	RG-59/U.
	LCOE's Reference:	III-3-CABL-052.
	Characteristic Z:	75 Ω.
	Length:	10 m.
Resistance:	Description:	Terminal resistance.
	Nominal value:	1 MΩ.
	LCOE's Reference:	III-3-CONC-002.
Measuring cable:	Description:	Coaxial cable.
	Type:	RG-59/U.
	LCOE's Reference:	III-3-CABL-067.
	Characteristic Z:	75 Ω.
	Length:	0.5 m.
Voltmeter:	Manufacturer:	Hewlett-Packard.
	Type:	3458A.
	Serial Nº:	2823 A 18964.
	LCOE's Reference:	III-1-MD-013.
Software:	Manufacturer:	LCOE.
	LCOE reference:	III-1-SOFT-003.

3.2 Reference measuring systems of participants

Each participating institute carried out the comparison measurements using the following devices:

BIM – Bulgaria
- Levels 1 kV to 90 kV:
  - Resistive divider DNV-100, sn 024/85.
  - Multimeter Hewlett-Packard P3458A, sn 2823A22007.

LCOE – Spain
- 1 kV:
  - Calibrator DATRON 4000.
- Levels 10 kV to 100 kV (only positive polarity):
  - Transducer DWINA-100 B, sn 001/98.
  - Multimeter Hewlett-Packard P3458A, III-1-MD-005.
- Levels 10 kV to 200 kV:
  - Resistive divider ROSS ENGNINEERING, VD240-3-CBD-K-B, sn 90050143.
  - Multimeter Hewlett Packard, 3458A, III-1-MD-005.
- Software:
  - Software LCOE, III-1-SOFT-017.

MIKES – Finland
- 1 kV:
  - Digital multimeter HP/Agilent 3458A.
- Levels 10 kV to 50 kV:
  - Resistive divider MIKES-TKK, SJT143/SJT143.1.
  - Multimeter Hewlett-Packard P3458A, SJT067.
- Levels 100 kV to 200 kV:
  - Resistive divider Spellman, HVD 200-1, SJT053.
  - Multimeter Hewlett Packard, 3458A, SJT067.
- Software:
  - Software MIKES-TKK, DC-HV-29.vee.

PTB – Germany
- Levels 1 kV to 100 kV:
  - Digital multimeter Fluke 8508 (s.n.: 991358181).
  - Divider PTB, MT100 (s.n.: 29619).
  - Source -100 kV, FUG HCN 140M-100000 (s.n.:8501143601).
  - Source +100 kV, FUG HCN 140M-100000 (s.n.:9305502101).
- Levels 50 kV to 300 kV:
  - Digital multimeter Fluke 8508 (s.n.: 991358181).
  - Divider: PTB, MT300 (s.n.: 30429).
  - Source +300 kV, Heinzinger, HNCs 300000 (s.n.:049438200).

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SP – Sweden

Level 1 kV:

Digital multimeter HP/Agilent 3458A.

50 kV:

Divider VISHAY, S9909, SP501616.

Levels 100 kV and 150 kV:

Divider VISHAY, S9986, SP603267.

Level 200 kV:

Divider VISHAY-MANN, SP603187.

Digital multimeters:

Digital multimeter HP/Agilent 3458A, SP502401.

Digital multimeter HP/Agilent 3458A, SP502935.

UME – Turkey

Levels 1 kV to 100 kV:

Resistive divider TÜBITAK-UME, 100kVDC, sn UMEEYG200501.

Multimeter Hewlett-Packard P3458A, sn MY45040360.

Levels 150 kV and 200 kV:

Resisitive divider HIGHVOLT, GMR 800/400, sn 883462.

Multimeter Hewlett-Packard P3458A, sn MY45040360.

VNIIMS – Russia

Transducer DWINA-100, s.n.: 002-93.

VSL – The Netherlands

Levels 1 kV to 100 kV (positive polarity):

Resistive divider VSL / Leeds & Northrop, 100 kV.

Multimeter Hewlett-Packard, 3458A

4 Organization of the comparison

The TRMS was transported during the comparison inside two robust containers made of metal, wood and styrofoam. As a result no damage of the TRMS occurred during the comparison measurements and it was not necessary to transport the standards personally.

The final time schedule of the comparison is shown in Table 2. The laboratory from Turkey, UME, was interested in the TRMS travelling back to the pilot laboratory to be checked before they performed the comparison measurements. Besides, Turkey is the only participating country that required ATA carnet. Therefore the coordinator of the comparison decided that the TRMS travelled from Sweden to Spain, where LCOE made a second set of measurements before sending it to Turkey with the ATA carnet.

The Bulgarian laboratory (BIM) became interested in this project at the end of November 2007, but this laboratory notified that they would only make measurements up to 100 kV and with negative polarity. The coordinator decided that UME (Turkey) would send the TRMS to Bulgaria instead of to Spain, changing the initial time schedule.

At the end of April 2008 the TRMS arrived at LCOE in Madrid where a new (third) set of measurements was performed in June.

In September 2009 the Russian Institute (VNIIMS) performed its comparison measurements in LCOE's facilities (Spain).

In September 2009 the German Institute PTB also took an interest in this comparison but they could only measure it in January 2010. The other participants in the comparison agreed so the measurements phase of the comparison was extended until the beginning of 2010.

When draft A was prepared, a major discrepancy was found between the two institutes (SP and PTB) claiming the lowest uncertainties. Both reviewed their work, and it was found that contrary to other participants, SP had waited for the divider to reach thermal balance for each measurement. Other participants made the measurements promptly in order to avoid self heating. SP re-examined their records and was able to provide the prompt measurement results. The timing was not clearly defined in the protocol.

Laboratory / Place of measurement	**Measurement month**
LCOE I / Madrid, Spain	November, 2007
VSL / Delft, The Netherlands	December, 2007 / January, 2008
MIKES / Helsinki, Finland	January, 2008
SP / Boras, Sweden	February, 2008
LCOE II / Madrid, Spain	March, 2008
UME / Gebze/Kocaeli, Turkey	March - April, 2008
BIM / Sofia, Bulgaria	April, 2008
LCOE III / Madrid, Spain	June, 2008
VNIIMS / Madrid, Spain	September, 2009
PTB / Braunschweig, Germany	February - March, 2010

Table 2. Final comparison schedule.

5 Comparison measurements

5.1 Measured quantity

Each participant compared the reading of the TRMS with the corresponding reading of the local reference measuring system.

Coordinator set the scale factor to be used for the TRMS at:

- 10 000 below 100 kV.
- 10 047 above 100 kV.

The difference between both readings was calculated according to this formula:

$$E_m[\%] = \frac{U_{TRMS} - U_{REF}}{U_{REF}} \cdot 100 \ , \qquad (1)$$

where: E_m: Measurement error of the TRMS.

U_{TRMS}: DC voltage value obtained by means of the TRMS.

U_{REF}: DC voltage value obtained by means of the reference measuring system of the laboratory (LRMS).

5.2 Conditioning and applied methods

Concerning the conditioning of the TRMS, every participant was asked to keep the TRMS in the test room for enough time before the comparison measurements to assure it reached stable temperature and humidity conditions.

All comparison measurements were done with direct voltage.

The measurement error of the TRMS was obtained considering a rated Scale Factor of 10 000 between 1 kV and 120 kV and 10 047 at higher voltage levels up to 240 kV.

The participating laboratories performed the measurements connecting the TRMS and the local reference measuring system to the same DC voltage source and measuring their output voltages using digital precision multimeters.

Time delay between application of voltage and the measurements was unfortunately not well specified, which led to different procedures in different laboratories.

Two different tests were proposed:

a) Determination of the Scale Factor of the TRMS and linearity test:

Measurements with both polarities at the following voltage levels: 1 kV, 10 kV, 50 kV, 100 kV, 150 kV and 200 kV were planned. At least 10 readings were taken in every voltage level. After finishing the measurements corresponding to a voltage level higher than 1 kV the laboratory had to wait the required time before applying voltage to the TRMS again in order to avoid the influence of the self-heating in the Scale Factor.

LCOE, SP and UME made all planned measurements. MIKES did not measure at 10 kV. VSL performed measurements at 1 kV, 10 kV, 50 kV and 100 kV levels with positive polarity, and only at 1 kV with negative polarity. Finally, BIM measured only with negative polarity at 1 kV, 50 kV and 90 kV levels.

b) Short-term stability test:

Three different sets of measurements were proposed:

b.1) Measurements only with positive polarity at 200 kV level. Both systems, LRMS and TRMS, had to be connected to the voltage source. A voltage of 200 kV had to be applied for at least 30 minutes. A set of 10 comparative measurements had to be taken initially and then every 5 minutes in order to obtain a curve of differences between both systems in time.

Every set of 10 comparative measurements had to be taken as soon as possible.

This test was performed by LCOE, PTB and UME.

b.2) Measurements only with positive polarity at 200 kV level. At first only the TRMS had to be connected to the voltage source. A voltage of 200 kV had to be applied for at least 30 minutes. At the end of this period the high voltage had to be interrupted, the LRMS had to be connected and then 200 kV applied again. This operation had to be done as quickly as possible. A set of 10 comparative measurements had to be taken initially and then every 5 minutes in order to obtain a curve of differences between both systems in time.

Every set of 10 comparative measurements had to be taken as soon as possible.

This test has been done by LCOE and UME. SP also performed this test, but used another divider as the warmed-up reference and they also did not interrupt the voltage, but made a live connection of the in-house divider. Since the purpose of the test was to demonstrate the short-term stability of the in-house divider, the use of a different reference is acceptable.

b.3) Measurements only with positive polarity at 200 kV level. At first only the LRMS had to be connected to the voltage source. A voltage of 200 kV had to be applied for at least 30 minutes. At the end of this period the high voltage had to be interrupted, the TRMS had to be connected and then 200 kV applied again. Again, this operation had to be done as quickly as possible. A set of 10 comparative measurements had to be taken initially and then every 5 minutes in order to obtain a curve of differences between both systems in time.

Every set of 10 comparative measurements had to be taken as soon as possible.

This test was made by SP, MIKES and UME. SP also here elected not to interrupt the high voltage and made a live connection of the TRMS.

6 Procedure of analysis of comparison results

6.1 Error of the TRMS

Concerning the obtained error of the TRMS (or Assigned Scale Factor), the analysis of comparison results have been performed using the weighted mean together with a consistency test based on classic statistics.

The followed procedure has been applied considering that the next three conditions are satisfied:

1. Each participant gives one result of the TRMS which has good short term stability and a good stability during transportation too.
2. Measurements of different institutes are independent among them. There is no mutual dependence among the measurements of the comparison participants.
3. A Gaussian distribution can be assigned to the measurements by each laboratory (mean value equals the laboratory measurement and standard deviation equals the corresponding standard uncertainty).

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6.1.1 *Comparison reference values calculation*

On each voltage level, the comparison reference value, CRV, is considered as an estimation of the measurand according to the measurements provided by the participating laboratories.

This estimation, *y*, is determined as a weighted mean of the provided results where the weights are the inverse values of the squares of the associated standard uncertainties. However, that cannot be applied in case of some of the measurements are not consistent with the others.

The number of participating laboratories, *N*, depends on the considered voltage level and polarity. It goes from 4 to 8.

The input magnitudes to evaluate are the errors of the TRMS as provided by the participants, ε_i, i = 1, 2, ..., N, and the corresponding standard uncertainties, $u(\varepsilon_i)$, i = 1, 2, ..., N.

The procedure is developed in the next steps:

1) Weighted means determination of the comparison reference value CRV (y) , calculating the weights as the inverse values of the squares of the uncertainties:

$$y = \frac{\sum_{i=1}^{N} \varepsilon_i \, u^{-2}(\varepsilon_i)}{\sum_{i=1}^{N} u^{-2}(\varepsilon_i)} \qquad (1)$$

2) Calculation of standard uncertainty of CRV, $u(y)$, according to the following expression:

$$u(y) = \frac{1}{\sqrt{\sum_{i=1}^{N} u^{-2}(\varepsilon_i)}} \qquad (2)$$

3) Consistency of results

   A chi-squared test has been applied to carry out an overall consistency check of the results obtained (i.e. if all results can be regarded as belonging to the same statistical ensemble). For each measurement point the observed chi-squared value χ^2_{obs} has been determined as:

$$\chi^2_{\mathrm{obs}} = \sum_{i=1}^{N} \frac{(\delta_{id} - \delta_R)^2}{u^2_{\mathrm{id}}} \qquad (15)$$

   The degrees of freedom are ν = N -1, for N results.

   The consistency check is considered failed if Pr{ $\chi^2(\nu) > \chi^2_{obs}$ }< 5%

where Pr denotes “probability of”.

If the chi-squared test fails, then the laboratory with the largest $|d_i|$ value (see below for definition) is excluded from the determination of the CRV and the consistency check repeated. The process is then repeated as needed.

4) Compatibility of each laboratory with the estimate of CRV (y):

In each voltage level, degrees of equivalence of laboratory i, i = 1, 2, ..., N, is determined as the pair of values for the deviation from the CRV and the uncertainty of this deviation [$\Delta\varepsilon_i$, $U(\Delta\varepsilon_i)$] according to the expressions:

$$\Delta\varepsilon_\mathrm{i} = \varepsilon_i - y \qquad (3)$$

$$U(\Delta\varepsilon_i) = 2 \cdot u(\Delta\varepsilon_i) \qquad (4)$$

Where $u(\Delta\varepsilon_i)$ is obtained applying the following expression:

$$u^2(\Delta\varepsilon_i) = u^2(\varepsilon_i) - u^2(y) \qquad (5)$$

Note 1: The factor 2 in expression (4) above indicates a coverage factor of 95 % corresponding to a Gaussian distribution function.

Note 2: Expression (5) establishes a difference of two variances as consequence of the mutual dependence (or correlation) between ε_i and *CRV*.

Compatibility index, d_i, is defined as the ratio between the difference from the reference value and the standard uncertainty:

$$d_i = \frac{\Delta\varepsilon_i}{u(\Delta\varepsilon_i)} = \frac{\varepsilon_i - y}{\sqrt{u^2(\varepsilon_i) - u^2(y)}} \qquad (6)$$

The compatibility index $|d_i|$ describes the deviation from the CRV in relation to the calculated standard uncertainty of the deviation.

The standard uncertainties of the differences corresponding to those laboratories whose results have not been considered in the reference value calculation are obtained applying the following expression:

$$u^2(\Delta\varepsilon_i) = u^2(\varepsilon_i) + u^2(y) \qquad (7)$$

since now the values are not correlated.

5) Compatibility between two laboratories:

Compatibility between laboratory i, i = 1, 2, ..., N and laboratory j, j = 1, 2, ..., N, with $i \neq j$, [$d_{i,j}$, $U(d_{i,j})$] is obtained according to:

$$\Delta\varepsilon_{i,j} = \varepsilon_i - \varepsilon_j \qquad (8)$$

$$U(\Delta\varepsilon_{i,j}) = 2 \cdot u(\Delta\varepsilon_{i,j}) \qquad (9)$$

$u(\Delta\varepsilon_{i,j})$ is calculated applying the following expression:

$$u^2(\Delta\varepsilon_{i,j}) = u^2(\varepsilon_i) + u^2(\varepsilon_j) \qquad (10)$$

Note 3: The difference $\Delta\varepsilon_{i,j}$ between the measurements of the laboratories ε_i and ε_j does not depend on the corresponding reference value, because:

$$\Delta\varepsilon_{i,j} = \Delta\varepsilon_i - \Delta\varepsilon_j = (\varepsilon_i - CRV) - (\varepsilon_j - CRV) = \varepsilon_i - \varepsilon_J \qquad (11)$$

Note 4: Expressions (9) and (10) are based on Gaussian distribution of measurands.

The compatibility index between two laboratories is analyzed using the following expression of $d_{i,j}$:

$$d_{i,j} = \frac{\Delta\varepsilon_{i,j}}{u(\Delta\varepsilon_{i,j})} = \frac{\varepsilon_i - \varepsilon_j}{\sqrt{u^2(\varepsilon_i) + u^2(\varepsilon_j)}} \qquad (12)$$

If $|d_{i,j}| \le 2$ then results of the corresponding laboratories are considered compatible.

6.2 Short-term stability tests

The test were performed to demonstrate the stability of the travelling reference measuring system and the local reference measuring systems respectively. Uncertainty of these results is not pertinent and has not been analyzed.

7 Comparison results

7.1 Measurements conditions

Table 3 shows ambient conditions in each participating laboratory during corresponding measurements.

Laboratory	Temperature (ºC)	Humidity (%)
LCOE	23 ± 2	< 50
VSL	23.3 ± 0.2	42.8 ± 4
MIKES	21 ± 3	20 ± 10
SP	22 ± 1	14 - 29
UME	23 ± 2	45 ± 2
BIM	23 ± 2	45 ± 5
VNIIMS	23 ± 2	< 50
PTB	22	25

Table 3. Ambient conditions.

7.2 Results of error of the TRMS / Linearity test

Tables 4 and 5 summarize the results obtained by every laboratory. The first one contains the error of the TRMS as given by the participating laboratories and the second one shows the corresponding expanded uncertainty (k = 2). The nominal scale factor of the TRMS was 10 000 up to 100 kV and 10 047 for higher voltages.

The pilot laboratory, LCOE, carried out three sets of measurements using two different reference systems in two of them:

- LCOE I: measurements in November 2007 using Ross Engineering VD240-3-CBD-K-B divider.
- LCOE I* measurements in November 2007 using DWINA-100 B transducer.
- LCOE II measurements in March 2008 using Ross Engineering VD240-3-CBD-K-B divider.
- LCOE III: measurements in June 2008 using Ross Engineering VD240-3-CBD-K-B divider.
- LCOE III* measurements in June 2008 using DWINA-100 B transducer.

Of the measurements performed by LCOE, only measurements LCOE I are taken into account when calculating the comparison reference values.

Voltage level (kV)	Reported TRMS measurement error, ε_i (ppm)											
	LCOE I	LCOE I*	VSL	SP	MIKES	LCOE II	UME	BIM	LCOE III	LCOE III*	VNIIMS	PTB
+ 1	-29	-	-24	0	-17	-	-324	-	-	-	-67	-24
+ 10	-25	-55	-30	-26	-	-34	-10	-	-31	-63	-85	-
+ 50	-46	-63	-50	+2	+5	-42	-3	-	-44	-38	-43	-26
+ 100	-78	-62	-70	-3	+3	-71	+5	-	-74	-48	-64	-17
+ 150	-117	-	-	-86	-81	-109	+14	-	-112	-	-	-104
+ 200	-126	-	-	-93	-56	-116	+28	-	-123	-	-	-98
- 1	-19	-	-17	-5	-11	-	+7	+20	-	-	31	-21
- 10	-36	-	-	-26	-	-17	-16	-	-31	-	-70	-
- 50	-48	-	-	-4	+1	-39	-10	+18	-44	-	-40	-23
- 100	-78	-	-	-1	-2	-69	0	+27	-73	-	-40	-13
- 150	-118	-	-	-104	-88	-107	-25	-	-107	-	-	-
- 200	-126	-	-	-85	-72	-116	-26	-	-112	-	-	-

Table 4. Comparison results. Error of TRMS.

Voltage level (kV)	Expanded uncertainty of reported TRMS error, $U(\varepsilon_i)$ (k = 2) (ppm)											
	LCOE I	LCOE I*	VSL	SP	MIKES	LCOE II	UME	BIM	LCOE III	LCOE III*	VNIIMS	PTB
+ 1	60	-	10	23	36	-	100	-	-	-	50	14
+ 10	90	100	52	22	-	90	100	-	90	100	50	-
+ 50	90	100	52	22	30	45	100	-	90	100	50	14
+ 100	90	100	66	22	32	90	102	-	90	100	50	14
+ 150	90	-	-	25	100	90	1000	-	90	-	-	14
+ 200	90	-	-	34	162	90	1000	-	90	-	-	14
- 1	60	-	10	23	20	-	100	200	-	-	50	14
- 10	90	-	-	22	-	90	100	-	90	-	50	-
- 50	90	-	-	24	30	90	100	170	90	-	50	14
- 100	90	-	-	28	32	90	100	210	90	-	50	14
- 150	90	-	-	32	102	90	1000	-	90	-	-	-
- 200	90	-	-	38	162	90	1000	-	45	-	-	-

Table 5. Comparison results. Expanded uncertainty.

7.2.1 Comparison reference values.

Table 6 shows the comparison reference values, *CRV*, and its expanded uncertainty, *U(CRV)*, at each voltage level. Furthermore, Annex I of this report develops step by step the application of the procedure described in the previous paragraph 7.

Voltage level (kV)	***CRV* (ppm)**	***U(CRV)* (k = 2) (ppm)**
+ 1	-22	7
+ 10	-34	18
+ 50	-18	10
+ 100	-16	11
+ 150	-100	12
+ 200	-98	13
- 1	-15	7
- 10	-33	19
- 50	-17	11
- 100	-12	11
- 150	-104	29
- 200	-90	34

Table 6. Comparison reference values and their uncertainties.

Table 7 summarizes the differences between each laboratory and the comparison reference value, and in table 8 the corresponding expanded uncertainties of those differences are included.

Voltage level (kV)	**Difference from CRV (ppm): $\Delta\varepsilon_i = \varepsilon_i - CRV$**								
	LCOE I	LCOE I*	VSL	SP	MIKES	UME	BIM	VNIIMS	PTB
+ 1	-7	-	-2	22	5	-302	-	-45	-2
+ 10	9	-21	4	8	-	24	-	-51	-
+ 50	-28	-45	-32	20	23	15	-	-25	-8
+ 100	-62	-46	-54	13	19	21	-	-48	-1
+ 150	-17	-	-	14	19	114	-	-	-4
+ 200	-28	-	-	5	42	126	-	-	0
-1	-4	-	-2	10	4	22	35	46	-6
-10	-3	-	-	7	-	17	-	-37	-
-50	-31	-	-	13	18	7	35	-23	-6
-100	-66	-	-	11	10	12	39	-28	-1
-150	-14	-	-	0	16	79	-	-	-
-200	-36	-	-	5	18	64	-	-	-

Table 7. Differences from the comparison reference value.

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Voltage level (kV)	Expanded uncertainty of the difference from CRV (ppm): $U(\Delta\varepsilon_i)$								
	LCOE I	LCOE I*	VSL	SP	MIKES	UME	BIM	VNIIMS	PTB
+ 1	60	-	7	22	35	100	-	49	12
+ 10	88	102	49	13	-	98	-	47	-
+ 50	89	101	51	19	28	99	-	49	9
+ 100	89	101	65	19	30	101	-	49	9
+ 150	89	-	-	22	99	1000	-	-	7
+ 200	89	-	-	32	161	1000	-	-	6
-1	60	-	7	22	19	100	200	50	12
-10	88	-	-	11	-	98	-	46	-
-50	89	-	-	21	28	99	170	49	9
-100	89	-	-	26	30	99	210	49	8
-150	85	-	-	14	98	1000	-	-	-
-200	83	-	-	17	158	999	-	-	-

Table 8. Standard uncertainties of with the differences from the comparison reference value.

Finally, table 9 shows the compatibility index, $|d_i|$, as defined in equation (6). The value(s) highlighted in red have been identified with the chi-squared test as deviant and have not been included in the calculation of reference values.

Voltage level (kV)	Compatibility index to *CRV*, $\|d_i\|$								
	LCOE I	LCOE I*	VSL	SP	MIKES	UME	BIM	VNIIMS	PTB
+ 1	0.23	-	0.52	2.04	0.30	6.02	-	1.81	0.29
+ 10	0.20	0.41	0.15	1.22	-	0.48	-	2.20	-
+ 50	0.63	0.89	1.27	2.04	1.62	0.30	-	1.03	1.76
+ 100	1.39	0.91	1.67	1.31	1.24	0.41	-	1.98	0.29
+ 150	0.38	-	-	1.25	0.38	0.23	-	-	1.19
+ 200	0.64	-	-	0.29	0.51	0.25	-	-	0.15
-1	0.13	-	0.54	0.92	0.43	0.44	0.35	1.86	0.98
-10	0.08	-	-	1.25	-	0.34	-	1.62	-
-50	0.70	-	-	1.20	1.28	0.14	0.41	0.95	1.37
-100	1.48	-	-	0.84	0.66	0.24	0.37	1.16	0.28
-150	0.33	-	-	0.01	0.33	0.16	-	-	-
-200	0.86	-	-	0.64	0.23	0.13	-	-	-

Table 9. Compatibility with the comparison reference value.

Annex II of this report summarizes graphically the results of the comparison.

Annex III shows the mutual compatibility between each pair of participants.

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7.3 Short term stability tests

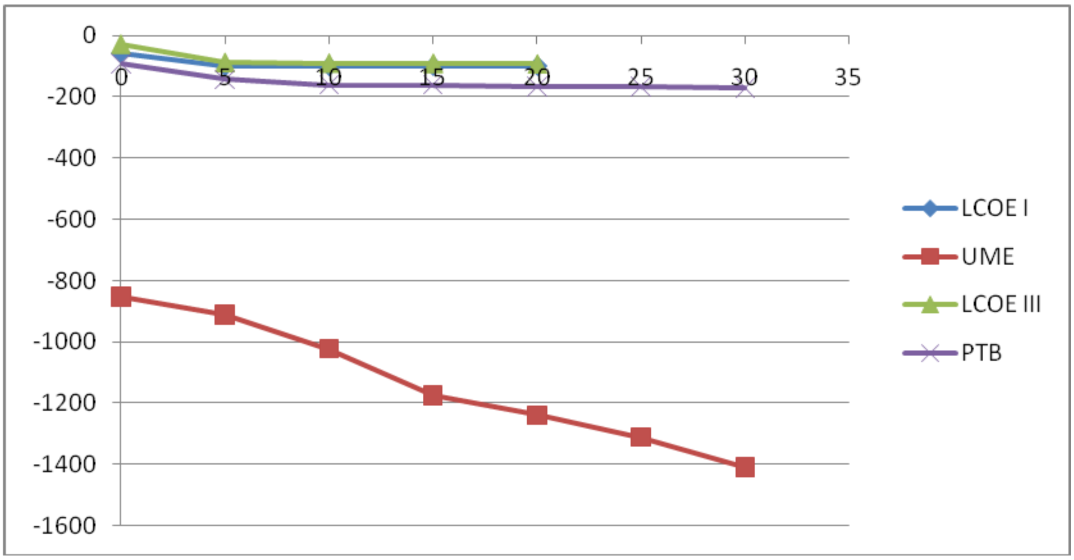
7.3.1 Short term stability test according to section b.1 of this report.

The test voltage was applied to both systems and measurements were made at intervals during a 30 minute period.

Three laboratories have performed these measurements, LCOE (twice), PTB, and UME. Table 10 and graph 1 show results obtained by all of them.

Instant (minutes)	Obtained measurement error of the TRMS (ppm)			
	LCOE I	UME	LCOE III	PTB
0	-59	-853	-28	-92
5	-101	-911	-88	-143
10	-101	-1023	-90	-161
15	-100	-1174	-91	-161
20	-100	-1239	-93	-166
25	-	-1311	-	-168
30	-	-1409	-	-171

Table 10.



Graph 1. Observed error of the TRMS as function of time after simultaneous application of voltage to both TRMS and LRMS

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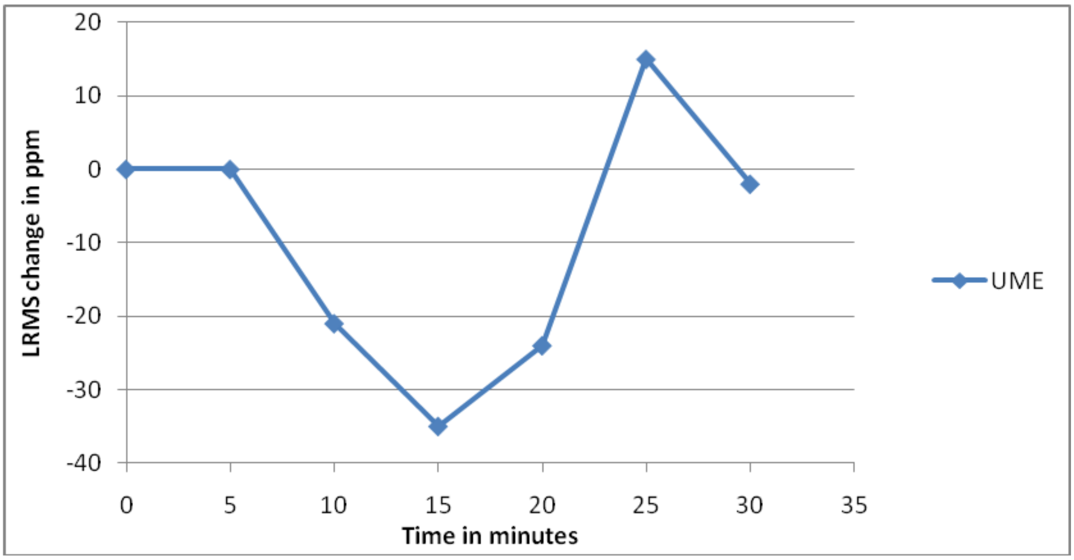
7.3.2 Short term stability test according to section b.2 of this report.

The test voltage was applied to the TRMS for a time sufficient to bring it to thermal stability. The laboratory divider was then connected as fast as possible and measurements were then made during a 30 minute period.

Two laboratories have performed measurements, UME and SP. Table 11 and graphs 2a through 2c show results obtained.

Instant (minutes)	**Obtained measurement error of the TRMS (ppm)**	
	UME	**Change in UME LRMS**
0	-148	0
5	-148	0
10	-127	-21
15	-113	-35
20	-124	-24
25	-163	15
30	-146	-2

Table 11.



Graph 2a. Observed error of the LRMS as function of time after application of voltage, but with the reference divider already at thermal stability.

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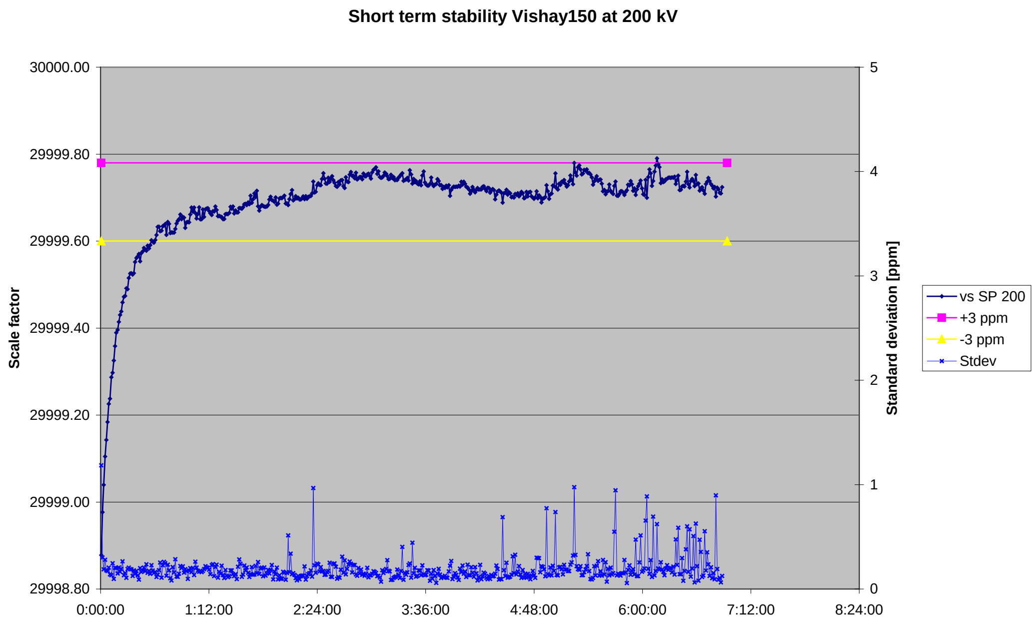


Figure 2b. Scale factor of SP Vishay 150 kV at 200 kV for a period of 7 hours. Reference is SP Vishay 200 kV. Each data point shown is the mean of 10 consecutive measurements. The standard deviation of the mean for each data point is given by the lower curve. The straight lines show ± 3 ppm deviation from the average scale factor after thermal equilibrium had been reached. Change from initial value to thermal stability is 27 ppm.

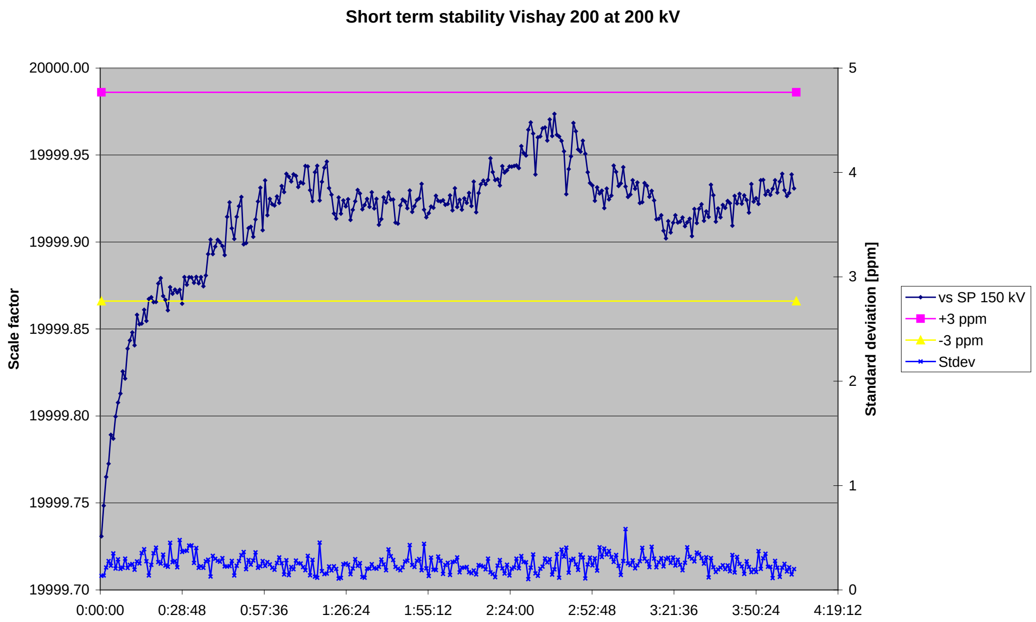


Figure 2c. Scale factor of SP Vishay 200 kV at 200 kV for a period of 7 hours. Reference is SP Vishay 150 kV. Each data point shown is the mean of 10 consecutive measurements. The standard deviation of the mean for each data point is given by the lower curve. The straight lines show ± 3 ppm deviation from the average scale factor after thermal equilibrium had been reached. Change from initial value to thermal stability is 7 ppm.

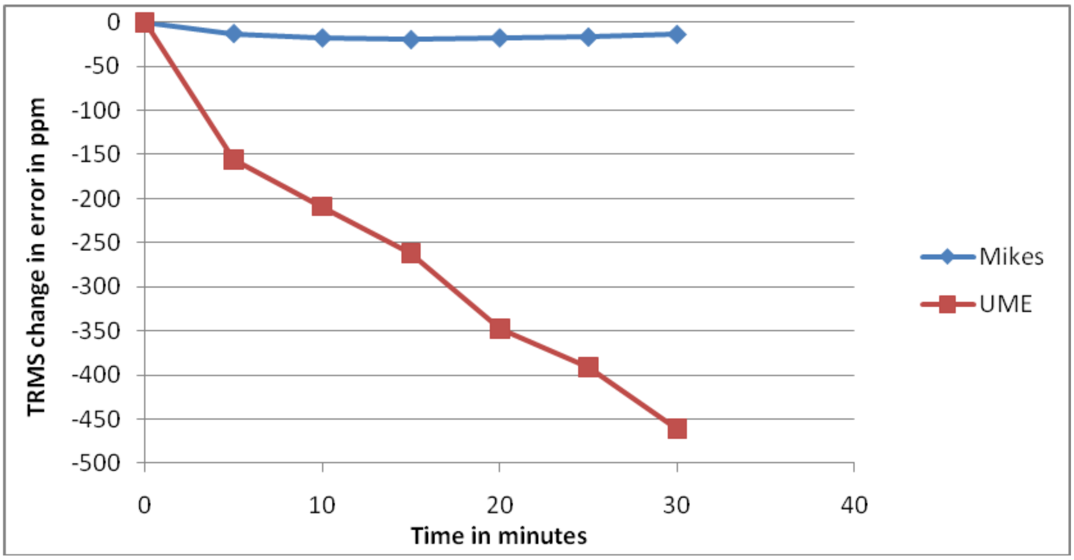
7.3.3 Short term stability test according to section b.3 of this report.

The test voltage was applied to the laboratory divider for a time sufficient to bring it to thermal stability. The TRMS was then connected as fast as possible and measurements were then made during a 30 minute period.

Three laboratories have performed these measurements, SP, MIKES and UME. Table 12 and graph 3 show results obtained by MIKES and UME.

Instant (minutes)	**Obtained measurement error of the TRMS (ppm)**	
	MIKES	**UME**
0	286	-683
5	273	-839
10	268	-892
15	266	-945
20	268	-1031
25	269	-1074
30	272	-1144

Table 12.



Graph 3. Observed error of the TRMS as function of time after application of voltage, with the LRMS already at thermal stability.

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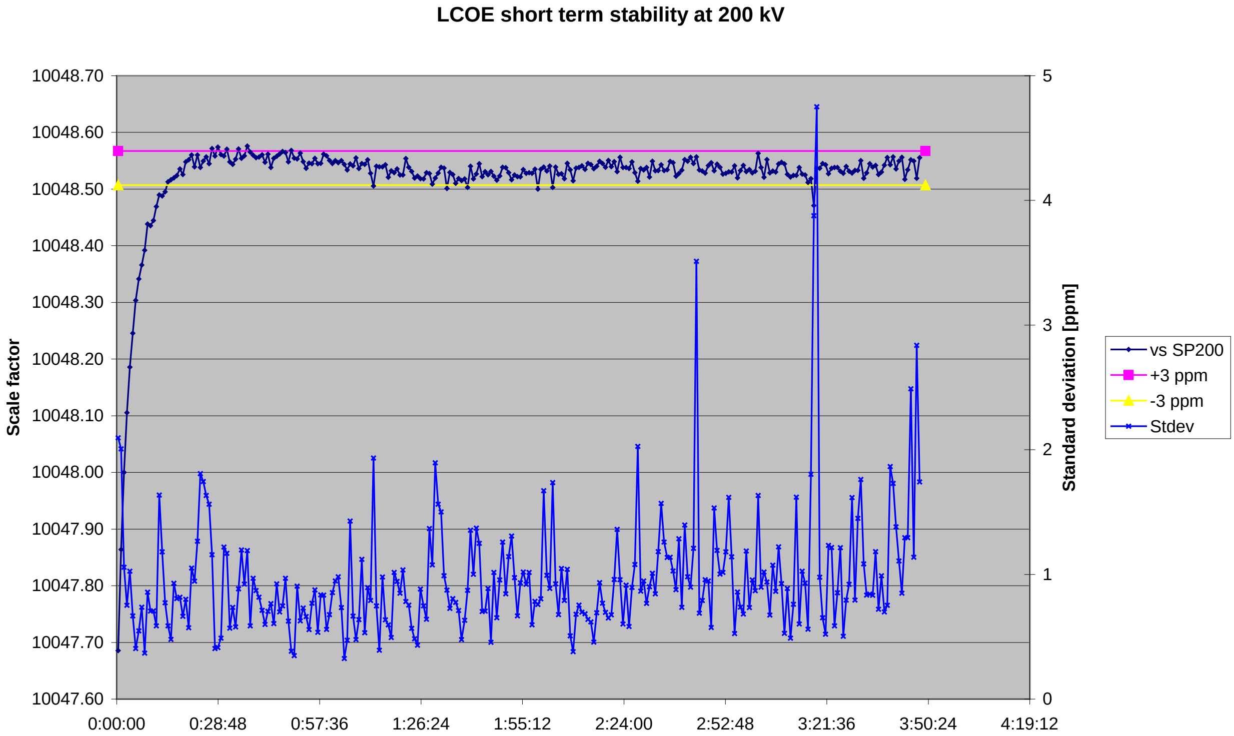
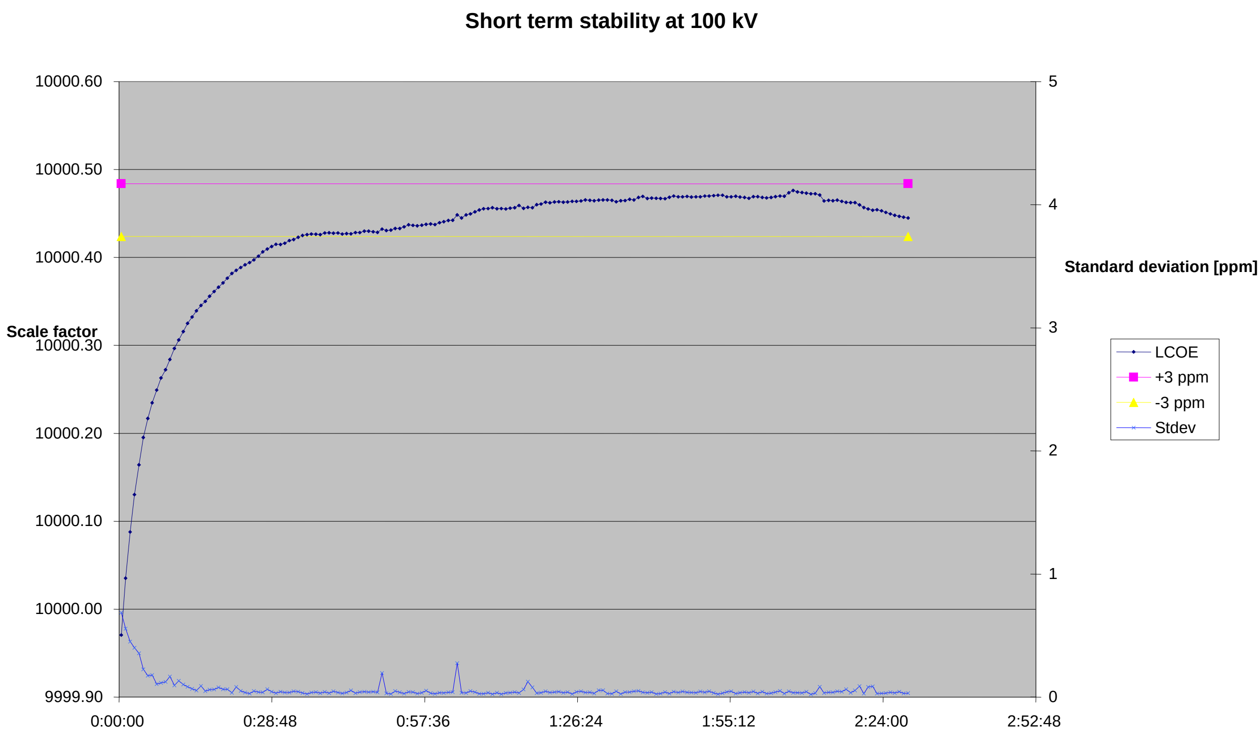
Graphs 4 and 5 below show the curves of variation of the scale factor of the TRMS obtained by SP.



Graph 4 Change of TRMS at 200 kV compared to SP Vishay 200 kV over a period of 3.5 h. Change from initial value is 85 ppm



Graph 5 Change of TRMS at 200 kV compared to SP Vishay 200 kV over a period of 2.5 h. Change from initial value is 48 ppm

8 Traceability

Each national metrology institute carried out the comparison measurements using their own national standards.

List the source for traceability lab by lab:
SP: internal.
PTB: internal.
LCOE: internal.
MIKES: internal.
BIM: internal.
UME: internal.
VSL: internal.
VNIIMS: internal

9 Final remarks

Seven EURAMET and one COOMET laboratory participated in this international supplementary comparison of DC high voltage measurement up to 200 kV. The same measurement method was used by all the participants: comparison with reference measuring system.

The comparison reference values, CRV, and their uncertainties were calculated as weighted means according to the above mentioned formulae. In each voltage level, the consistency of the CRV was checked studying the difference of each provided result and the estimation of the comparison reference value (weighted mean), together with the standard uncertainties of those differences. Those results non consistent were not included in the calculation of the comparison CRV.

The differences from the CRV and their uncertainties together with the compatibility with the CRV and between any pair of laboratories are presented.

Results of the comparison offer a good opportunity to check the calibration and measurement capabilities of the participants in the field of high voltage DC measurement.

Reported results demonstrate that more care should have been put to cancel the influence of the self heating of the TRMS, e.g. by carefully specifying the voltage application and/or measurement times.

References

[1] Technical protocol of the comparison "*Traceability of DC High Voltage Reference Measuring Systems up to 200 kV*".

[2] BIPM-IEC-ISO-OIML. Guide to the Expression of the Uncertainty in Measurement 1993.

Cox M. G.: The Evaluation of Key Comparison Data. Metrology 39, pp. 589-595, 2002.

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ANNEX I

Determination of comparison reference values

Level: + 1 kV

Laboratory	x_i (ppm)	$u(x_i)$ (ppm)	$1/u^2(x_i)$ (ppm^{-2})	Weight (%)	x_0 (ppm)	Δx_i (ppm)	$u(\Delta x_i)$ (ppm)	d_i	chi^2 test	Exclude
LCOE I	-29	30	0.0011	1.5%	-24	-5	30	-0.17	0.03	
VSL	-24	5	0.0400	53.9%		0	3	-0.03	0.00	
SP	0	11.5	0.0076	10.2%	$u(x_0)$ (ppm)	24	11	2.19	4.31	
MIKES	-17	18	0.0031	4.2%	4	7	18	0.39	0.15	
UME	-324	50	0.0004	0.5%		-300	50	-6.02	36.03	
BIM										
VNIIMS	-67	25	0.0016	2.2%		-43	25	-1.74	2.97	
PTB	-24	7	0.0204	27.5%		0	6	-0.02	0.00	

χ^2_{obs}	43.49
N-1	6
Probability	0.0%

Rejected

Laboratory	x_i (ppm)	$u(x_i)$ (ppm)	$1/u^2(x_i)$ (ppm^{-2})	Weight (%)	x_0 (ppm)	Δx_i (ppm)	$u(\Delta x_i)$ (ppm)	d_i	χ^2 test	Exclude
LCOE I	-29	30	0.0011	1.5%	-22	-7	30	-0.23	0.05	
VSL	-24	5	0.0400	54.2%		-2	3	-0.52	0.12	
SP	0	11.5	0.0076	10.3%	$u(x_0)$ (ppm)	22	11	2.04	3.75	
MIKES	-17	18	0.0031	4.2%	4	5	18	0.30	0.09	
UME	-324	50				-302	50	-6.02		X
BIM										
VNIIMS	-67	25	0.0016	2.2%		-45	25	-1.81	3.20	
PTB	-24	7	0.0204	27.7%		-2	6	-0.29	0.06	

χ^2_{obs}	7.27
N-1	5
Probability	20.1%

Accepted

Level: + 10 kV

Laboratory	x_i (ppm)	$u(x_i)$ (ppm)	$1/u^2(x_i)$ (ppm^{-2})	Weight (%)	x_0 (ppm)	Δx_i (ppm)	$u(\Delta x_i)$ (ppm)	d_i	chi^2 test	Exclude
LCOE I	-25	45	0.0005	4.0%	-34	9	44	0.20	0.04	
VSL	-30	26	0.0015	12.1%		4	24	0.15	0.02	
SP	-26	11	0.0083	67.5%	$u(x_0)$ (ppm)	8	6	1.22	0.48	
MIKES					9					
UME	-10	50	0.0004	3.3%		24	49	0.48	0.22	
BIM										
VNIIMS	-85	25	0.0016	13.1%		-51	23	-2.20	4.22	
PTB										
								χ^2_{obs}	4.98	
								N-1	4	
								Probability	28.9%	

Accepted

Level: + 50 kV

Laboratory	x_i (ppm)	$u(x_i)$ (ppm)	$1/u^2(x_i)$ (ppm^{-2})	Weight (%)	x_0 (ppm)	Δx_i (ppm)	$u(\Delta x_i)$ (ppm)	d_i	chi^2 test	Exclude
LCOE I	-46	45	0.0005	1.3%	-18	-28	45	-0.63	0.39	
VSL	-50	26	0.0015	4.0%		-32	25	-1.27	1.54	
SP	2	11	0.0083	22.3%	$u(x_0)$ (ppm)	20	10	2.04	3.23	
MIKES	5	15	0.0044	12.0%	5	23	14	1.62	2.30	
UME	-3	50	0.0004	1.1%		15	50	0.30	0.09	
BIM										
VNIIMS	-43	25	0.0016	4.3%		-25	24	-1.03	1.02	
PTB	-26	7	0.0204	55.0%		-8	5	-1.76	1.39	
								χ^2_{obs}	9.95	
								N-1	6	
								Probability	12.7%	

Accepted

Level: + 100 kV

Laboratory	x_i (ppm)	$u(x_i)$ (ppm)	$1/u^2(x_i)$ (ppm^{-2})	Weight (%)	x_0 (ppm)	Δx_i (ppm)	$u(\Delta x_i)$ (ppm)	d_i	chi^2 test	Exclude
LCOE I	-78	45	0.0005	1.4%	-16	-62	45	-1.39	1.92	
VSL	-70	33	0.0009	2.6%		-54	33	-1.67	2.71	
SP	-3	11	0.0083	23.0%	$u(x_0)$ (ppm)	13	10	1.31	1.32	
MIKES	3	16	0.0039	10.9%	5	19	15	1.24	1.36	
UME	5	51	0.0004	1.1%		21	51	0.41	0.16	
BIM										
VNIIMS	-64	25	0.0016	4.4%		-48	24	-1.98	3.74	
PTB	-17	7	0.0204	56.7%		-1	5	-0.29	0.04	
								χ^2_{obs}	11.25	
								N-1	6	
Accepted								Probability	8.1%	

Level: + 150 kV

Laboratory	x_i (ppm)	$u(x_i)$ (ppm)	$1/u^2(x_i)$ (ppm^{-2})	Weight (%)	x_0 (ppm)	Δx_i (ppm)	$u(\Delta x_i)$ (ppm)	d_i	chi^2 test	Exclude
LCOE I	-117	45	0.0005	1.8%	-100	-17	45	-0.39	0.15	
VSL										
SP	-86	12.5	0.0064	23.1%	$u(x_0)$ (ppm)	14	11	1.25	1.21	
MIKES	-81	50	0.0004	1.4%	6	19	50	0.38	0.14	
UME	14	500	0.0000	0.0%		114	500	0.23	0.05	
BIM										
VNIIMS										
PTB	-104	7	0.0204	73.7%		-4	4	-1.19	0.37	
								χ^2_{obs}	1.92	
								N-1	4	
Accepted								Probability	75.1%	

Level: + 200 kV

Laboratory	x_i (ppm)	$u(x_i)$ (ppm)	$1/u^2(x_i)$ (ppm^{-2})	Weight (%)	x_0 (ppm)	Δx_i (ppm)	$u(\Delta x_i)$ (ppm)	d_i	chi^2 test	Exclude
LCOE I	-126	45	0.0005	2.0%	-98	-28	45	-0.64	0.40	
VSL										
SP	-93	17	0.0035	14.1%	$u(x_0)$ (ppm)	5	16	0.29	0.07	
MIKES	-56	81	0.0002	0.6%	6	42	81	0.51	0.26	
UME	28	500	0.0000	0.0%		126	500	0.25	0.06	
BIM										
VNIIMS										
PTB	-98	7	0.0204	83.2%		0	3	-0.15	0.00	

χ^2_{obs}	0.80
N-1	4
Probability	93.8%

Accepted

Level: - 1 kV

Laboratory	x_i (ppm)	$u(x_i)$ (ppm)	$1/u^2(x_i)$ (ppm^{-2})	Weight (%)	x_0 (ppm)	Δx_i (ppm)	$u(\Delta x_i)$ (ppm)	d_i	chi^2 test	Exclude
LCOE I	-19	30	0.0011	1.4%	-15	-4	30	-0.13	0.02	
VSL	-17	5	0.0400	49.3%		-2	4	-0.54	0.15	
SP	-5	11.5	0.0076	9.3%	$u(x_0)$ (ppm)	10	11	0.92	0.77	
MIKES	-11	10	0.0100	12.3%	4	4	9	0.43	0.17	
UME	7	50	0.0004	0.5%		22	50	0.44	0.19	
BIM	20	100	0.0001	0.1%		35	100	0.35	0.12	
VNIIMS	31	25	0.0016	2.0%		46	25	1.86	3.40	
PTB	-21	7	0.0204	25.1%		-6	6	-0.98	0.72	

χ^2_{obs}	5.53
N-1	7
Probability	59.6%

Accepted

Level: - 10 kV

Laboratory	x_i (ppm)	$u(x_i)$ (ppm)	$1/u^2(x_i)$ (ppm^{-2})	Weight (%)	x_0 (ppm)	Δx_i (ppm)	$u(\Delta x_i)$ (ppm)	d_i	chi^2 test	Exclude
LCOE I	-36	45	0.0005	4.6%	-33	-3	44	-0.08	0.01	
VSL										
SP	-26	11	0.0083	76.8%	$u(x_0)$ (ppm)	7	5	1.25	0.36	
MIKES					10					
UME	-16	50	0.0004	3.7%		17	49	0.34	0.11	
BIM										
VNIIMS	-70	25	0.0016	14.9%		-37	23	-1.62	2.23	
PTB										

χ^2_{obs}	2.71
N-1	3
Probability	43.8%

Accepted

Level: - 50 kV

Laboratory	x_i (ppm)	$u(x_i)$ (ppm)	$1/u^2(x_i)$ (ppm^{-2})	Weight (%)	x_0 (ppm)	Δx_i (ppm)	$u(\Delta x_i)$ (ppm)	d_i	chi^2 test	Exclude
LCOE I	-48	45	0.0005	1.4%	-17	-31	45	-0.70	0.48	
VSL										
SP	-4	12	0.0069	20.2%	$u(x_0)$ (ppm)	13	11	1.20	1.16	
MIKES	1	15	0.0044	12.9%	5	18	14	1.28	1.42	
UME	-10	50	0.0004	1.2%		7	50	0.14	0.02	
BIM	18	85	0.0001	0.4%		35	85	0.41	0.17	
VNIIMS	-40	25	0.0016	4.6%		-23	24	-0.95	0.85	
PTB	-23	7	0.0204	59.3%		-6	4	-1.37	0.76	

χ^2_{obs}	4.86
N-1	6
Probability	56.2%

Accepted

Level: - 100 kV

Laboratory	x_i (ppm)	$u(x_i)$ (ppm)	$1/u^2(x_i)$ (ppm^{-2})	Weight (%)	x_0 (ppm)	Δx_i (ppm)	$u(\Delta x_i)$ (ppm)	d_i	chi^2 test	Exclude
LCOE I	-78	45	0.0005	1.5%	-12	-66	45	-1.48	2.16	
VSL										
SP	-1	14	0.0051	15.9%	$u(x_0)$ (ppm)	11	13	0.84	0.60	
MIKES	-2	16	0.0039	12.2%	6	10	15	0.66	0.38	
UME	0	50	0.0004	1.2%		12	50	0.24	0.06	
BIM	27	105	0.0001	0.3%		39	105	0.37	0.14	
VNIIMS	-40	25	0.0016	5.0%		-28	24	-1.16	1.27	
PTB	-13	7	0.0204	63.8%		-1	4	-0.28	0.03	

χ^2_{obs}	4.63
N-1	6
Probability	59.2%

Accepted

Level: - 150 kV

Laboratory	x_i (ppm)	$u(x_i)$ (ppm)	$1/u^2(x_i)$ (ppm^{-2})	Weight (%)	x_0 (ppm)	Δx_i (ppm)	$u(\Delta x_i)$ (ppm)	d_i	chi^2 test	Exclude
LCOE I	-118	45	0.0005	10.3%	-104	-14	43	-0.33	0.10	
VSL										
SP	-104	16	0.0039	81.6%	$u(x_0)$ (ppm)	0	7	0.01	0.00	
MIKES	-88	51	0.0004	8.0%	14	16	49	0.33	0.10	
UME	-25	500	0.0000	0.1%		79	500	0.16	0.03	
BIM										
VNIIMS										
PTB										

χ^2_{obs}	0.22
N-1	3
Probability	97.4%

Accepted

Level: - 200 kV

Laboratory	x_i (ppm)	$u(x_i)$ (ppm)	$1/u^2(x_i)$ (ppm^{-2})	Weight (%)	x_0 (ppm)	Δx_i (ppm)	$u(\Delta x_i)$ (ppm)	d_i	chi^2 test	Exclude
LCOE I	-126	45	0.0005	14.4%	-90	-36	42	-0.86	0.63	
VSL										
SP	-85	19	0.0028	81.0%	$u(x_0)$ (ppm)	5	8	0.64	0.08	
MIKES	-72	81	0.0002	4.5%	17	18	79	0.23	0.05	
UME	-26	500	0.0000	0.1%		64	500	0.13	0.02	
BIM										
VNIIMS										
PTB										

χ^2_{obs}	0.77
N-1	3
Probability	85.5%

Accepted

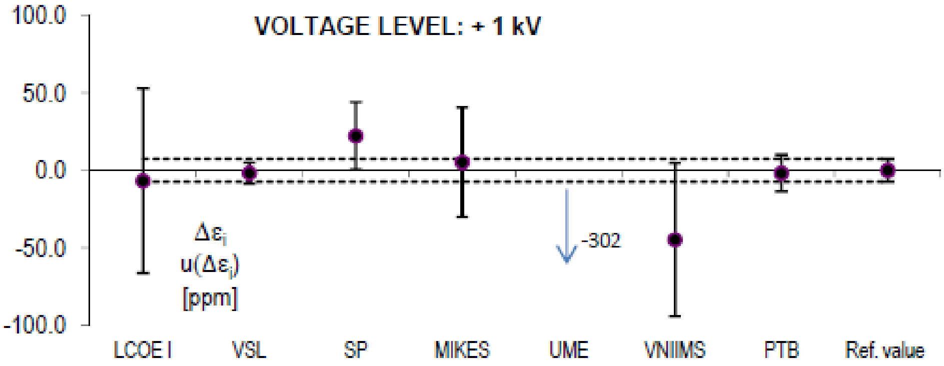
ANNEX II

Graphs of differences to the reference values and their uncertainties.

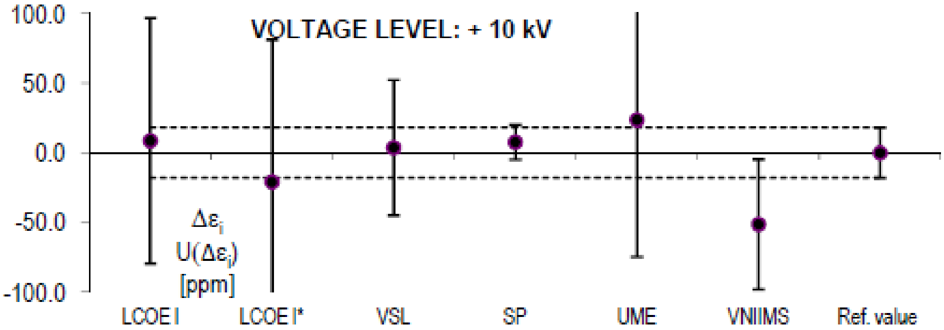
Positive Polarity

DIFFERENCES $\Delta(\varepsilon_i) = \varepsilon_i - y$ and their expanded uncertainties

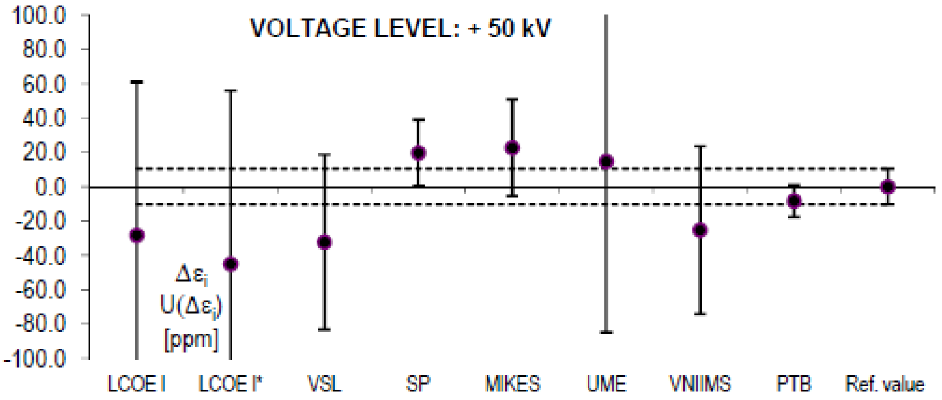
+ 1kV	$\Delta\varepsilon_i$ [ppm]	$U(\Delta\varepsilon_i)$ [ppm]
LCOE I	-7	60
VSL	-2	7
SP	22	22
MIKES	5	35
UME	-302	100
VNIIMS	-45	49
PTB	-2	12
Ref. value	0	7



+ 10kV	$\Delta\varepsilon_i$ [ppm]	$U(\Delta\varepsilon_i)$ [ppm]
LCOE I	9	88
LCOE I*	-21	102
VSL	4	49
SP	8	13
UME	24	98
VNIIMS	-51	47
Ref. value	0	18



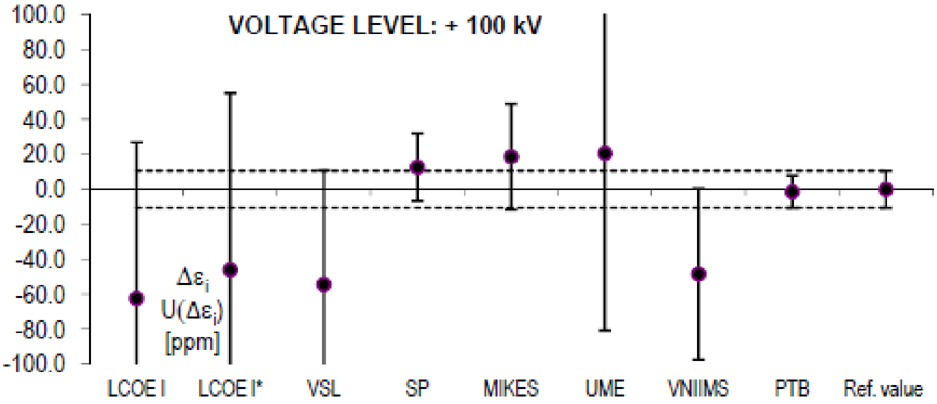
+ 50kV	$\Delta\varepsilon_i$ [ppm]	$U(\Delta\varepsilon_i)$ [ppm]
LCOE I	-28	89
LCOE I*	-45	101
VSL	-32	51
SP	20	19
MIKES	23	28
UME	15	99
VNIIMS	-25	49
PTB	-8	9
Ref. value	0	10



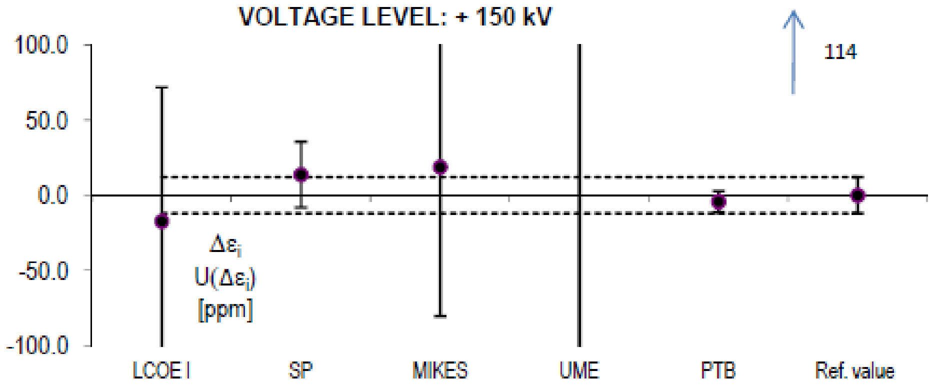
Positive Polarity (Cont.)

DIFFERENCES $\Delta(\varepsilon_i) = \varepsilon_i - y$ and their expanded uncertainties

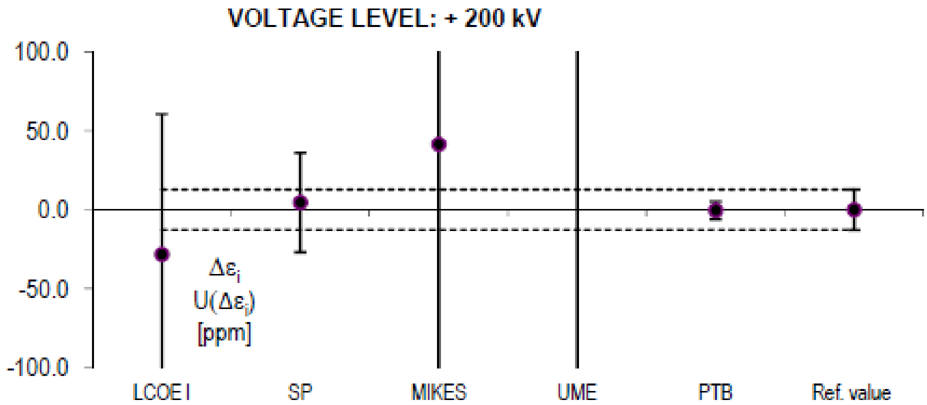
+ 100kV	$\Delta\varepsilon_i$ [ppm]	U ($\Delta\varepsilon_i$) [ppm]
LCOE I	-62	89
LCOE I*	-46	101
VSL	-54	65
SP	13	19
MIKES	19	30
UME	21	101
VNIIMS	-48	49
PTB	-1	9
Ref. value	0	11



+ 150kV	$\Delta\varepsilon_i$ [ppm]	U ($\Delta\varepsilon_i$) [ppm]
LCOE I	-17	89
SP	14	22
MIKES	19	99
UME	114	1000
PTB	-4	7
Ref. value	0	12



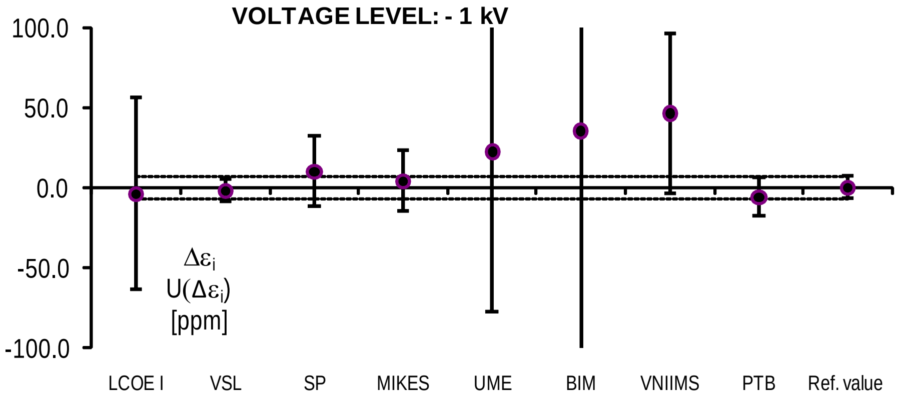
+ 200kV	$\Delta\varepsilon_i$ [ppm]	U ($\Delta\varepsilon_i$) [ppm]
LCOE I	-28	89
SP	5	32
MIKES	42	161
UME	126	1000
PTB	0	6
Ref. value	0	13



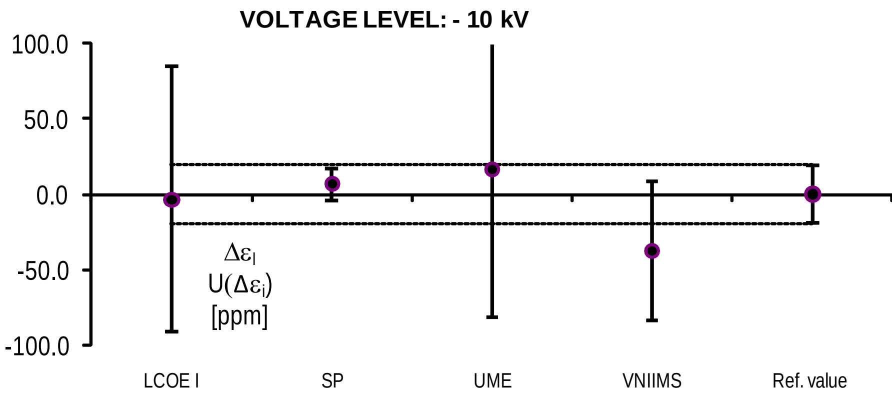
Negative Polarity

DIFFERENCES $\Delta(\varepsilon_i) = \varepsilon_i - y$ and their expanded uncertainties

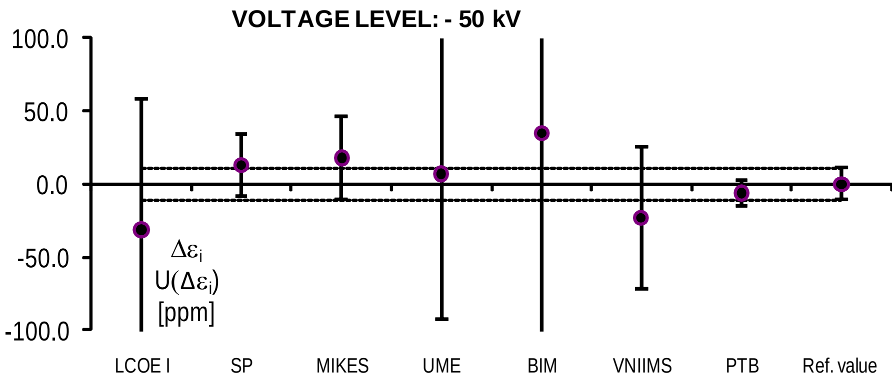
- 1kV	$\Delta\varepsilon_i$ [ppm]	$U(\Delta\varepsilon_i)$ [ppm]
LCOE I	-4	60
VSL	-2	7
SP	10	22
MIKES	4	19
UME	22	100
BIM	35	200
VNIIMS	46	50
PTB	-6	12
Ref. value	0	7



- 10kV	$\Delta\varepsilon_i$ [ppm]	$U(\Delta\varepsilon_i)$ [ppm]
LCOE I	-3	88
SP	7	11
UME	17	98
VNIIMS	-37	46
Ref. value	0	19

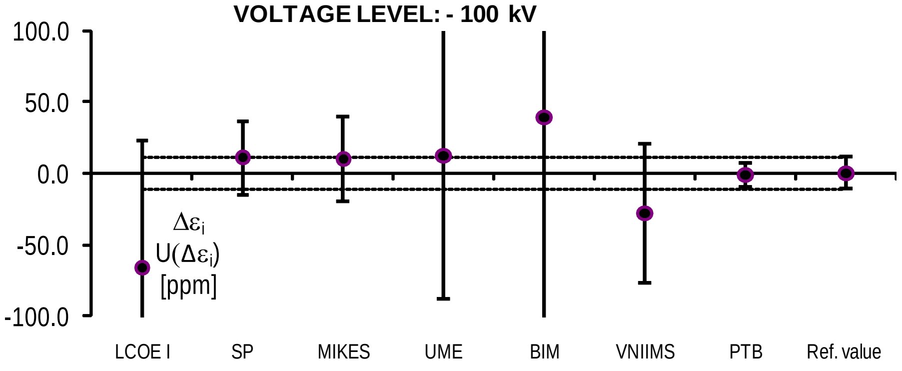


- 50kV	$\Delta\varepsilon_i$ [ppm]	$U(\Delta\varepsilon_i)$ [ppm]
LCOE I	-31	89
SP	13	21
MIKES	18	28
UME	7	99
BIM	35	170
VNIIMS	-23	49
PTB	-6	9
Ref. value	0	11

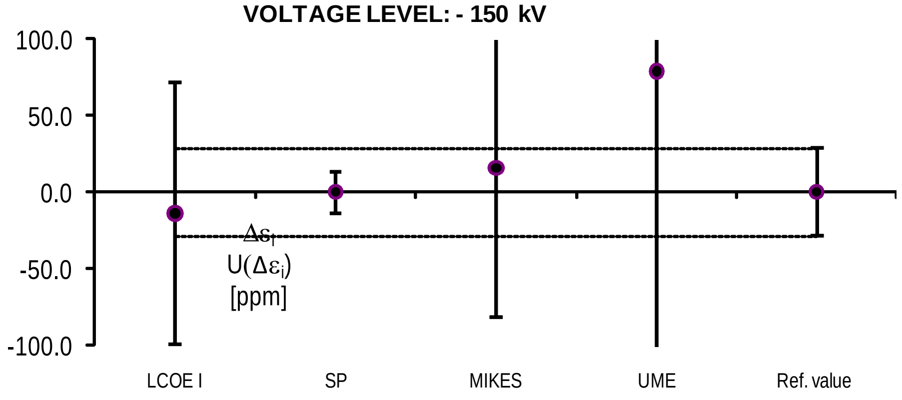


DIFFERENCES $\Delta(\varepsilon_i) = \varepsilon_i - y$ and their expanded uncertainties

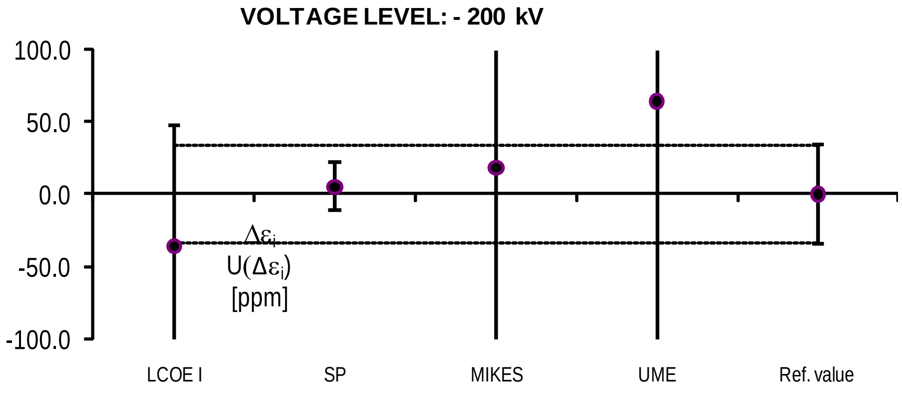
- 100kV	$\Delta\varepsilon_i$ [ppm]	U ($\Delta\varepsilon_i$) [ppm]
LCOE I	-66	89
SP	11	26
MIKES	10	30
UME	12	99
BIM	39	210
VNIIMS	-28	49
PTB	-1	8
Ref. value	0	11



- 150kV	$\Delta\varepsilon_i$ [ppm]	U ($\Delta\varepsilon_i$) [ppm]
LCOE I	-14	85
SP	0	14
MIKES	16	98
UME	79	1000
Ref. value	0	29



- 200kV	$\Delta\varepsilon_i$ [ppm]	U ($\Delta\varepsilon_i$) [ppm]
LCOE I	-36	83
SP	5	17
MIKES	18	158
UME	64	999
Ref. value	0	34



ANNEX III

Degree of equivalence between two laboratories.

Degree of equivalence between laboratories at level: + 1 kV

Differences $\Delta\varepsilon_{i,j}$ from comparison reference value:

	Lab.	LCOE I	VSL	SP	MIKES	UME	BIM	VNIIMS	PTB
Lab.	ε_i (ppm)	-29	-24	0	-17	-324		-67	-24
LCOE I	-29		-5	-29	-12	295		38	-5
VSL	-24	5		-24	-7	300		43	0
SP	0	29	24		17	324		67	24
MIKES	-17	12	7	-17		307		50	7
UME	-324	-295	-300	-324	-307			-257	-300
BIM									
VNIIMS	-67	-38	-43	-67	-50	257			-43
PTB	-24	5	0	-24	-7	300		43	

Expanded uncertainties of differences $\Delta\varepsilon_{i,j}$, $U(\Delta\varepsilon_{i,j})$

	Lab.	LCOE I	VSL	SP	MIKES	UME	BIM	VNIIMS	PTB
Lab.	u(ε_i) (ppm)	60	10	23	36	100		50	14
LCOE I	60		61	64	70	117		78	62
VSL	10	61		25	37	100		51	17
SP	23	64	25		43	103		55	27
MIKES	36	70	37	43		106		62	39
UME	100	117	100	103	106			112	101
BIM									
VNIIMS	50	78	51	55	62	112			52
PTB	14	62	17	27	39	101		52	

Compatibility index, $d_{i,j}$:

Lab.	LCOE I	VSL	SP	MIKES	UME	BIM	VNIIMS	PTB
LCOE I		-0.16	-0.90	-0.34	5.06		0.97	-0.16
VSL	0.16		-1.91	-0.37	5.97		1.69	0.00
SP	0.90	1.91		0.80	6.32		2.43	1.78
MIKES	0.34	0.37	-0.80		5.78		1.62	0.36
UME	-5.06	-5.97	-6.32	-5.78			-4.60	-5.94
BIM								
VNIIMS	-0.97	-1.69	-2.43	-1.62	4.60			-1.66
PTB	0.16	0.00	-1.78	-0.36	5.94		1.66	

Note: Values of $d_{i,j} \leq 2$ are considered compatible.

Degree of equivalence between laboratories at level: + 10 kV

	Lab.	LCOE I	VSL	SP	MIKES	UME	BIM	VNIIMS	PTB
Lab.	ε_i (ppm)	-25	-30	-26		-10		-85	
LCOE I	-25		5	1		-15		60	
VSL	-30	-5		-4		-20		55	
SP	-26	-1	4			-16		59	
MIKES									
UME	-10	15	20	16				75	
BIM									
VNIIMS	-85	-60	-55	-59		-75			
PTB									

Expanded uncertainties of differences $\Delta\varepsilon_{i,j}$, $U(\Delta\varepsilon_{i,j})$

	Lab.	LCOE I	VSL	SP	MIKES	UME	BIM	VNIIMS	PTB
Lab.	u(ε_i) (ppm)	90	52	22		100		50	
LCOE I	90		104	93		135		103	
VSL	52	104		56		113		72	
SP	22	93	56			102		55	
MIKES									
UME	100	135	113	102				112	
BIM									
VNIIMS	50	103	72	55		112			
PTB									

Compatibility index, $d_{i,j}$:

Lab.	LCOE I	VSL	SP	MIKES	UME	BIM	VNIIMS	PTB
LCOE I		0.10	0.02		-0.22		1.17	
VSL	-0.10		-0.14		-0.35		1.52	
SP	-0.02	0.14			-0.31		2.16	
MIKES								
UME	0.22	0.35	0.31				1.34	
BIM								
VNIIMS	-1.17	-1.52	-2.16		-1.34			
PTB								

Note: Values of $d_{i,j} \leq 2$ are considered compatible.

Degree of equivalence between laboratories at level: + 50 kV

	Lab.	LCOE I	VSL	SP	MIKES	UME	BIM	VNIIMS	PTB
Lab.	ε_i (ppm)	-46	-50	2	5	-3		-43	-26
LCOE I	-46		4	-48	-51	-43		-3	-20
VSL	-50	-4		-52	-55	-47		-7	-24
SP	2	48	52		-3	5		45	28
MIKES	5	51	55	3		8		48	31
UME	-3	43	47	-5	-8			40	23
BIM									
VNIIMS	-43	3	7	-45	-48	-40			-17
PTB	-26	20	24	-28	-31	-23		17	

Expanded uncertainties of differences $\Delta\varepsilon_{i,j}$, $U(\Delta\varepsilon_{i,j})$

	Lab.	LCOE I	VSL	SP	MIKES	UME	BIM	VNIIMS	PTB
Lab.	$u(\varepsilon_i)$ (ppm)	90	52	22	30	100		50	14
LCOE I	90		104	93	95	135		103	91
VSL	52	104		56	60	113		72	54
SP	22	93	56		37	102		55	26
MIKES	30	95	60	37		104		58	33
UME	100	135	113	102	104			112	101
BIM									
VNIIMS	50	103	72	55	58	112			52
PTB	14	91	54	26	33	101		52	

Compatibility index, $d_{i,j}$:

Lab.	LCOE I	VSL	SP	MIKES	UME	BIM	VNIIMS	PTB
LCOE I		0.08	-1.04	-1.08	-0.64		-0.06	-0.44
VSL	-0.08		-1.84	-1.83	-0.83		-0.19	-0.89
SP	1.04	1.84		-0.16	0.10		1.65	2.15
MIKES	1.08	1.83	0.16		0.15		1.65	1.87
UME	0.64	0.83	-0.10	-0.15			0.72	0.46
BIM								
VNIIMS	0.06	0.19	-1.65	-1.65	-0.72			-0.65
PTB	0.44	0.89	-2.15	-1.87	-0.46		0.65	

Note: Values of $d_{i,j} \leq 2$ are considered compatible.

Degree of equivalence between laboratories at level: + 100 kV

	Lab.	LCOE I	VSL	SP	MIKES	UME	BIM	VNIIMS	PTB
Lab.	ε_i (ppm)	-78	-70	-3	3	5		-64	-17
LCOE I	-78		-8	-75	-81	-83		-14	-61
VSL	-70	8		-67	-73	-75		-6	-53
SP	-3	75	67		-6	-8		61	14
MIKES	3	81	73	6		-2		67	20
UME	5	83	75	8	2			69	22
BIM									
VNIIMS	-64	14	6	-61	-67	-69			-47
PTB	-17	61	53	-14	-20	-22		47	

Expanded uncertainties of differences $\Delta\varepsilon_{i,j}$, $U(\Delta\varepsilon_{i,j})$

	Lab.	LCOE I	VSL	SP	MIKES	UME	BIM	VNIIMS	PTB
Lab.	$u(\varepsilon_i)$ (ppm)	90	66	22	32	102		50	14
LCOE I	90		112	93	96	136		103	91
VSL	66	112		70	73	121		83	67
SP	22	93	70		39	104		55	26
MIKES	32	96	73	39		107		59	35
UME	102	136	121	104	107			114	103
BIM									
VNIIMS	50	103	83	55	59	114			52
PTB	14	91	67	26	35	103		52	

Compatibility index, $d_{i,j}$:

Lab.	LCOE I	VSL	SP	MIKES	UME	BIM	VNIIMS	PTB
LCOE I		-0.14	-1.62	-1.70	-1.22		-0.27	-1.34
VSL	0.14		-1.93	-1.99	-1.23		-0.14	-1.57
SP	1.62	1.93		-0.31	-0.15		2.23	1.07
MIKES	1.70	1.99	0.31		-0.04		2.26	1.15
UME	1.22	1.23	0.15	0.04			1.21	0.43
BIM								
VNIIMS	0.27	0.14	-2.23	-2.26	-1.21			-1.81
PTB	1.34	1.57	-1.07	-1.15	-0.43		1.81	

Note: Values of $d_{i,j} \leq 2$ are considered compatible.

Degree of equivalence between laboratories at level: + 150 kV

	Lab.	LCOE I	VSL	SP	MIKES	UME	BIM	VNIIMS	PTB
Lab.	ε_i (ppm)	-117		-86	-81	14			-104
LCOE I	-117			-31	-36	-131			-13
VSL									
SP	-86	31			-5	-100			18
MIKES	-81	36		5		-95			23
UME	14	131		100	95				118
BIM									
VNIIMS									
PTB	-104	13		-18	-23	-118			

Expanded uncertainties of differences $\Delta\varepsilon_{i,j}$, $U(\Delta\varepsilon_{i,j})$

	Lab.	LCOE I	VSL	SP	MIKES	UME	BIM	VNIIMS	PTB
Lab.	$u(\varepsilon_i)$ (ppm)	90		25	100	1000			14
LCOE I	90			93	135	1004			91
VSL									
SP	25	93			103	1000			29
MIKES	100	135		103		1005			101
UME	1000	1004		1000	1005				1000
BIM									
VNIIMS									
PTB	14	91		29	101	1000			

Compatibility index, $d_{i,j}$:

Lab.	LCOE I	VSL	SP	MIKES	UME	BIM	VNIIMS	PTB
LCOE I			-0.66	-0.54	-0.26			-0.29
VSL								
SP	0.66			-0.10	-0.20			1.26
MIKES	0.54		0.10		-0.19			0.46
UME	0.26		0.20	0.19				0.24
BIM								
VNIIMS								
PTB	0.29		-1.26	-0.46	-0.24			

Note: Values of $d_{i,j} \leq 2$ are considered compatible.

Degree of equivalence between laboratories at level: + 200 kV

	Lab.	LCOE I	VSL	SP	MIKES	UME	BIM	VNIIMS	PTB
Lab.	ε_i (ppm)	-126		-93	-56	28			-98
LCOE I	-126			-33	-70	-154			-28
VSL									
SP	-93	33			-37	-121			5
MIKES	-56	70		37		-84			42
UME	28	154		121	84				126
BIM									
VNIIMS									
PTB	-98	28		-5	-42	-126			

Expanded uncertainties of differences $\Delta\varepsilon_{i,j}$, $U(\Delta\varepsilon_{i,j})$

	Lab.	LCOE I	VSL	SP	MIKES	UME	BIM	VNIIMS	PTB
Lab.	$u(\varepsilon_i)$ (ppm)	90		34	162	1000			14
LCOE I	90			96	185	1004			91
VSL									
SP	34	96			166	1001			37
MIKES	162	185		166		1013			163
UME	1000	1004		1001	1013				1000
BIM									
VNIIMS									
PTB	14	91		37	163	1000			

Compatibility index, $d_{i,j}$:

Lab.	LCOE I	VSL	SP	MIKES	UME	BIM	VNIIMS	PTB
LCOE I			-0.69	-0.76	-0.31			-0.61
VSL								
SP	0.69			-0.45	-0.24			0.27
MIKES	0.76		0.45		-0.17			0.52
UME	0.31		0.24	0.17				0.25
BIM								
VNIIMS								
PTB	0.61		-0.27	-0.52	-0.25			
LCOE I			-0.69	-0.76	-0.31			-0.61

Note: Values of $d_{i,j} \leq 2$ are considered compatible.

Degree of equivalence between laboratories at level: - 1 kV

	Lab.	LCOE I	VSL	SP	MIKES	UME	BIM	VNIIMS	PTB
Lab.	ε_i (ppm)	-19	-17	-5	-11	7	20	31	-21
LCOE I	-19		-2	-14	-8	-26	-39	-50	2
VSL	-17	2		-12	-6	-24	-37	-48	4
SP	-5	14	12		6	-12	-25	-36	16
MIKES	-11	8	6	-6		-18	-31	-42	10
UME	7	26	24	12	18		-13	-24	28
BIM	20	39	37	25	31	13		-11	41
VNIIMS	31	50	48	36	42	24	11		52
PTB	-21	-2	-4	-16	-10	-28	-41	-52	

Expanded uncertainties of differences $\Delta\varepsilon_{i,j}$, $U(\Delta\varepsilon_{i,j})$

	Lab.	LCOE I	VSL	SP	MIKES	UME	BIM	VNIIMS	PTB
Lab.	$u(\varepsilon_i)$ (ppm)	60	10	23	20	100	200	50	14
LCOE I	60		61	64	63	117	209	78	62
VSL	10	61		25	22	100	200	51	17
SP	23	64	25		30	103	201	55	27
MIKES	20	63	22	30		102	201	54	24
UME	100	117	100	103	102		224	112	101
BIM	200	209	200	201	201	224		206	200
VNIIMS	50	78	51	55	54	112	206		52
PTB	14	62	17	27	24	101	200	52	

Compatibility index, $d_{i,j}$:

Lab.	LCOE I	VSL	SP	MIKES	UME	BIM	VNIIMS	PTB
LCOE I		-0.07	-0.44	-0.25	-0.45	-0.37	-1.28	0.06
VSL	0.07		-0.96	-0.54	-0.48	-0.37	-1.88	0.46
SP	0.44	0.96		0.39	-0.23	-0.25	-1.31	1.19
MIKES	0.25	0.54	-0.39		-0.35	-0.31	-1.56	0.82
UME	0.45	0.48	0.23	0.35		-0.12	-0.43	0.55
BIM	0.37	0.37	0.25	0.31	0.12		-0.11	0.41
VNIIMS	1.28	1.88	1.31	1.56	0.43	0.11		2.00
PTB	-0.06	-0.46	-1.19	-0.82	-0.55	-0.41	-2.00	

Note: Values of $d_{i,j} \leq 2$ are considered compatible.

Degree of equivalence between laboratories at level: - 10 kV

	Lab.	LCOE I	VSL	SP	MIKES	UME	BIM	VNIIMS	PTB
Lab.	ε_i (ppm)	-36		-26		-16		-70	
LCOE I	-36			-10		-20		34	
VSL									
SP	-26	10				-10		44	
MIKES									
UME	-16	20		10				54	
BIM									
VNIIMS	-70	-34		-44		-54			
PTB									

Expanded uncertainties of differences $\Delta\varepsilon_{i,j}$, $U(\Delta\varepsilon_{i,j})$

	Lab.	LCOE I	VSL	SP	MIKES	UME	BIM	VNIIMS	PTB
Lab.	$u(\varepsilon_i)$ (ppm)	90		22		100		50	
LCOE I	90			93		135		103	
VSL									
SP	22	93				102		55	
MIKES									
UME	100	135		102				112	
BIM									
VNIIMS	50	103		55		112			
PTB									

Compatibility index, $d_{i,j}$:

Lab.	LCOE I	VSL	SP	MIKES	UME	BIM	VNIIMS	PTB
LCOE I			-0.22		-0.30		0.66	
VSL								
SP	0.22				-0.20		1.61	
MIKES								
UME	0.30		0.20				0.97	
BIM								
VNIIMS	-0.66		-1.61		-0.97			
PTB								

Note: Values of $d_{i,j} \leq 2$ are considered compatible.

Degree of equivalence between laboratories at level: - 50 kV

	Lab.	LCOE I	VSL	SP	MIKES	UME	BIM	VNIIMS	PTB
Lab.	ε_i (ppm)	-48		-4	1	-10	18	-40	-23
LCOE I	-48			-44	-49	-38	-66	-8	-25
VSL									
SP	-4	44			-5	6	-22	36	19
MIKES	1	49		5		11	-17	41	24
UME	-10	38		-6	-11		-28	30	13
BIM	18	66		22	17	28		58	41
VNIIMS	-40	8		-36	-41	-30	-58		-17
PTB	-23	25		-19	-24	-13	-41	17	

Expanded uncertainties of differences $\Delta\varepsilon_{i,j}$, $U(\Delta\varepsilon_{i,j})$

	Lab.	LCOE I	VSL	SP	MIKES	UME	BIM	VNIIMS	PTB
Lab.	u(ε_i) (ppm)	90		24	30	100	170	50	14
LCOE I	90			93	95	135	192	103	91
VSL									
SP	24	93			38	103	172	55	28
MIKES	30	95		38		104	173	58	33
UME	100	135		103	104		197	112	101
BIM	170	192		172	173	197		177	171
VNIIMS	50	103		55	58	112	177		52
PTB	14	91		28	33	101	171	52	

Compatibility index, $d_{i,j}$:

Lab.	LCOE I	VSL	SP	MIKES	UME	BIM	VNIIMS	PTB
LCOE I			-0.94	-1.03	-0.56	-0.69	-0.16	-0.55
VSL								
SP	0.94			-0.26	0.12	-0.26	1.30	1.37
MIKES	1.03		0.26		0.21	-0.20	1.41	1.45
UME	0.56		-0.12	-0.21		-0.28	0.54	0.26
BIM	0.69		0.26	0.20	0.28		0.65	0.48
VNIIMS	0.16		-1.30	-1.41	-0.54	-0.65		-0.65
PTB	0.55		-1.37	-1.45	-0.26	-0.48	0.65	

Note: Values of $d_{i,j} \leq 2$ are considered compatible.

Degree of equivalence between laboratories at level: - 100 kV

	Lab.	LCOE I	VSL	SP	MIKES	UME	BIM	VNIIMS	PTB
Lab.	ε_i (ppm)	-78		-1	-2	0	27	-40	-13
LCOE I	-78			-77	-76	-78	-105	-38	-65
VSL									
SP	-1	77			1	-1	-28	39	12
MIKES	-2	76		-1		-2	-29	38	11
UME	0	78		1	2		-27	40	13
BIM	27	105		28	29	27		67	40
VNIIMS	-40	38		-39	-38	-40	-67		-27
PTB	-13	65		-12	-11	-13	-40	27	

Expanded uncertainties of differences $\Delta\varepsilon_{i,j}$, $U(\Delta\varepsilon_{i,j})$

	Lab.	LCOE I	VSL	SP	MIKES	UME	BIM	VNIIMS	PTB
Lab.	$u(\varepsilon_i)$ (ppm)	90		28	32	100	210	50	14
LCOE I	90			94	96	135	228	103	91
VSL									
SP	28	94			43	104	212	57	31
MIKES	32	96		43		105	212	59	35
UME	100	135		104	105		233	112	101
BIM	210	228		212	212	233		216	210
VNIIMS	50	103		57	59	112	216		52
PTB	14	91		31	35	101	210	52	

Compatibility index, $d_{i,j}$:

Lab.	LCOE I	VSL	SP	MIKES	UME	BIM	VNIIMS	PTB
LCOE I			-1.63	-1.59	-1.16	-0.92	-0.74	-1.43
VSL								
SP	1.63			0.05	-0.02	-0.26	1.36	0.77
MIKES	1.59		-0.05		-0.04	-0.27	1.28	0.63
UME	1.16		0.02	0.04		-0.23	0.72	0.26
BIM	0.92		0.26	0.27	0.23		0.62	0.38
VNIIMS	0.74		-1.36	-1.28	-0.72	-0.62		-1.04
PTB	1.43		-0.77	-0.63	-0.26	-0.38	1.04	

Note: Values of $d_{i,j} \leq 2$ are considered compatible.

Degree of equivalence between laboratories at level: - 150 kV

	Lab.	LCOE I	VSL	SP	MIKES	UME	BIM	VNIIMS	PTB
Lab.	ε_i (ppm)	-118		-104	-88	-25			
LCOE I	-118			-14	-30	-93			
VSL									
SP	-104	14			-16	-79			
MIKES	-88	30		16		-63			
UME	-25	93		79	63				
BIM									
VNIIMS									
PTB									

Expanded uncertainties of differences $\Delta\varepsilon_{i,j}$, $U(\Delta\varepsilon_{i,j})$

	Lab.	LCOE I	VSL	SP	MIKES	UME	BIM	VNIIMS	PTB
Lab.	$u(\varepsilon_i)$ (ppm)	90		32	102	1000			
LCOE I	90			96	136	1004			
VSL									
SP	32	96			107	1001			
MIKES	102	136		107		1005			
UME	1000	1004		1001	1005				
BIM									
VNIIMS									
PTB									

Compatibility index, $d_{i,j}$:

Lab.	LCOE I	VSL	SP	MIKES	UME	BIM	VNIIMS	PTB
LCOE I			-0.29	-0.44	-0.19			
VSL								
SP	0.29			-0.30	-0.16			
MIKES	0.44		0.30		-0.13			
UME	0.19		0.16	0.13				
BIM								
VNIIMS								
PTB								

Note: Values of $d_{i,j} \leq 2$ are considered compatible.

Degree of equivalence between laboratories at level: - 200 kV

	Lab.	LCOE I	VSL	SP	MIKES	UME	BIM	VNIIMS	PTB
Lab.	ε_i (ppm)	-126		-85	-72	-26			
LCOE I	-126			-41	-54	-100			
VSL									
SP	-85	41			-13	-59			
MIKES	-72	54		13		-46			
UME	-26	100		59	46				
BIM									
VNIIMS									
PTB									

Expanded uncertainties of differences $\Delta\varepsilon_{i,j}$, $U(\Delta\varepsilon_{i,j})$

	Lab.	LCOE I	VSL	SP	MIKES	UME	BIM	VNIIMS	PTB
Lab.	u(ε_i) (ppm)	90		38	162	1000			
LCOE I	90			98	185	1004			
VSL									
SP	38	98			166	1001			
MIKES	162	185		166		1013			
UME	1000	1004		1001	1013				
BIM									
VNIIMS									
PTB									

Compatibility index, $d_{i,j}$:

Lab.	LCOE I	VSL	SP	MIKES	UME	BIM	VNIIMS	PTB
LCOE I			-0.84	-0.58	-0.20			
VSL								
SP	0.84			-0.16	-0.12			
MIKES	0.58		0.16		-0.09			
UME	0.20		0.12	0.09				
BIM								
VNIIMS								
PTB								

Note: Values of $d_{i,j} \leq 2$ are considered compatible.