

§9 International Comparison

9.1 Introduction

Due to the increasing demands for smaller uncertainties in the calibration of ac-dc standards at the national standard laboratories, CCE and EUROMET has decided to perform an international comparison of ac-dc transfer standard. The international comparison has started from the PTB as the pilot laboratories at April 1994, and 20 national laboratories has participated in the comparison.

The main purpose of the comparison is to confirm the international agreement on ac-dc transfer standard at the basic voltage (3V) and at the basic frequency (1 kHz) from which the traceability chains start. All the participating laboratories are requested to perform the calibration at their lowest possible uncertainties (<1 ppm).

The participating laboratories are as follows;

Physikalisch-Technische Bundesanstalt.
(PTB), Germany.
National Physical Laboratory.
(NPL), U.K.
Istituto Elettrotecnico Nazionale.
(IEN), Italy.
NMI Van Swinden Laboratory.
(VSL), The Netherlands.
Laboratoire Central des Industries Électriques.
(LCIE), France.
Technical Research Centre of Finland.
(VTT), Finland.
Sveriges Provnings-och Forskningsinstitut.
(SP), Sweden.
Office fédéral de métrologie.
(OFMET), Switzerland.
Bundesamt für Eich- und Vermessungswesen.
(BEV), Austria.
Instituto Nacional de Engenharia e Tecnologia Ind.
(INETI), Portugal.
Centro Español de Metrologia.
(CEM), Spain.
National Research Council.
(NRC), Canada.
National Institute of Standards and Technology.
(NIST), USA.
National Measurement Laboratory.
(NML), Australia.
Korean Research Institute for Standards and Science.
(KRISS), Republic of Korea.
National Physical Laboratory.
(NPL), India.
National Metrology Laboratory.

(NML SA), South Africa.
Center for Measurement Standards.
(CMS), Taiwan.
Instituto Nacional de Tecnologia Industrial.
(INTI), Argentina.
National Institute of Metrology.
(NIM), China.

The comparison has been carried out by the Round-Robin method using a traveling standard. ETL was the 16th participant in the comparison, and the calibration was carried out at October 1995. The results of the calibration of the traveling standard with respect to the primary standard of ETL are reported in section 9.3.

The ac-dc transfer difference of the traveling standard was also evaluated using the FRDC method. The HF-TVC was used for the determination of the frequency dependence of the traveling standard. The results of the evaluation using the FRDC source and the HF-TVC are reported in section 9.4.

9.2 Testing scheme

Since the most accurate measurements are requested for each participating laboratory, a Multijunction thermal converter (MJTC#4) made by PTB[13] has been used as the traveling standard. The specifications of the traveling standard are shown in **table 9.1**. Testing voltage is specified as 3V which is the nominal input voltage of MJTC#4.

The testing frequency of 1 kHz is selected because both the low-frequency effect and the high-frequency effect are estimated to be smaller than 0.1 ppm at 1 kHz[13]. In addition to 1 kHz, three other frequencies (20 kHz, 100 kHz, 1 MHz) were selected as an optional testing point. Since the high-frequency effect becomes dominant at those frequencies, it was requested to specify the type of connector used as the tee connector in the comparison measurement.

Table 9.1 The specifications of the traveling standard (MJTC#4), a Multijunction thermal voltage converter made by PTB.

Input voltage	2.84 V
Output voltage	100 mV
Input resistance	183 Ω
Output resistance	765 Ω
TC of sensitivity	-120 ppm/K
Time-constant	3 s

9. 3 Calibration by the primary standard

The traveling standard (MJTC#4) was calibrated using the primary standard of ETL (T04R11). The T04R11 is a 10V thermal voltage converter composed of a 10 mA single-junction thermal converter and a 1 kΩ range resistor. The T04R11 has been calibrated three times (1992, 1993 and 1995) by PTB. The uncertainties at the $k=2$ confident level were 2 ppm, 2 ppm, 3 ppm and 30 ppm, respectively, for the test frequency of 1 kHz, 20 kHz, 100 kHz and 1 MHz. The results of the three calibrations are listed in the upper part of **table 9.2**. The latest calibrated value (1995) at 1 MHz differed from the former two values (1992 and 1993) by about 50 ppm. While the difference was larger than the specified uncertainties, no change in the 1 MHz value of the T04R11 was observed relative to the other reference standard (10V01) in ETL. These data indicated that the former two values have better reliability than the latest calibrated value. Hence, the mean value of the three calibrations (1992, 1993 and 1995) was used as the more reliable value for the T04R11 at the time of the calibration (1995) for the traveling standard (MJTC#4).

9. 3. 1 Measurement

The schematic diagram of the calibration is shown in **figure 9.1**. The output EMF of the T04R11 is about 0.5 mV at the input voltage of 3V. Since it is very difficult to obtain an uncertainty of the order of 0.1 ppm for this low output EMF voltage, a working standard (10V01), which can produce 2 mV output at 3V input, has been used as an intermediate standard.

The calibration of the traveling standard (MJTC#4) was performed using the ac-dc difference comparator of ETL at the test frequency of 1 kHz, 20 kHz, 100 kHz, and 1 MHz. The results of the calibration are summarized in the lower part of the table 9.2.

In the table, the data specified as “T04R11(10V) by PTB” represent the mean value of the calibration of the T04R11 by PTB at the voltage of 10V. The data specified as “10V01/T04R11(10V)” show the relative ac-dc transfer difference of the 10V01 with respect to the T04R11 measured at 10V. The type N-TA-PPP connector was used as the tee connector.

The data “10V01(3V)/(10V)” represent the voltage de-

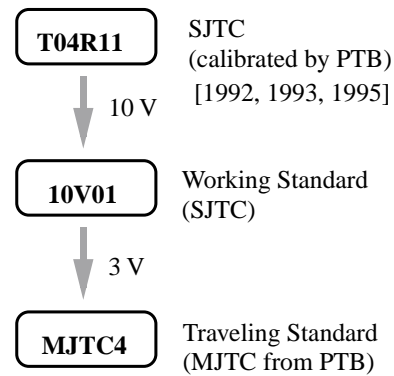


Figure 9.1 The schematic diagram of the calibration of traveling standard (MJTC#4) using the primary standard of ETL (T04R11). The T04R11 is a 10V thermal voltage converter calibrated by PTB with the uncertainty of 2 ppm at 1 kHz. Since the T04R11 can produce only 0.5 mV of EMF at the input voltage of 3V, a working standard (10V01) was used as an intermediate standard.

Table 9.2 The result of the calibration of the traveling standard (MJTC#4) using the primary standard of ETL (T04R11). The data specified as “XXX/YYYY” show the relative ac-dc transfer difference of XXX with respect to YYY. The data specified as “10V01(3V)/(10V)” represent the voltage dependence of 10V01 measured using the FRDC source. The values specified as “ZZZ by PTB” represent the calculated ac-dc transfer difference of ZZZ with respect to the standard of PTB.

	Date	1kHz	20kHz	100kHz	1MHz
T04R11(10V) by PTB	1992 Feb.	1.1	1.2	-0.3	-61.1
	1993 Apr.	0.6	0.1	-2.3	-64.4
	1995 Dec.	0.8	0.5	-1.5	-110.2
T04R11(10V) by PTB	(average)	0.83	0.60	-1.37	-78.57
10V01/T04R11(10V)	1995/10/16	-0.02	-0.19	-0.04	36.88
10V01(3V)/(10V)	1995/10/21	0.49	0.49	0.49	0.49
10V01(3V) by PTB		1.30	0.90	-0.92	-41.20
MJTC#4/10V01(3V)	1995-10/24	-0.16	1.09	8.92	144.74
MJTC#4 by PTB		1.14	1.99	8.00	103.54

(in ppm)

pendence of 10V01 between 3V and 10V. The voltage dependence was measured using the FRDC source. The values specified as “10V01(3V) by PTB” represent the calculated ac-dc transfer difference of 10V01 with respect to the standard of PTB. The data specified as “MJTC#4/10V01(3V)” show the relative ac-dc transfer difference of the MJTC#4 with respect to the 10V01 measured at 3V. Since the MJTC#4 has a type-GR874 connector, and the 10V01 uses type-N connector as their input, a special tee connector made by PTB was used. The connector was offered from the PTB for the CCE comparison. Finally, the values specified as “MJTC#4 by PTB” represent the calculated ac-dc transfer difference of MJTC#4 with respect to the standard of PTB, calibrated via the primary standard of ETL (T04R11).

9.3.2 Uncertainty

The uncertainties in the calibration of the traveling standard (MJTC#4) are summarized in **table 9.3**. The T04R11 has been calibrated by PTB with the $k=2$ confident level of 2 ppm (1kHz), 2 ppm (20kHz), 3 ppm (100kHz) and 30 ppm (1MHz), respectively. In the table, the values listed in “T04R11(10V) by PTB” represent the uncertainty (1σ -equivalent) for the calibration by the PTB. The values listed in “10V01 by T04R11(10V)” represent the uncertainties associated with the comparison of the 10V01 and the T04R11 at 10 V. Each value is calculated as the RSS of type A component and type B component of the measurement uncertainties. The values “10V01(3V)/(10V)” represent the uncertainties associated with the evaluation of the voltage dependence of 10V01 between 3 V and 10 V. The values listed in “MJTC#4 by 10V01(3V)” represent the uncertainty associated with the comparison of the MJTC#4 and the 10V01 at 3 V. Finally, the uncertainties listed in “MJTC#4 by PTB” are the total uncertainties calculated as the RSS of the four sources of uncertainties described above.

The type-A uncertainties were determined by measured standard deviation of the 10 sets of measurement sequence [AC, DC(+), DC(-), AC]. The sources of type-A uncertainty are as follows;

- (a) Instability and noise of the voltage source.
- (b) Thermal noise due to the output impedance of the thermocouple.
- (c) Input-equivalent noise of the detector (Keithley 182).
- (d) External noise induced in the input or output circuits of the TC.

The sources of type-B uncertainty, as described in section 3.3, are as follows;

- (e) Frequency characteristic of the TC-input circuit.
- (f) Effect of external noise.
- (g) Temperature drift of thermal converters.
- (h) Non-linearity of DVMS.
- (i) Effect of the off-time.

In the case of measurement for CCE comparison, the total type-B uncertainty was evaluated to be 0.3 ppm, 0.3 ppm, 0.6 ppm, and 5 ppm, at the test frequencies 1 kHz, 20 kHz, 100 kHz, and 1 MHz, respectively. The type B uncertainties for the voltage dependence using the FRDC source are described in section 8.4.

9.4 Measurement based on FRDC

The ‘intrinsic’ or ‘frequency-independent’ ac-dc transfer difference of a thermal converter results from the thermoelectric transfer difference. The thermoelectric transfer difference may be evaluated using a FRDC source, as described in previous chapters. At the testing frequency of 1 kHz, at which both the low-frequency effect and the high-frequency effect become negligibly small, the ac-dc difference of the traveling standard can be evaluated by the FRDC method with an accuracy of 0.1 ppm level.

Table 9.3 The uncertainties in the calibration of the traveling standard (MJTC#4) using the primary standard of ETL (T04R11). The total uncertainties are calculated as the RSS of each uncertainty.

	1kHz	20kHz	100kHz	1MHz
T04R11(10V) by PTB	1.00	1.00	1.50	15.00
10V01 by T04R11(10V)	0.33	0.34	0.62	5.00
Type A	0.14	0.16	0.14	0.12
Type B	<0.3	<0.3	<0.6	<5.0
10V01(3V)/(10V)	0.31	0.31	0.31	0.31
Type A	0.08	0.08	0.08	0.08
Type B	<0.3	<0.3	<0.3	<0.3
MJTC#4 by 10V01(3V)	0.44	0.52	1.21	5.44
Type A	0.32	0.42	1.05	2.15
Type B	<0.3	<0.3	<0.6	<5.0
MJTC#4 by PTB	1.18	1.22	2.05	16.73

Values represent one standard deviation in ppm.

At the test frequencies of 20 kHz, 100 kHz, and 1 MHz, the ac-dc transfer differences are dominated by the high-frequency effect due to skin-effects, dielectric loss, and leakage inductance and capacitance in the input circuit of a thermal converter. Hence, the high-frequency-standard TVC (HF-TVC) has also been used as a reference standard. The structure and the frequency characteristic of the HF-TVC are described in section 2.4.

9. 4. 1 Measurement

The schematic diagram of the calibration is shown in **figure 9.2**. At the test frequency of 1 kHz, the ac-dc difference of the MJTC#4 was directly evaluated using a FRDC source (SN95A007). The FRDC-DC difference of the MJTC#4 was measured to be less than 0.1 ppm, as listed in the data “MJTC#4 by FRDC”.

At the test frequencies of 20 kHz, 100 kHz, and 1 MHz, the HF-TVC was used to determine the frequency characteristic of the ac-dc transfer difference. Since the MJTC#4 has a type-GR874 connector which does not match with the type-N connector of the HF-TVC, the 10V01 was used as an intermediate standard. The comparison between the 10V01 and the MJTC#4 was carried out using the special tee connector made by PTB.

The results of the evaluation are summarized in **table 9.4**. In the table, the data specified as “HF-TVC” represents the calculated value of HF-TVC (#393). The data specified as “Fdep(10V01/HF-TVC)” show the frequency dependence of relative ac-dc transfer difference of the 10V01 with respect to the HF-TVC measured at 3V. Here, the high-frequency effect is assumed to be zero at 1 kHz for both the HF-TVC and the 10V01. The data specified as “Fdep(MJTC#4/10V01)” show the frequency dependence of relative ac-dc transfer difference of the MJTC#4 with respect to the 10V01 measured at 3V. Though the high-frequency effect of MJTC#4 is estimated to be less than 0.1 ppm at 1 kHz, residual effect was evaluated using a curve fitting of the data

around 1 kHz, assuming a linear frequency dependence of MJTC#4 around 1 kHz. Using the assumption that the high-frequency effect of 10V01 is much smaller than MJTC#4, the residual high-frequency effect of MJTC#4 was evaluated as 0.05 ± 0.01 ppm at 1 kHz. At higher testing frequencies (20 kHz, 100 kHz, 1 MHz), the data represent measured relative ac-dc transfer difference of the MJTC#4 with respect to the 10V01.

Combining the high-frequency effects and the thermoelectric effects, the ac-dc difference of the traveling standard was determined, as shown in the list “MJTC#4 by ETL”.

9. 4. 2 Uncertainty

The uncertainty associated with the measurements are summarized in **table 9.5**. The values listed in “HF-TVC”

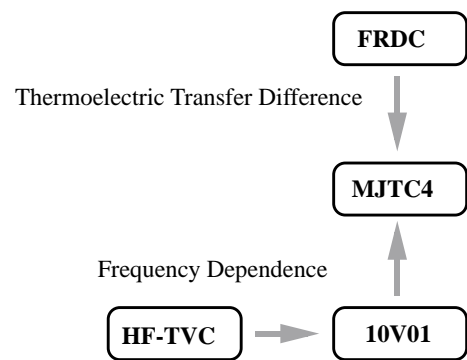


Figure 9.2 The schematic diagram of the calibration using FRDC and HF-TVC. The frequency independent ac-dc difference of the MJTC#4 was evaluated using a FRDC source. The HF-TVC was used to determine the frequency characteristic of the ac-dc transfer difference at the test frequencies of 20 kHz, 100 kHz, and 1 MHz. Since the MJTC#4 has a type-GR874 connector which does not match with the type-N connector of the HF-TVC, the working standard (10V01) was used as an intermediate standard.

Table 9.4 The result of the calibration of the traveling standard (MJTC#4) using the FRDC method and a HF-TVC. The data specified as “Fdep(XXX/YYY)” show the relative frequency dependence of XXX with respect to YYY. The data specified as “MJTC#4 by HF-TVC” represent the frequency dependence of MJTC#4 evaluated by the HF-TVC. The data specified as “MJTC#4 by FRDC” represent the frequency-independent part of ac-dc difference of MJTC#4 evaluated by the FRDC method.

	Date	1kHz	20kHz	100kHz	1MHz
HF-TVC		0.00	0.00	0.08	7.70
F-dep.(10V01/HF-TVC)	1995/10/25	0.00	-0.07	-0.02	-34.65
F-dep. (MJTC4/10V01)	1995/10/24	0.05	1.30	9.13	144.94
MJTC#4 by HF-TVC		0.05	1.23	9.19	117.99
MJTC4# by FRDC	1995/10/20	0.00	0.00	0.00	0.00
MJTC#4 by ETL		0.05	1.23	9.19	117.99

(in ppm)

Table 9.5 The uncertainties in the calibration of the traveling standard (MJTC#4) using the FRDC method and a HF-TVC. The total uncertainties are calculated as the RSS of each uncertainty.

	1kHz	20kHz	100kHz	1MHz
MJTC#4 by FRDC(3V)	0.30	0.30	0.30	0.30
Type A	0.04	0.04	0.04	0.04
Type B	<0.3	<0.3	<0.3	<0.3
HF-TVC(calculation)	0.10	0.10	0.10	7.70
F-dep.(10V01/HF-TVC)		0.51	0.74	5.02
Type A		0.41	0.43	0.44
Type B		<0.3	<0.6	<5.0
F-dep. (MJTC#4/10V01)	0.01	0.57	1.26	5.45
Type A		0.55	1.11	2.18
Type B	0.01	0.13	0.60	5.00
MJTC#4 by ETL	0.32	0.82	1.50	10.69

Values represent one standard deviation in ppm

Table 9.6 Summary of calibration for the traveling standard by ETL. Values in the upper column represent the result of calibration using the primary ac-dc transfer standard of ETL (T04R11) which has been calibrated by PTB. Values in the lower column represent the result of calibration using a FRDC source and a HF-TVC developed at ETL.

Frequency	1kHz	20kHz	100kHz	1MHz
Calibrated by T04R11 (Ref. PTB)	1.1 ± 1.2	2.0 ± 1.2	8.0 ± 2.0	103.5 ± 16.7
Calibrated by FRDC & HF-TVC	0.1 ± 0.3	1.2 ± 0.8	9.2 ± 1.5	118.0 ± 10.7

The uncertainty represent one standard deviation in ppm.

represent the uncertainty in the frequency characteristic of the HF-TVC (#393), as evaluated in section 2.4. The values listed in “Fdep(10V01/HF-TVC)” represent the uncertainty associated with the evaluation of high-frequency effect of the 10V01 using the HF-TVC(#393) as the reference standard. Each value is calculated as the RSS of type A component and type B component of the measurement. The uncertainty due to the use of N-P plug as the part of tee connector was estimated to be less than 0.1 ppm at 100 kHz and less than 1 ppm at 1 MHz. Since the high-frequency effect is assumed to be zero for both the HF-TVC and the 10V01 at 1 kHz, no uncertainties are attributed to 1 kHz data.

The data specified as “Fdep(MJTC#4/10V01)” represent the uncertainty associated with the evaluation of frequency dependence of the MJTC#4 with respect to the 10V01. The value for 1 kHz represents the uncertainty in the evaluation of the residual high-frequency effect of MJTC#4 by the use of curve fitting.

The values listed in “MJTC#4 by FRDC(3V)” represent

the uncertainty associated with the measurement of FRDC-DC difference of the MJTC#4 using the FRDC source (SN95A007) at 3V. The type A uncertainties are calculated from the 5 sets of 10 times-repeated measurement (total 50 measurement). For the standard deviation of the mean, $1/\sqrt{5}$ times the RMS of the standard deviation for each set of measurement is used. The main sources of type-A uncertainties, as described in section 8.4.1, are as follows;

- (a) Instability and noise of the FRDC source.
- (b) Thermal noise due to the output impedance of the thermocouple.
- (c) Input-equivalent noise of the detector (Keithley 182).
- (d) External noise induced in the input or output circuits of the TC.

The sources of type-B uncertainties, as described in section 8.4.2 are as follows;

- (e) Memory effect.
- (f) Effect of unmatched dummy resistance.
- (g) Interference between the Sources A/B.

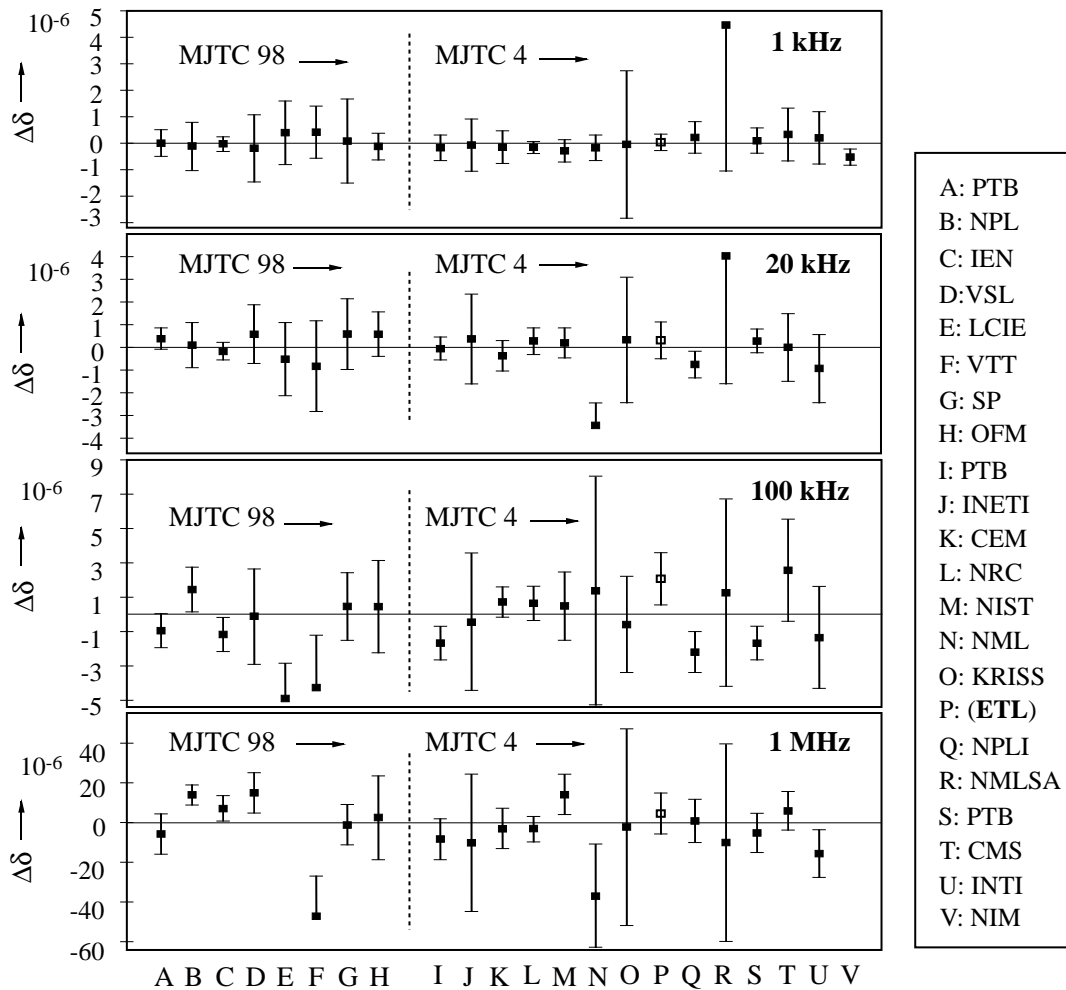


Figure 9.3 Summary of reported values for the CCE international comparison. The ETL-value, which was not reported to CCE, was added in the figure as a reference. The ETL-value is the independent value based on FRDC and HF-TVC.

- (h) Dielectric absorption in the TC-input circuit.
- (i) Effect of the off-time.
- (j) Temperature drift of TVC.

Each source of uncertainties has been evaluated to be smaller than 0.1 ppm. The uncertainties listed in “MJTC#4 by PTB” represent the total uncertainties calculated as the RSS of the six sources of uncertainties.

9.5 Summary

The traveling standard was calibrated using the two independent basis;

- (a) The primary ac-dc transfer standard of ETL calibrated by PTB.
- (b) A FRDC source and a HF-TVC developed at ETL.

In the former method, the ac-dc difference of MJTCs was estimated by a calculation using a mathematical modeling. In the latter method, the thermoelectric transfer difference was determined experimentally.

As summarized in table 9.6, the results obtained by the two methods have agreed within their uncertainty. The agreement at 1 kHz confirmed the feasibility of FRDC method as a basis for ac-dc transfer standard, and the agreement at higher frequency confirmed the correctness of the evaluation of high-frequency characteristic of the HF-TVC. In addition, the agreement also assures that the ac-dc comparator of ETL has been operating properly.

In January 1996, three months after the completion of the measurement for the CCE international comparison, ETL decided to stop maintaining the primary standard, and the results of the measurements at ETL were not reported to the CCE. Nevertheless, according to the summary of reported values issued by PTB[44], the two values for the MJTC#4 measured at the ETL have agreed with the values reported by the other countries, as shown in **figure 9.3**. The agreement confirms that ac-dc transfer standard of Japan had been in accordance with that of the other countries at 1 ppm level.