BUREAU INTERNATIONAL DES POIDS ET MESURES

COMITÉ CONSULTATIF D'ÉLECTRICITÉ

Rapport de la 20e session
Report of the 20th Meeting

1995

Organisation intergouvernementale de la Convention du Mètre

COMITÉ CONSULTATIF D'ÉLECTRICITÉ

SESSION DE 1995

MEETING OF 1995

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LISTE DES SIGLES UTILISÉS DANS LE PRÉSENT VOLUME
LIST OF ACRONYMS USED IN THE PRESENT VOLUME

1. Sigles des laboratoires, commissions et conférences
Acronyms for laboratories, committees and conferences

ARCS	Austrian Research Centre, Seibersdorf (Autriche)
*ASMW	Amt für Standardisierung, Messwesen und Warenprüfung, Berlin (Allemagne), *voir* PTB
*BCMN/CBNM	Bureau central de mesures nucléaires/Central Bureau for Nuclear Measurements, IMMR-CCE, Geel (Belgique), voir IMMR/ IRMM
BIPM	Bureau international des poids et mesures
BNM	Bureau national de métrologie, Paris (France)
BNM-INM	Bureau national de métrologie, Institut national de métrologie, Paris (France)
BNM-LCIE	Bureau national de métrologie, Laboratoire central des industries électriques, Fontenay-aux-Roses (France)
CCE	Comité consultatif d'électricité
CEI/IEC	Commission électrotechnique internationale/International Electrotechnical Commission
CIPM	Comité international des poids et mesures
CNET	Centre national d'études des télécommunications, Issy-les-Moulineaux (France)
CODATA	Committee on Data for Science and Technology
CPEM	Conference on Precision Electromagnetic Measurements
CRL	Communications Research Laboratory, Tokyo (Japon)
CSELT	Centro Studi Elettronica e Telecommunicazioni, Turin (Italie)
CSIC	Consejo Superior de Investigaciones Cientificas, Madrid (Espagne)

* Les laboratoires ou organisations marqués d'un astérisque soit n'existent plus soit figurent sous un autre sigle.

Organizations marked with an asterisk either no longer exist or operate under a different acronym.

CSIR/AEROTEK	(ex NPRL) Council for Scientific and Industrial Research, National Metrology Laboratory [CSIR], Pretoria (Afrique du Sud)
CSIRO	(ex NML) Commonwealth Scientific and Industrial Research Organization, Division of Applied Physics, Lindfield (Australie)
*CSMU	Československý Metrologický Ústav, Bratislava et Prague (Tchécoslovaquie), *voir* SMU
*DSIR	Department of Scientific and Industrial Research, Lower Hutt (Nouvelle-Zélande), *voir* MSL
EAL	European Accreditation of Laboratories
ETL	Electrotechnical Laboratory, Tsukuba (Japon)
EUROMET	European Collaboration on Measurement Standards
FTZ	Fernmeldetechnisches Zentralamt, Darmstadt (Allemagne)
GT-RF	Groupe de travail pour les grandeurs aux radiofréquences/ Working group on radiofrequency quantities
IEC	*voir* CEI
IEEE	Institute of Electrical and Electronics Engineers
IEN	Istituto Elettrotecnico Nazionale Galileo Ferraris, Turin (Italie)
IMGC	Istituto di Metrologia G. Colonnetti, Turin (Italie)
*IMM	*voir* VNIIM
IMMR/IRMM	(ex BCMN/CBNM) Institut des matériaux et mesures de référence/Institute for Reference Materials and Measurements, Geel (Belgique)
INM	Institut national de métrologie, Paris (France), *voir* BNM
IRMM	*voir* IMMR
ISO	Organisation internationale de normalisation/International Organization for Standardization
JQA	Japan Quality Assurance Organization (Japon)
KEC	Kansai Electronic Industry Development Center (Japon)
KRISS	(ex KSRI) Korea Research Institute of Standards and Science, Taejon (Rép. de Corée)
*KSRI	Korea Standards Research Institute, Taejon (Rép. de Corée), *voir* KRISS
LCIE	Laboratoire central des industries électriques, Fontenay-aux-Roses (France), *voir* BNM
LEP	Laboratoires d'électronique Philips, Limeil-Brévannes (France)
MSL	(ex DSIR) Measurement Standards Laboratory of New Zealand, Lower Hutt (Nouvelle-Zélande)
NAMAS	National Measurement Accreditation Service (Royaume-Uni)

*NBS	National Bureau of Standards, Gaithersburg (É.-U. d'Amérique), *voir* NIST
NIM	Institut national de métrologie/National Institute of Metrology, Beijing (Rép. pop. de Chine)
NIST	(ex NBS) National Institute of Standards and Technology, Gaithersburg (É.-U. d'Amérique)
NMi	(ex VSL) Nederlands Meetinstituut, Delft (Pays-Bas)
*NML	National Measurement Laboratory, Lindfield (Australie), *voir* CSIRO
NORAMET	North and Central American Metrology Cooperation
NPL	National Physical Laboratory, Teddington (Royaume-Uni)
NPLI	National Physical Laboratory of India, New Delhi (Inde)
*NPRL	National Physical Research Laboratory, Pretoria (Afrique du Sud), *voir* CSIR
NRC	Conseil national de recherches du Canada/National Research Council of Canada, Ottawa (Canada)
NRLM	National Research Laboratory of Metrology, Tsukuba (Japon)
OFMET	Office fédéral de métrologie/Eidgenössisches Amt für Messwesen, Wabern (Suisse)
OMH	Országos Mérésügyi Hivatal, Budapest (Hongrie)
PTB	Physikalisch-Technische Bundesanstalt, Braunschweig (Allemagne)
SESC	Service Electrical Standards Centre, Bromley (Royaume-Uni)
SMU	(ex CSMU) Slovenský Metrologický Ústav/Slovak Institute of Metrology, Bratislava (Slovaquie)
SNIIM	Institut de recherche scientifique sibérien en métrologie, Moscou (Féd. de Russie)
SP	(ex Statens Provningsanstalt) Sveriges Provnings- och Forskningsinstitut/Swedish National Testing and Research Institute, Borås (Suède)
SPTT	Direction générale des PTT de Suisse, Centre technique recherches et développement/Swiss PTT General Directorate, Research and Development Technical Centre, Berne (Suisse)
TF	Telecom Finland, Helsinki (Finlande)
TUD	Technical University of Denmark, Lyngby (Danemark)
VNIIM	Institut de métrologie D.I. Mendéléev/D.I. Mendeleyev Institute for Metrology, Saint-Pétersbourg (Féd. de Russie)
*VSL	Van Swinden Laboratorium, Delft (Pays-Bas), *voir* NMi

2. Sigles des termes scientifiques
Acronyms for scientific terms

MOSFET	Transistor à effet de champ métal-oxyde-semiconducteur/Metal-oxide-semiconductor field-effect transistor
QHE	Effet Hall quantique/Quantum Hall Effect
QHR	*voir* RHQ
RHQ/QHR	Résistance de Hall quantifiée/Quantum Hall resistance
SET	Effet tunnel monoélectrique/Single electron tunnelling
SI	Système international d'unités/International System of Units

THE BIPM

AND THE CONVENTION DU MÈTRE

The Bureau International des Poids et Mesures (BIPM) was set up by the Convention du Mètre signed in Paris on 20 May 1875 by seventeen States during the final session of the diplomatic Conference of the Metre. This Convention was amended in 1921.

BIPM has its headquarters near Paris, in the grounds (43 520 m^2) of the Pavillon de Breteuil (Parc de Saint-Cloud) placed at its disposal by the French Government; its upkeep is financed jointly by the Member States of the Convention du Mètre*.

The task of the BIPM is to ensure world-wide unification of physical measurements; it is responsible for:

— establishing the fundamental standards and scales for measurement of the principal physical quantities and maintaining the international prototypes;

— carrying out comparisons of national and international standards;

— ensuring the co-ordination of corresponding measuring techniques;

— carrying out and co-ordinating determinations relating to the fundamental physical constants that are involved in the above-mentioned activities.

BIPM operates under the exclusive supervision of the Comité International des Poids et Mesures (CIPM) which itself comes under the authority of the Conférence Générale des Poids et Mesures (CGPM).

The Conférence Générale consists of delegates from all the Member States of the Convention du Mètre and meets at present every four years. At each meeting it receives the Report of the Comité International on the work accomplished, and it is responsible for:

— discussing and instigating the arrangements required to ensure the propagation and improvement of the International System of Units (SI), which is the modern form of the metric system;

— confirming the results of new fundamental metrological determinations and the various scientific resolutions of international scope;

— adopting the important decisions concerning the organization and development of BIPM.

The Comité International consists of eighteen members each belonging to a different State: it meets at present every year. The officers of this committee issue an Annual Report on the administrative and financial position of BIPM to the Governments of the Member States of the Convention du Mètre.

The activities of the BIPM, which in the beginning were limited to the measurements of length and mass and to metrological studies in relation to these quantities, have been extended to standards of measurement of electricity (1927), photometry (1937), ionizing radiation (1960), to time scales (1988) and to amount of substance (1993). To this end the original laboratories, built in 1876-1878, were enlarged in 1929; new buildings were constructed in 1963-1964 for the ionizing radiation laboratories, in 1984 for the laser work and in 1988 a new building for a library and offices was opened.

* As of 31 December 1995, forty-eight States were members of this Convention: Argentina (Rep. of), Australia, Austria, Belgium, Brazil, Bulgaria, Cameroon, Canada, Chile, China (People's Rep. of), Czech Republic, Denmark, Dominican Republic, Egypt, Finland, France, Germany, Hungary, India, Indonesia, Iran, Ireland, Israel, Italy, Japan, Korea (Dem. People's Rep. of), Korea (Rep. of), Mexico, Netherlands, New Zealand, Norway, Pakistan, Poland, Portugal, Romania, Russian Federation, Singapore, Slovak Republic, South Africa, Spain, Sweden, Switzerland, Thailand, Turkey, United Kingdom, U.S.A., Uruguay, Venezuela.

Some forty physicists or technicians work in the BIPM laboratories. They mainly conduct metrological research, international comparisons of realizations of units and the verification of standards used in the above-mentioned areas. An annual report published in the Procès-Verbaux des séances du Comité International des Poids et Mesures gives the details of the work in progress.

In view of the extension of the work entrusted to the BIPM, the CIPM has set up since 1927, under the name of Comités Consultatifs, bodies designed to provide it with information on matters that it refers to them for study and advice. These Comités Consultatifs, which may form temporary or permanent working groups to study special subjects, are responsible for co-ordinating the international work carried out in their respective fields and proposing recommendations concerning units. In order to ensure world-wide uniformity in units of measurement, the Comité International accordingly acts directly or submits proposals for sanction by the Conférence Générale.

The Comités Consultatifs have common regulations (*BIPM Proc.-Verb. Com. Int. Poids et Mesures*, 1963, **31**, 97). Each Comité Consultatif, the chairman of which is normally a member of CIPM, is composed of delegates from the major metrology laboratories and specialized institutes, a list of which is drawn up by CIPM, as well as individual members also appointed by CIPM and one representative of BIPM. These committees hold their meetings at irregular intervals; at present there are nine of them in existence:

1. The Comité Consultatif d'Électricité (CCE), set up in 1927.
2. The Comité Consultatif de Photométrie et Radiométrie (CCPR), new name given in 1971 to the Comité Consultatif de Photométrie (CCP) set up in 1933 (between 1930 and 1933 the preceding committee (CCE) dealt with matters concerning Photometry).
3. The Comité Consultatif de Thermométrie (CCT), set up in 1937.
4. The Comité Consultatif pour la Définition du Mètre (CCDM), set up in 1952.
5. The Comité Consultatif pour la Définition de la Seconde (CCDS), set up in 1956.
6. The Comité Consultatif pour les Étalons de Mesure des Rayonnements Ionisants (CCEMRI), set up in 1958. In 1969 this committee established four sections: Section I (Measurement of x and γ rays, electrons), Section II (Measurement of radionuclides), Section III (Neutron measurements), Section IV (α-energy standards). In 1975 this last section was dissolved and Section II was made responsible for its field of activity.
7. The Comité Consultatif des Unités (CCU), set up in 1964 (this committee replaced the "Commission for the System of Units" set up by the CIPM in 1954).
8. The Comité Consultatif pour la Masse et les grandeurs apparentées (CCM), set up in 1980.
9. The Comité Consultatif pour la Quantité de Matière (CCQM), set up in 1993.

The proceedings of the Conférence Générale, the Comité International, the Comités Consultatifs, and the Bureau International are published under the auspices of the latter in the following series:

— *Comptes Rendus des Séances de la Conférence Générale des Poids et Mesures;*
— *Procès-Verbaux des Séances du Comité International des Poids et Mesures;*
— *Sessions des Comités Consultatifs.*

The Bureau International also publishes monographs on special metrological subjects and, under the title *"Le Système International d'Unités (SI)"*, a booklet, periodically updated, in which all the decisions and recommendations concerning units are collected.

The collection of the *Travaux et Mémoires du Bureau International des Poids et Mesures* (22 volumes published between 1881 and 1966) ceased by a decision of the CIPM, as well as the *Recueil de Travaux du Bureau International des Poids et Mesures* (11 volumes published between 1966 and 1988).

Since 1965 the international journal *Metrologia*, edited under the auspices of the CIPM, has published articles on the more important work on scientific metrology carried out throughout the world, on the improvement in measuring methods and standards, on units, etc., as well as reports concerning the activities, decisions, and recommendations of the various bodies created under the Convention du Mètre.

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OFFICE FÉDÉRAL DE MÉTROLOGIE [OFMET], Wabern.

PHYSIKALISCH-TECHNISCHE BUNDESANSTALT [PTB], Braunschweig.

The Director of the Bureau International des Poids et Mesures [BIPM], Sèvres.

AGENDA
for the 20th meeting

1. Opening of the meeting; appointment of a rapporteur.

2. Matters related to fundamental constants and the SI:
   - 2.1 Report of the working group on electrical methods to monitor the stability of the kilogram,
   - 2.2 Report on the status of the 1995 least squares adjustment of the fundamental constants,
   - 2.3 Advances in the realizations of the SI electrical units; improved knowledge of K_J and R_K; prospects for the metrological use of single electron tunnelling devices.

3. Accurate measurements of the quantized Hall resistance at frequencies in the kilohertz range.

4. Availability of arrays of Josephson junctions and quantum Hall effect samples:
   - 4.1 Availability of arrays of Josephson junctions,
   - 4.2 Availability of quantum Hall effect samples.

5. International comparisons:
   - 5.1 On-site comparisons of basic reference standards using travelling Josephson array voltage standards and quantum Hall resistance standards,
   - 5.2 Conventional travelling standards for electrical quantities,
   - 5.3 Reports on international comparisons (at DC or low frequency AC) organized by the CCE:
     - 5.3.1 Comparison of inductance at 10 mH (pilot laboratory: PTB),
     - 5.3.2 Comparison 92-1 of 10 pF capacitors (pilot laboratory: NIST),
     - 5.3.3 Comparison 92-2 of AC power and energy, between 50 Hz and 60 Hz (pilot laboratory: NIST),
     - 5.3.4 Comparison 92-3 of multi-junction AC/DC transfer devices (pilot laboratory: PTB),
     - 5.3.5 Comparison 92-4 of single junction thermal voltage converters, between 50 kHz and 100 kHz (pilot laboratory: BNM-LCIE),

5.3.6 Comparison 92-5 of single junction thermal voltage converters, between 1 MHz and 50 MHz (pilot laboratory: NMi-VSL),

5.4 Proposals for new comparisons to assure compatibility among national electrical standards.

6. Report on the meeting of the working group on radiofrequency quantities.

7. Activities of the Electricity section of the BIPM:

7.1 Comparisons of Josephson and quantum Hall standards via transportable instruments,

7.2 BIPM programme of bilateral comparisons of electrical standards using conventional travelling standards,

7.3 Calibrations:

7.3.1 Improvements in voltage and resistance calibrations,

7.3.2 Prospects for providing capacitance calibrations,

7.3.3 Proposal to change the reference temperature for standard cell and resistance calibrations at the BIPM from 20 °C to 23 °C.

8. Future activities of the CCE.

9. Other business.

REPORT

OF THE

COMITÉ CONSULTATIF D'ÉLECTRICITÉ

(20th Meeting — 1995)

TO THE

COMITÉ INTERNATIONAL DES POIDS ET MESURES

by B. M. WOOD, Rapporteur

The Comité Consultatif d'Électricité (CCE) held its twentieth meeting on 14 and 15 June 1995 at the Bureau International des Poids et Mesures, Pavillon de Breteuil, at Sèvres.

The following were present:

D. KIND, President of the CCE.

The delegates from the member laboratories:

Bureau National de Métrologie – Laboratoire Central des Industries Électriques [BNM-LCIE], Fontenay-aux-Roses (L. ÉRARD, G. GENEVÈS).

CSIR-AEROTEK, National Metrology Laboratory [CSIR], Pretoria (R. E. DRESSLER).

CSIRO, Division of Applied Physics [CSIRO], Lindfield (G. W. SMALL).

D.I. Mendeleyev Institute for Metrology [VNIIM], Saint-Petersburg (Yu. V. TARBEYEV, E. T. FRANTSUZ).

Electrotechnical Laboratory [ETL], Tsukuba (T. ENDO).

Istituto Elettrotecnico Nazionale Galileo Ferraris [IEN], Turin (F. CABIATI, G. MARULLO REEDTZ).

Korea Research Institute of Standards and Science [KRISS], Taejon (R. D. LEE).

National Institute of Metrology [NIM], Beijing (R. LIU).

National Institute of Standards and Technology [NIST], Gaithersburg (R. E. HEBNER, B. N. TAYLOR, E. R. WILLIAMS).

National Physical Laboratory [NPL], Teddington (B. P. KIBBLE).

National Research Council of Canada [NRC], Ottawa (B. M. WOOD, E. SO).

Nederlands Meetinstituut – Van Swinden Laboratorium [NMi-VSL], Delft (R. KAARLS, J. P. M. DE VREEDE).

Office Fédéral de Métrologie [OFMET], Wabern (U. FELLER).

Physikalisch-Technische Bundesanstalt [PTB], Braunschweig (H. BACHMAIR, E. BRAUN).

The Director of the Bureau International des Poids et Mesures [BIPM] (T. J. QUINN).

Invited guests:

Industrial Research Ltd., Measurement Standards Laboratory [MSL], Lower Hutt (K. JONES).

Swedish National Testing and Research Institute [SP], Borås (H. NILSSON).

Also attending the meeting: P. GIACOMO (Director Emeritus of the BIPM); F. DELAHAYE, J. MONPROFIT, D. REYMANN, T. J. WITT, J. BOHÁČEK (BIPM).

Absent:

National Physical Laboratory of India [NPLI], New Delhi.

1. Opening of the meeting; appointment of a rapporteur

The President of the CCE and the Director of the BIPM welcomed the participants. Dr Wood was appointed rapporteur. A total of 57 documents was presented to the meeting for consideration by the CCE. A list is given in Appendix E 1 (page E 29). The provisional agenda was considered and it was decided to include specific consideration of document CCE/95-41, on equivalence between national measurement standards, under item 5.4. The agenda was approved by the members.

2. Matters related to fundamental constants and the SI

2.1 Report of the working group on electrical methods to monitor the stability of the kilogram

The President asked the participants to report on the current work on fundamental constants and SI units in the national laboratories.

Dr Kibble reported on the progress of the working group on electrical monitoring of the stability of the kilogram (CCE/95-26). He then detailed the status of the NPL watt balance (CCE/95-29). For this, the resolution and repeatability of the ratio of induced voltage to coil velocity approach 1 part in 10^8. Although the resolution of the measurement of the ratio of current to force is also 1 part in 10^8, the repeatability of this ratio is only about 1 part in 10^7. This was attributed to hysteresis in the knife edges of the balance which have subsequently been improved. Dr Kibble noted that the mercury-cell voltage standards are being replaced by the NPL Josephson array and remarked that both he and a colleague, Dr Robinson, now spend more than half of their time on the watt balance project. Dr Kibble also noted that work based on determinations of the Avogadro constant may be useful for monitoring the kilogram, but only as a backup; an optimistic extrapolation of present achievements indicates an eventual reproducibility of about 5 parts in 10^8. Finally, he noted that vacuum weighing of silicon mass artefacts is being investigated in several laboratories.

Mr Frantsuz discussed progress on superconducting magnetic levitation measurements (CCE/95-12). He outlined some of the factors which limit accuracy, including gas adsorption in the levitated body, completeness of the Meissner effect in the body, assurance of a single degree of freedom in the body motion and the link to Josephson and quantum Hall effect (QHE) standards. He made several suggestions for improvements in the design of the next version of the apparatus and suggested that the same apparatus could be used to obtain an accurate determination of *g in situ* by measuring the motion of an oscillating levitated body. He concluded that the area of measurements of $h/2e$ by levitation methods has great promise and pointed out that international support and cooperation on this project would be most valuable and welcome. Several delegates agreed that increased international cooperation is needed in this work.

2.2 Report on the status of the 1995 least squares adjustment of the fundamental constants

Dr Taylor discussed the next CODATA least square adjustments of the values of the fundamental constants. He noted that the earlier target date of 1995 was set back to avoid basing the new adjustment on only a few new results. The intention now is to set 1 July 1996 as the date limit for acceptance of new data, a date which coincides with CPEM'96 in Braunschweig. The next adjustment is scheduled for publication in late 1996 or early 1997.

2.3 Advances in the realizations of the SI electrical units; improved knowledge of K_J and R_K; prospects for the metrological use of single electron tunnelling devices

Dr Taylor described the present status of the SI values of K_J and R_K (CCE/95-38). Since the CCE's 1988 analysis, new data concerning K_J include results from the volt balance at the PTB, determinations of the Avogadro constant by the PTB and the IRMM and by IMGC and the IRMM, and measurements of γ'_p(hi) and γ'_p(lo) at the NIM. New results concerning R_K include: a new calculation of the fine structure constant using the same value of the electron-magnetic moment anomaly as in 1988, a new result for α^{-1} implied by the PTB h/m_n measurements, two new quantum Hall resistance (QHR) calculable capacitor measurements by the CSIRO and the NIM and a refinement in the calculation of α^{-1} from previous experimental data on muonium hyperfine splitting. Dr Taylor concluded that for $K_{J\text{-}90}$ and $R_{K\text{-}90}$, both the values and the assigned uncertainties are still reasonable.

Dr Williams noted that the NIST will shortly carry out new calculable capacitor-QHR measurements and that results are expected in time for the next adjustment of the constants. He also described progress on the NIST watt determination arising from the use of an inductance technique, developed in the NIST γ'_p(lo) experiment, to solve alignment problems. He expects a result from the NIST watt determination by the CPEM'96.

Mr Érard added that the BNM-LCIE hopes to complete a determination of R_K before the CPEM'96.

The subject of single electron tunnelling (SET) was introduced and a number of CCE laboratories, including the BNM-LCIE, ETL, NIST, NPL, NRC, PTB, SP, VNIIM and NMi-VSL, indicated that they are involved in projects in this area. Dr Genevès described the second EUROMET meeting on SET devices and quantum current standards (CCE/95-9), held at the BNM-LCIE on 8-9 March 1994. He mentioned that metrology laboratories have great interest in this work and that a third meeting will be held at the PTB on 21 June 1996, immediately following the CPEM'96.

Dr Bachmair described the PTB's progress in the fabrication of SET devices. Dr Kibble pointed out that the seven-pump devices developed at the NIST in Boulder can produce accurate currents but that there remains a problem of measuring small currents. Dr Williams discussed recent metrological work in which an SET electrometer is used to measure recently developed low-leakage 0,5 pF vacuum-gap capacitors. He estimated the preliminary standard uncertainty to be about 5 parts in 10^7.

3. Accurate measurements of the quantized Hall resistance at frequencies in the kilohertz range

Mr Delahaye described the BIPM AC QHR results for $i = 2$ and $i = 4$ on two different samples at 1600 Hz (CCE/95-1 bis). A number of difficulties were outlined including sample-dependent structure on the Hall plateau, non-zero minima of R_{xx} and oscillations of the leads in the magnetic field that appear as an inductance of about 100 μH. A small dependence of the Hall resistance on current was observed; $R_H(2)$ increased linearly by 2 parts in 10^8 for a 10 μA increase in current and $R_H(4)$ increased at the rate of 0,5 parts in 10^8 per 10 μA increase in current. Despite these problems, he observed equality of the AC Hall resistances $R_H(2)$ and $2R_H(4)$ at 1600 Hz to within (8 ± 2) parts in 10^8 and an AC/DC difference in the ratio of the QHR to a Vishay-type AC reference resistance of less than 2 parts in 10^7.

Dr Kibble outlined the NPL results. They have measured the frequency dependence of the ratio of the QHR to the resistance of an AC/DC resistor. Taking into account Prof. Boháček's calculations for the reference resistor, they observed a linear dependence of the QHR on frequency and found that the value deduced by extrapolation to 0 Hz is equal to the DC value of the QHR. This suggests that the QHR may have better AC/DC characteristics than the best conventional resistor, although resonances and plateau structure have also been observed. Dr Kibble also commented that it will be necessary to write technical guidelines for reliable measurements of the AC QHR, but that it is probably premature to write them now.

Dr Braun described the status of the PTB QHR measurements using AC and an innovative cryogenic quadrature bridge. He noted that, while the bridge is working properly, there is still a problem with the samples and there is structure on the plateau. He also noted that Dr Melcher of the PTB will join the BIPM for two years to work on these measurements.

Dr Genevès commented on measurements at the BNM-LCIE which show that ρ_{xx} is independent of frequency and that the AC results are similar to those at DC.

Dr Wood noted that the first AC QHR measurements at the NRC have been carried out on two samples at frequencies of 700 Hz to 4000 Hz, at $i = 2$ and $i = 4$ and at several current values. The preliminary results show curved plateaus and non-zero R_{xx} minima, but the AC and DC resistances agree to about 2 parts in 10^7.

Prof. Boháček described his construction and modelling of Gibbings-type resistors and their application to these AC measurements. Dr Marullo Reedtz commented that AC QHR measurements have begun at the IEN and that preliminary results have just become available.

4. Availability of arrays of Josephson junctions and of quantum Hall effect samples

4.1 Availability of arrays of Josephson junctions

Dr Hebner stated that the NIST has now transferred the Josephson array technology to an American company, Hypres, and no longer supplies one volt or ten volt arrays. Hypres is manufacturing all-niobium arrays. A one volt array costs $ 7 500 and a ten volt array costs $ 20 000.

Dr Bachmair stated that the PTB is producing one volt niobium arrays and some may be available under cooperative loan agreements. Production of ten volt arrays should begin during 1995. He also indicated that there are plans to transfer this technology to a private company some time in the next three years.

Dr Endo explained that the ETL is making one volt and ten volt niobium arrays. While the ETL is not in a position to sell arrays, some one volt arrays may be available through cooperative loan agreements. Ten volt arrays have only recently been produced and none are yet available for other laboratories. Dr Endo also indicated that commercial assistance is being sought from Japanese companies.

Dr Lee indicated that the KRISS is now producing one volt niobium arrays, but that from July 1995 the sputtering equipment will be committed for a period of one year to the fabrication of multi-junction thermal voltage converters. After that the KRISS may be able to make arrays available commercially. Dr Kibble indicated that Oxford Instruments is continuing its work on the development of Josephson arrays.

4.2 Availability of quantum Hall effect samples

Dr Genevès described some of the details of a new initiative for the production of quantum Hall resistance samples (CCE/95-56). The LEP will produce 500 samples using the fabrication techniques previously used for unprotected samples made under the BIPM-EUROMET cooperation. The samples will be made in two sizes: 2,2 mm × 0,4 mm and 2,2 mm × 0,8 mm. Interested laboratories are asked to contact the BNM-LCIE which will purchase the samples from the LEP.

Dr Braun showed data on a new set of QHR samples (CCE/95-54) produced at the PTB. For these samples the $i = 2$ plateau occurs at 11,5 T, the QHR is well quantized at 1,7 K and $\rho_{xx} < 1\ \mu\Omega$ at 35 μA. The PTB will make these samples available to other laboratories on request.

Laboratories accepting them will be asked to report back to the PTB on their measurements of sample characteristics.

At this time Dr Braun presented Dr Quinn with a sample as a gift to the BIPM from the PTB. Dr Quinn thanked Dr Braun and the PTB for this generous gift.

Dr Witt reminded laboratories of the importance of reporting the characteristics of QHR samples back to their source as this is an obvious way to accumulate accurate statistics on samples and so to perfect the processes of fabrication.

On related subjects, Dr Kibble indicated that the NPL has made a printed circuit board sample holder for 4-terminal AC QHR measurements and may be able to make this holder available to other laboratories.

Dr Witt reminded participants that the ETL was organizing a purchase of mercury batteries (CCE/95-39) for use in stable current and voltage sources. A letter had been sent to all CCE members noting that orders should be placed by the end of June 1995.

Dr Williams related NIST experience with two types of mercury batteries from Panasonic which exhibit a high or a low temperature coefficient depending on chemical composition. There was some confusion over just which type of battery is involved in the ETL purchase proposal. Dr Reymann stated that he had achieved drift rates of 3 parts in 10^7 per hour with Panasonic batteries. He also noted a potential problem with the pressed fits of the positive terminals of these cells which have occasionally been observed to provide a poor contact and unstable resistance. Dr Endo stated that he would advise Panasonic about the contact problem. Dr Kibble stated that, in his experience, the drift rates and temperature coefficients of mercury batteries depend on the temperature at which they are used and that this may affect the interpretation of these results.

Before leaving the subject of QHR, Dr Taylor reminded the CCE of several reports of QHR discrepancies, especially when using silicon MOSFETs from Sony. Dr Feller was then asked to present document CCE/95-30 on this subject. He described the results of a very detailed and comprehensive examination of MOSFETs, from Sony and from the University of Southampton (via the University of Nottingham), and of GaAs samples. The study resulted from a collaboration between the OFMET and the NRC and it includes measurements from different samples using different combinations of plateau, current and field direction. For the Sony samples, but not for those from Nottingham, it was found that V_{xx} sometimes varies as a function of gate voltage and that, at points along the plateau where V_{xx} is not zero on one side of the sample, the Hall voltage is anomalous. When V_{xx} is essentially zero on both sides of the sample, normal Hall voltages are observed. The study concludes that the discrepancies in R_{H} reported for Sony MOSFETs are real, device-dependent effects, but they

do not occur when V_{xx} is zero on both sides of the sample. Anomalous values of R_H were not observed when the *Technical Guidelines for Reliable Measurements of the Quantized Hall Resistance* were fully applied. The study concludes that the *Guidelines* are adequate as they stand.

5. International comparisons

5.1 On-site comparisons of basic reference standards using travelling Josephson array voltage standards and quantum Hall resistance standards

Dr Witt outlined the programme of international comparisons. To date, fifteen comparisons have been carried out with twelve different laboratories using the BIPM travelling Josephson array voltage standard system. The BIPM travelling QHR system has been used in comparisons with two laboratories, the BNM-LCIE and the OFMET.

Dr Reymann discussed the "Asian loop" of Josephson array comparisons (CCE/95-40). The comparison with the KRISS was performed in January 1995 with good agreement. The comparison with the MSL was performed in March 1995, again with good agreement, however some interference problems were encountered especially in the indirect comparisons. Next the comparison with the CSIRO was performed. During this comparison the cause of the interference was shown to be the power supply of the BIPM computer and the comparison was completed without the computer. The final results of all BIPM Josephson standard comparisons differ by less than 2 parts in 10^9.

Dr Kibble noted that these comparisons are an excellent process for disseminating the techniques of metrology and measurement.

Mr Delahaye reviewed the results of comparisons of the travelling quantized Hall system with the BNM-LCIE and the OFMET. The results of the BNM-LCIE comparison were presented at the CPEM'94 and have been published. The OFMET comparison (CCE/95-4) was completed in the fall of 1994. In each case, the agreement achieved was excellent. The results of measurements of a 100 Ω resistor with respect to each laboratory's QHR differed by less than 2 parts in 10^9; the results of measurements of the ratio of 10 kΩ to 100 Ω resistors differed by less than 3 parts in 10^9 and results of measurements of the ratio of 100 Ω to 1 Ω resistors differed by less than 4 parts in 10^9.

In response to a question from Prof. Tarbeyev, it was pointed out that there is no particular need to standardize the wiring of probes for these comparison systems. The outputs of all Josephson standards are normally adapted to measure a secondary standard. In a Josephson comparison, the

output from the second array simply replaces the secondary standard. The QHR comparisons are carried out using the BIPM travelling cryostat and magnet, and involve measuring a four-terminal resistor with each QHR system. A modest degree of compatibility is required for the BIPM's Josephson cryogenic probe. This is usually used in a He storage vessel for which the throat diameter must exceed 38 mm and the level of liquid He should range between 60 cm and 130 cm below the insertion port.

Dr Witt explained new criteria (CCE/95-2) being used to determine if specific future comparisons warrant the use of the travelling Josephson array system or the travelling quantized Hall resistance system. In each case the host laboratory should demonstrate measurement uncertainties below 1 part in 10^8, excluding the uncertainty associated with the secondary voltage standard. Dr Witt went on to add that, considering the cost in time and money, the BIPM staff anticipate carrying out only one or two QHR and Josephson comparisons a year in the near future.

5.2 Conventional travelling standards for electrical quantities

Dr Witt noted that the BIPM has had extensive experience in the use of Zener voltage standards and drew attention to the influence of electromagnetic interference and humidity on some standards. He went on to note that Mr B. Pritchard at the CSIRO has observed hysteresis in Leeds & Northrup 1 Ω resistors due to temperature cycling. Following a moderate increase in temperature, the value of one resistor changed by 1,5 parts in 10^7. This observation confirms the report of the PTB (CCE/92-59) at the 1992 CCE meeting.

Mr Small recounted the results of a comparison between the BIPM, the Gakushuin University and the CSIRO (CCE/95-47) using three CSIRO 1 Ω resistors. The scatter of the results from these three resistors was below 1 part in 10^8.

Dr Kibble indicated that the NPL and the NAMAS have gained some experience in the use of Andeen Hagerling capacitors as travelling standards. These 10 pF and 100 pF capacitors have shown good stability even when shipped without temperature stabilization.

Prof. Tarbeyev outlined the advantages and disadvantages of metal foil resistors manufactured in Russia and used as travelling resistance standards.

Dr Reymann recounted some of the problems in obtaining permission to ship thermostated and powered standards by air. While this can often be done in Europe, it is a particular problem on overseas travel. Dr Bachmair indicated that, by informing airlines in advance and accompanying the equipment in person, the PTB has had some success in gaining their cooperation, but this approach is not always practical. The President asked

the participants to report any progress on this problem and to add it to the agenda of the next CCE meeting.

5.3 Reports on international comparisons (at DC or low frequency AC) organized by the CCE

5.3.1 Comparison of inductance at 10 mH (pilot laboratory: PTB)

Dr Bachmair discussed the 10 mH comparison (CCE/95-36) in which eleven laboratories have completed their measurements. The agreement reported is within about 1 part in 10^5 and the long duration of the comparison does not seem to have compromised the quality of the results. The agreement seems better than it should be, given the uncertainty claims made by most of the laboratories.

5.3.2 Comparison 92-1 of 10 pF capacitors (pilot laboratory: NIST)

Dr Hebner stated that the 10 pF comparison has not yet begun but that the transfer standards have been chosen and completion is expected by the time of the CPEM in 1998.

5.3.3 Comparison 92-2 of AC power and energy, between 50 Hz and 60 Hz (pilot laboratory: NIST)

Dr Hebner stated that, while the comparison of AC power and energy at 50 Hz to 60 Hz had not yet begun, suitable transfer standards are being investigated. Dr Bachmair said that the PTB could supply a 5 A, 50 Hz standard for the EUROMET part of this comparison.

5.3.4 Comparison 92-3 of multi-junction AC/DC transfer devices (pilot laboratory: PTB)

Dr Bachmair reviewed the completed EUROMET portion of the comparison of multi-junction AC/DC transfer devices (CCE/95-35). The results are generally in good agreement (better than 1 part in 10^6 at 1 kHz) and the other laboratories are continuing the comparison. It was pointed out that this comparison also tests the coherence of AC resistance

standards. Dr Reymann commented that the laboratories appear to have over-estimated their uncertainties, given the close agreement of the results. Dr Wood congratulated the pilot laboratory (the PTB) on the regular and timely manner in which the comparison was progressing but expressed concern that the EUROMET portion of the results had been published before the comparison was completed in other countries. It was noted, in this connection, that only the deviations from the means had been published and that measurement results had not been divulged.

5.3.5 Comparison 92-4 of single junction thermal voltage converters, between 50 kHz and 100 kHz (pilot laboratory: BNM-LCIE)

Mr Érard referred to the progress report on the comparison of single junction thermal voltage converters at 50 kHz to 100 kHz (CCE/95-8), adding that it was proceeding smoothly and that a number of laboratories have completed their measurements.

5.3.6 Comparison 92-5 of single junction thermal voltage converters, between 1 MHz and 50 MHz (pilot laboratory: NMi-VSL)

Dr de Vreede stated that the comparison of single junction thermal voltage converters at frequencies from 1 MHz to 50 MHz is in progress (CCE/95-23) and noted that additional laboratories wishing to participate in this comparison are still free to do so.

5.4 Proposals for new comparisons to assure compatibility among national electrical standards

Prof. Tarbeyev suggested three possible comparisons. He indicated that a comparison of power and energy had been carried out involving the VNIIM and laboratories in Australia, Bulgaria, Finland and others; he felt it would be useful to extend this to other CCE countries. Dr de Vreede stated that this activity was included in comparison CCE 92-2 and there was no need for a separate new comparison. A later suggestion was to look at the possibility of linking the two comparisons.

Prof. Tarbeyev recommended a voltage comparison at 30 MHz to 1000 MHz but was reminded by Dr de Vreede that the comparison 92-6 already organized by the working group on radiofrequency quantities (GT-RF) covered this range. As this comparison was not yet completed, laboratories could still join it. Finally, Prof. Tarbeyev felt that there was

need for a working group to organize DC voltage comparisons at high voltages. Dr Bachmair stated that an EAL comparison at 10 kV was being organized and that there was a need for improved resistive divider travelling standards.

Noting that the BIPM cannot provide calibrations for all electrical quantities, Dr Kibble commented on the comparisons undertaken by the different regional metrology groups, pointing out that some countries have not joined any of these groups, among them most African countries. Mr Dressler said that, while South Africa is not a member of a regional metrology group, it has performed bilateral comparisons with the BNM-LCIE, the NPL, the PTB and the SP and thus maintains a link to EUROMET.

The CCE then took up the discussion of the question, raised by Dr Quinn in document CCE/95-41, of demonstrating the equivalence of national measurement standards. Dr Quinn, in reference to document CCE/95-57 (a document from the 18 and 19 May 1995 meeting of the EUROMET Committee), explained that there is a growing need for realistic demonstrations of the equivalence of national standards by means of a small number of key comparisons chosen to demonstrate competence in the principal techniques in each given field. This need is in part driven by the need to certify and accredit calibration activities throughout the world, but it also has an impact on the consistency of practical representations of units of the SI. He added that the key comparisons would have to be repeated at intervals but that, to avoid wasteful and needless repetition, they should be carried out on a multilateral basis. Since the people actively engaged in a field are the ones most qualified to identify the key comparisons and the intervals at which they should be repeated, he asked the CCE to address this question in the electrical area. He also pointed out that there is a need to document equivalence between laboratories, and asked the CCE to provide guidelines designed to assist the different national laboratories to document the equivalence of standards and calibration activities. He also suggested that, as is already done for BIPM comparisons, *Metrologia* could periodically publish summaries of results of key comparisons. He finished by stating that the objective of the CIPM, and hence of the BIPM, is to provide the scientific basis upon which equivalence is established.

A long discussion followed this presentation in which almost everyone participated. The topics of this discussion were varied and concerned: the scope of the key comparisons and how often they should be repeated; the differences between accreditation systems in different countries; the question of whether the equivalence of scaled values of quantities should be treated by direct comparison or by documentation; the role of regional metrology groups (such as EUROMET, NORAMET...); whether the term “equivalence” of standards is to be taken as meaning that we accept that different laboratories have different standards; the recognition of different

levels of uncertainty in the equivalence scheme; whether to recognize the standards, the metrologists, the measurement systems or the entire calibration process; and the need for documentation as proof of equivalence. To focus these concerns, an *ad hoc* working group was formed to prepare a more concise proposal for consideration by the CCE, this taking the form of a response to Dr Quinn's letter (CCE/95-41). The agreed *ad hoc* working group was: Dr Bachmair, Mr Érard, Dr Hebner (chairman), Dr Kaarls, Dr Witt and Dr Wood. It met at the close of the session on 14 June and reported back to the CCE at the opening session on 15 June. It had reached agreement on a short list of key comparisons, assigned to them three levels of priority and noted that most had already been carried out at least once. It identified three areas for which proposals for new comparisons should be formulated. These are: DC resistances of over 10^9 Ω, DC voltage ratio up to 1000 : 1, and a comparison of inductive voltage dividers.

Dr Quinn thanked the *ad hoc* working group, saying that theirs was the kind of response he had in mind when he wrote document CCE/95-41. The President decided that a regular CCE working group on international comparisons should be established and named the following laboratories as members: BIPM, BNM-LCIE, CSIRO-NML, IEN, NIST, NMi-VSL, NRC, PTB and VNIIM. He asked Dr Hebner to be chairman of the working group until the next CCE meeting. The working group was asked to meet immediately after the present CCE meeting to consider proposals for the new comparisons just identified and, if possible, to proceed with them.

Those present at the 1995 CCE consider that the results of the ensemble of recent, active and approved international comparisons organized by the CCE already constitute a basis for mutual recognition of measurement capabilities in DC, low frequency and high frequency electrical metrology. After discussing this ensemble in terms of "key comparisons" they attached a level of priority to each comparison on a scale in which 1 represents the highest priority. The agreed priorities are shown in brackets in the following list:

Key comparisons, DC and low frequency:

Voltage

- Josephson array comparisons (using the BIPM transportable apparatus) {1}
- DC voltage ratio 1 V : 1 000 V (or 10 V : 1 000 V), *new comparison* {2}
- AC voltage ratio using inductive voltage dividers, at up to 100 V, 400 Hz, *new comparison* {2}

Impedance

- Quantized Hall resistance (through the 1990 resistance comparison or the BIPM transportable apparatus) {1}

- High DC resistance exceeding 1 GΩ, *new comparison* {2}
- Capacitance 10 pF, 1592 Hz {2}
- Inductance 10 mH, 1000 Hz {2}
- AC resistance using the quantum Hall effect {4}

Power

- Power at a frequency in the range 50 Hz to 60 Hz, voltages from 120 V to 240 V and currents from 5 A to 50 A {3}

AC/DC transfer

- AC/DC transfer at voltages between 1 V and 10 V, at a discrete set of frequencies between 100 Hz and 1 MHz {1}
- AC/DC transfer at 100 V, at a discrete set of frequencies between 1 kHz and 1 MHz {3}

Key comparisons, radiofrequency:

The report of the meeting of the GT-RF on 12 and 13 June 1995 is given after the CCE report (*see* on page E 62). The GT-RF has named a sub-group to identify the key comparisons in its area. Key topics for comparison have already been identified: these are the new comparison mentioned in Table IV and the topics listed in Table V as suitable subjects for future comparisons.

Representatives of the member laboratories of the working group on international comparisons met at the end of the CCE meeting. The agenda agreed for this meeting listed five items:

1. Publication of a summary of results of previous comparisons;
2. Discussion of the list of comparisons;
3. Consideration of how often key comparisons should be repeated;
4. Guidelines for carrying out CCE comparisons;
5. Selection of pilot laboratories for the three newly proposed comparisons.

6. Report on the meeting of the working group on radiofrequency quantities

Mr Érard, chairman of the working group on radiofrequency quantities, presented the report of the group's meeting held at the BIPM on 12 and 13 June 1995. The text is given at the end of this report.

7. Activities of the Electricity section of the BIPM

7.1 Comparisons of Josephson and quantum Hall standards via transportable instruments

Dr Witt reported on the work of the Electricity section of the BIPM (CCE/95-1 to 6), drawing particular attention to the international comparisons of Josephson arrays and quantized Hall resistances. These items had already been considered in sections 5.1 and 5.2.

7.2 The BIPM programme of bilateral comparisons of electrical standards using conventional travelling standards

Dr Witt explained the process of bilateral comparisons (CCE/95-3) as implemented at the BIPM. In this procedure a national metrology institute provides its best estimate of the value and uncertainty of a travelling resistance or voltage standard, both before and after calibration at the BIPM. The institute is also requested to indicate if the results of the comparison will be used to change its national reference standard and in what manner this will be done. With the agreement of the institute, the results are published in *Metrologia* and the *Procès-Verbaux du CIPM*. As Dr Witt explained, this process ensures and publicly documents traceability between the laboratory and the BIPM. To date, seven bilateral comparisons have been carried out and three more are presently under way. The first set of tabulated results has been published in *Metrologia*, 1994, **31**, 63-68.

A discussion ensued concerning the meaning and use of the word “traceability”. Dr Hebner was specifically concerned that, in the USA, a calibration from the NIST still provides the client with traceability. It was evident from the discussion that in different countries the word “traceability” is used in different contexts.

7.3 Calibrations

7.3.1 Improvements in voltage and resistance calibrations

Dr Witt outlined improvements (CCE/95-1) in the BIPM automated standard cell comparator. He also mentioned humidity and noise studies of Zener-diode voltage standards used to characterize the quality of other standards.

7.3.2 Prospects for providing capacitance calibrations

Dr Witt indicated that work continues with the objective of establishing capacitance calibration capability, particularly at 10 pF. The BIPM 10 pF reference standard will be derived from the QHR via measurements at 1541 Hz. This project requires the development of a quadrature bridge to link multiples of the QHR to 2 nF capacitors, and a capacitance bridge to scale from 2 nF to 10 pF.

7.3.3 Proposal to change the reference temperature for standard cell and resistance calibrations at the BIPM from 20 °C to 23 °C

Dr Witt reviewed two documents providing information on a proposed change, from 20 °C to 23 °C, of the reference temperature used at the BIPM for standard cell and resistance calibrations. The first document (CCE/95-6) gives the results of a survey of the practices in the national laboratories. Then Dr Witt outlined the results of a summary of temperature coefficients (CCE/95-5) of 1 Ω and 10 kΩ resistors measured at the BIPM. The proposal to change room and oil-bath temperatures from 20 °C to 23 °C has practical advantages. For some types of resistors the change to 23 °C can reduce the temperature coefficient and so possibly improve the measurement results. Dr Marullo Reedtz presented a report (CCE/95-7) showing a change in the drift rate of a group of nine 1 Ω Thomas-type resistors following a change in the temperature (from 20 °C to 23 °C) of the oil bath in which they are kept. Laboratories contemplating a change in the maintained temperature of resistance standards were cautioned to anticipate such an effect.

Most laboratories indicated that they did not expect to be adversely affected by the change proposed by the BIPM. The participants agreed that the BIPM could change its reference temperatures if it so decided.

The BIPM will shortly take steps to change the reference temperature it uses for routine calibration and comparisons of resistance standards to 23 °C. Resistors under study will be maintained in air or oil at a nominal temperature of 23 °C. After further consideration of the practical consequences, the BIPM decided to keep 20 °C as the reference (and physical) temperature for naked standard cells, to avoid having to rebuild several temperature-regulated standard cell enclosures. The implementation of the new reference temperature for resistance will require some modification of the equipment for maintaining the temperatures of travelling standards. The dates from which the change will take effect will be announced later.

8. Future activities of the CCE

It was agreed that the working group on international comparisons should continue to oversee the status of international comparisons used for the purpose of recognizing the equivalence of national standards and calibration systems.

Dr Quinn asked that the electricity representatives of all regional metrology groups keep the BIPM and other regional metrology groups advised of activities relating to electricity, particularly activities relating to comparisons.

It was mentioned that NORAMET would try to set up a home page providing information on NORAMET activities on the world wide web.

It was proposed that the next meeting of the CCE should be held in 1997 but no date was set.

9. Other business

In closing, the President thanked the delegates and the BIPM staff for their participation in the meeting. He went on to wish everyone good luck in the continued progress of their work.

July 1995
Modified, September 1995

Report of the working group on radiofrequency quantities

The working group on radiofrequency quantities (GT-RF) met at the Bureau International des Poids et Mesures, Sèvres (France), on 12 and 13 June 1995.

Present: Mr L. ÉRARD, Chairman, Dr R. COOK (NPL), Dr R. HEBNER (NIST), Mr R. M. JUDISH (NIST), Mr M. W. SINCLAIR (NPL), Dr U. STUMPER (PTB), Dr J. P. M. DE VREEDE (NMi-VSL), Dr B. M. WOOD (NRC), Dr H. YAJIMA (ETL).

The Director of the BIPM, Dr T. J. QUINN.

Also present at the meeting: Dr T. J. WITT (BIPM).

Apologies for absence were received from Dr L. BRUNETTI (IEN) and Dr XI Dexiong (NIM).

Invited guests: Mr E. DRESSLER (NML) and Dr R. D. LEE (KRISS).

Absent: the representatives of the CSIRO, the OMH and the VNIIM.

The chairman welcomed the members of the working group. He read a message from the former chairman of the GT-RF, Mr A. E. Bailey, who sent his greetings to the meeting and his regrets that he was unable to attend.

The Director of the BIPM welcomed the participants and wished them a successful meeting.

The agenda was considered and approved.

Dr Witt was appointed rapporteur.

1. International comparisons completed since the last meeting of the working group (June 1992)

Eight comparisons have been completed and the results were discussed at the meeting: details are given in Table I.

2. Comparisons almost completed

The status of five comparisons, which were complete except for the preparation of the final reports, is given in Table II. Representatives of

the pilot laboratories affirmed that the final reports would be sent to the chairman and the BIPM before the end of 1995.

3. Progress on continuing comparisons

A summary of the state of progress of comparisons which were arranged in 1986 and 1992, and which are still active, is given in Table III. These should be completed before the end of 1997 so that the results may be presented at CPEM'98.

4. New comparisons and future work

The Director of the BIPM commented on the letter (CCE/95-41) he sent to those participating at the CCE meeting on the subject of equivalence between the primary measurement standards of national metrology institutes. He asked the help of all participants to identify the key multilateral comparisons needed to ensure equivalence, and to specify the intervals at which they should be repeated.

After a discussion which took into account both recently completed comparisons and those currently in progress, the working group proposed several key comparisons with different levels of priority:

- One key comparison was agreed by the participants; the details are given in Table IV;
- Some details of the future key comparisons are listed in Table V.

One sub-group made up of R. Cook, L. Érard, R. M. Judish, U. Stumper and J. P. M. de Vreede, will prepare a list of the comparisons completed by the GT-RF over the last twenty years. This list will be helpful in determining which comparisons should be considered key, in the sense of document CCE/95-41, and the appropriate intervals at which they should be repeated.

5. Coordination of GT-RF comparisons with those of other groups

Mr Érard reminded the pilot laboratories of GT-RF comparisons that one of their tasks is to serve as relays to regional groups of national metrology institutes in order to avoid duplication of comparisons. Dr Wood will inform NORAMET.

Mr Érard informed the working group of two EUROMET comparisons in progress: power in a 50 Ω coaxial line (type N connector) over the band 10 MHz to 18 GHz and noise in a waveguide over the band 12,4 GHz to 18 GHz.

6. Other business

Mr Érard reminded participants that he sends an annual questionnaire on the progress of each comparison to the pilot laboratories. Pilot laboratories are strongly urged to answer the questionnaire.

Mr Érard reminded the participants that the calculations of uncertainties should follow the recommendations of the ISO *Guide to the expression of uncertainty in measurement*.

Dr Witt mentioned the possibility of publishing short summaries of the results of GT-RF comparisons in *Metrologia*.

7. Date of the next meeting

For its next meeting the group proposed either Gaithersburg in 1998, shortly before or after CPEM'98, or in 1997 just before the next CCE meeting but no date was set.

June 1995

Rapporteur	Chairman
T. J. WITT	L. ÉRARD

TABLE I

Comparisons completed since the last meeting of the working group
(June 1992)

75-A4 Reflection coefficient in 50 Ω coaxial line at 500 MHz, 3 GHz and 7 GHz.
(Pilot laboratory: PTB; participants: CSIRO, ETL, NIM, NIST, NPL, NRC, OMH, SMU, SNIIM).
The final report was presented at the meeting. The results were presented at the CPEM'94 in Boulder. The final report was published in *IEEE Trans. Instrum. Meas.*, 1995, **44**, 985-990.

75-A6 Voltage (100 V) in 50 Ω coaxial line at 30 MHz.
(Pilot laboratory: PTB; participants: NIST, NPLI).
The final report was presented at the meeting. The results were presented at the CPEM'94 in Boulder. The final report was published in *IEEE Trans. Instrum. Meas.*, 1995, **44**, 312-315.

75-A7 Voltage (1 mV) in 50 Ω coaxial line at 30 MHz.
(Pilot laboratory: PTB; participants: ex ASMW, NIM, NIST, NPLI, OMH, TF).
The final report was presented at the meeting. The results were presented at the CPEM'94 in Boulder. The final report was published in *IEEE Trans. Instrum. Meas.*, 1995, **44**, 312-315.

75-A11 Power in coaxial line at 12 GHz, 14 GHz and 17 GHz: effective efficiency of bolometer mounts with APC-7 connectors.
(Pilot laboratory: PTB; participants: BNM-LCIE, CSIRO, IEN, NIST, NMi-VSL, NRC, OMH).
The final report was presented at the meeting. It was published in *IEEE Trans. Instrum. Meas.*, 1994, **43**, 3-6.

75-B3 Reflection coefficient in 75 Ω coaxial line at 1 GHz.
(Pilot laboratory: NRC; participants: BNM-LCIE, NMi-VSL, NPL, OMH, PTB, SMU, TF).
The final report was presented at the meeting. The results were presented at the CPEM'94 in Boulder. The final report will be published in *IEEE Trans. Instrum. Meas.* in February 1996.

86-4 Laser power at 1,3 μm and 1,55 μm.
(Pilot laboratory: NIST; participants: CSELT, CSIC, CSIRO, ETL, BNM-INM, NMi-VSL, NPL, NPRL, NRC, OMH, PTB, SP).
The results were presented at the CPEM'92. The final report was published in *Appl. Opt.*, 1992, **31**, 7226-7231.

86-6 Power in waveguide R 220 at 20 GHz: effective efficiency of bolometer mounts.
(Pilot laboratory: BNM-LCIE; participants: NIST, NPL, NRC, PTB).
The final report was presented at the meeting and an effort will be made to publish it: one possibility is a short communication in *Metrologia*.

86-8 Attenuation (< 25 dB) in waveguide R 320 at 27 GHz, 35 GHz and 40 GHz.
(Pilot laboratory: NPL; participants: BNM-LCIE, NRC, PTB).
The final report was presented at the meeting. A summary will be published in *Metrologia* and the whole report will appear elsewhere.

TABLE II

Comparisons nearly completed

78-5 Horn gain and transverse polarization ratio at 8 GHz and 12 GHz.
(Pilot laboratory: NIST; participants: CNET, CSIRO, FTZ, NMi-VSL, NPL, TUD; the ETL, IEN and NRC withdrew).
The final report is required before the end of October 1995.

78-13 Noise power in waveguide R 100.
(Pilot laboratory: NPL; participants: BNM-LCIE, CSIRO, NIM, NIST, PTB).
All laboratories have completed their measurements.
The final report will be available in October 1995.

83-4 Measurements of scattering coefficients (*S* parameters) by broad-band methods over the band 2 GHz – 18 GHz.
(Pilot laboratory: NPL; participants: BNM-LCIE, CSIRO, NIST, NMi-VSL, PTB, SPTT, TF).
All laboratories have completed their measurements.
The final report is in preparation and will be available before the end of 1995.

86-2 *Q*-factor at frequencies up to 30 MHz.
(Pilot laboratory: NIST; participants: BNM-LCIE, Marconi Instrum., PTB, SESC).
The final report will be available in October 1995.

86-3 Complex reflection coefficient in waveguide R 320 at 27 GHz, 35 GHz and 40 GHz.
(Pilot laboratory: NPL; participants: BNM-LCIE, CSIRO, NIM, NIST, PTB).
All laboratories have completed their measurements.
The final report will be available in October 1995.

TABLE III

Comparisons in progress

a. Comparison discontinued

After reviewing the state of progress and the degree of interest shown, the working group decided that the following comparison should be discontinued.

92-5 Measurement of dielectric constant of liquids at frequencies up to 10 GHz.
(Pilot laboratory: NPL).

b. Continuing comparisons*

86-1 Power flux density at 2,45 GHz and 10 GHz.
Electric field strength between 300 MHz and 1000 MHz.
(Pilot laboratory: NIST; participants: CRL, KRISS, JQA, KEC, ETL, PTB, IEN, NMi-VSL, NPL, BNM-LCIE, ARCS).
The travelling standards are presently in the European loop. Participants were reminded that only one laboratory per country should participate in the comparison. This should be either the national laboratory or another laboratory acting as such for the purpose of this comparison.

92-1 Horn antenna gain in IEC R 320 waveguide over the band 26,4 GHz – 40 GHz.
(Pilot laboratory: NPL; participants: NMi-VSL, BNM-LCIE, KRISS, CSIRO**, NIST**).
The comparison is scheduled to start before the end of 1995.

92-2 Noise power in 50 Ω coaxial line (type N connector) at 30 MHz and 4 GHz.
(Pilot laboratory: NIST; participants: CSIRO**, BNM-LCIE, NPL, NRC**, PTB, KRISS).
It is expected that the comparison will start during the third trimester of 1995 and that results will be available for the CPEM'98.

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* Where possible, in this section, the order of participating laboratories corresponds to the order of shipment of the travelling standards.

** The participation of this laboratory has yet to be confirmed.

92-3 Measurement of scattering coefficients (*S* parameters) by the broad-band method over the band 2 GHz – 18 GHz (type N connector).
(Pilot laboratory: NPL; participants: CSIRO, IEN**, BNM-LCIE, NIST, NRC**, NML, PTB, SPTT, NMi-VSL, KRISS).
The comparison will start after the completion of comparison 83-4.

92-4 Power in waveguide R 320: effective efficiency of bolometer mounts at 33 GHz.
(Pilot laboratory: BNM-LCIE; participants: NIST, NRC, KRISS, CSIRO, PTB, NMi-VSL).
The travelling standards are now at the KRISS.

92-6 Voltage (1 V) in 50 Ω coaxial line at frequencies between 1 MHz and 300 MHz
(Pilot laboratory: NMi-VSL; participants: CSIRO, IEN, BNM-LCIE, NIST, NPL, NRC, PTB, KRISS).
Arrangements for the comparison will be completed before the end of 1995 and the comparison will begin in early 1996.

92-7 Antenna factor at frequencies between 5 kHz and 30 MHz.
(Pilot laboratory: NPL; participants: NIST, NMi-VSL, IEN**, CSIRO**, KRISS, PTB).
The comparison will start soon.

92-8 Antenna factor at frequencies between 30 MHz and 1000 MHz.
(Pilot laboratory: NPL; participants: NIST, CSIRO, ETL, KRISS).

TABLE IV

New comparison

95-1 Power in waveguide R 500: effective efficiency of bolometer mounts at 45 GHz and 62 GHz.
(Pilot laboratory: BNM-LCIE; participants: NIST**, NPL).

TABLE V

Possible future topics for comparisons

Priority 1

T1 Measurement of scattering coefficients (*S* parameters) over the frequency band 2 GHz – 18 GHz (3,5 mm connector).

Priority 2

T2 Impedance over the frequency band 1 MHz to 100 MHz.

T3 Noise in waveguides at frequencies above 18 GHz.

T4 Attenuation at frequencies above 50 GHz.

T5 Power in 50 Ω coaxial line with bolometer mounts equipped with type N connectors.

APPENDIX E 1

Working documents
submitted to the CCE at its 20th meeting

(*see* the list of documents on page E 29)

ANNEXE E 1

Documents de travail présentés à la 20e session du CCE

Ces documents de travail peuvent être obtenus dans leur langue originale sur demande adressée au BIPM.

Document CCE/	
95-1	BIPM. — Work of the Electricity Section of the BIPM for the period October 1991 - September 1994, Extract of the Director's Report on the Activity and Management of the Bureau International des Poids et Mesures, 12 p.
1 bis	Work of the Electricity Section of the BIPM for the period October 1994 - September 1995, Extract of the Director's Report on the Activity and Management of the Bureau International des Poids et Mesures, 6 p.
95-2	BIPM. — BIPM On-site Comparisons of Quantum Electrical Standards, 3 p.
95-3	BIPM. — The BIPM Program of Bilateral Comparisons of Electrical Standards Using Conventional Traveling Standards, by T. J. Witt, 4 p.
95-4	BIPM, OFMET (Suisse). — Comparison of Quantum Hall Effect Resistance Standards of the OFMET and the BIPM, by F. Delahaye, T. J. Witt, B. Jeckelmann and B. Jeanneret, 9 p.
95-5	BIPM. — Statistical Summary of the Temperature Characteristics of 1 Ω and 10 kΩ Resistors Measured at the BIPM, by T. J. Witt, 5 p.
95-6	BIPM. — Results of the Questionnaire on a Possible Change of Maintained and Reference Temperatures of BIPM Electrical Standards, by T. J. Witt, 5 p.
95-7	IEN (Italie). — Change in drift of the IEN primary group of standard resistors following the change of their working temperature, by G. Boella and G. Marullo Reedtz, 4 p.
95-8	BNM-LCIE (France). — CCE comparison 92-4 of transfer devices (EUROMET Project No 266), by A. Poletaeff, 3 p.

Document CCE/

95-9 BNM-LCIE (France). — EUROMET meeting on single electron tunneling devices and quantum current standards – Minutes for 2nd meeting 8-9 March 1994, 2 p.

95-10 BNM-LCIE (France). — Progress in the domain of the volt metrology at the BNM-LCIE, by G. Genevès and J.-P. Lo-Hive, 2 p.

95-11 BNM-LCIE (France). — Developments in the quantum Ohm metrology at BNM-LCIE, by F. Piquemal and G. Genevès, 31 p.

95-12 VNIIM (Féd. de Russie), BNM-LCIE (France), NRLM (Japon). — On the program of accurate electrical measurements with superconducting system of magnetic levitation intended to refine the values of the Planck constant and elementary charge, by E. T. Frantsuz, V. M. Khavinson, G. Genevès, F. Piquemal, F. Shiota and Y. Miki, 20 p.

95-13 NIM (Rép. pop. de Chine). — A Recent Determination for the SI Values of γ'_p and $2e/h$ at NIM, by Liu Ruimin, Liu Hengji, Jin Tiruo, Lu Zhirong, Du Xianhe, Xue Shouqing, Kong Jingwen, Yu Baijiang, Zhou Xianan, Liu Tiebin and Zhang Wei, 9 p.

95-14 EUROMET. — Progress Report CCE-comparison 92-3/ EUROMET Project, 1 p.

95-15 KRISS (Rép. de Corée). — General progress report in electrical measurements at KRISS, by Rae Duk Lee, 8 p.

95-16 KRISS (Rép. de Corée). — List of documents submitted to the CCE, 1 p.

95-17 KRISS (Rép. de Corée), VNIIM (Féd. de Russie). — Atom magnetic resonance based current source, by V. Ya Shifrin, C. G. Kim, B. C. Woo and P. G. Park, 4 p.

95-18 KRISS (Rép. de Corée), VNIIM (Féd. de Russie). — High uniform single current solenoid corrected by two turns, by C. G. Kim, V. Ya Shifrin, P. G. Park and B. C. Woo, 3 p.

95-19 KRISS (Rép. de Corée), VNIIM (Féd. de Russie). — Adjustable Capacitor for Absolute Measurement of Loss Angle, by Rae Duk Lee, Han Jun Kim and Y. P. Semenov, 7 p.

95-20 MSL (Nouvelle-Zélande). — Electrical Measurements at the Measurement Standards Laboratory of New Zealand, by K. Jones and L. A. Christian, 1 p.

95-21 MSL (Nouvelle-Zélande). — New Zealand's 1 V Josephson Array Voltage Standard, by L. A. Christian, 5 p.

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95-22 NMi-VSL (Pays-Bas). — General progress report of VSL during 1992-1995, by J. P. M. de Vreede, 2 p.

95-23 NMi-VSL (Pays-Bas). — Status report on CCE intercomparison 92-5, by C. van Mullem and J. P. M. de Vreede, 1 p.

95-24 ETL (Japon). — Report to the CCE (Comitte Consultatif Electrique) from Electrotechnical Laboratory (ETL) on the activities of DC/LF Electricity Standards in Japan – Activity during the period June 1993-April 1995, 5 p.

95-25 NRLM (Japon). — Abstract: Determination of the Avogadro constant by the XRCD method, Magnetic levitation, 2 p.

95-26 Report of the C.C.E. working group on electrical methods to monitor the stability of the kilogram, by B. P. Kibble, 2 p.

95-27 OFMET (Suisse). — List of Publications Submitted to the CCE by the OFMET, Wabern, Switzerland, 1 p.

95-28 NIM (Rép. pop. de Chine). – List of Publications Submitted to the CCE by the NIM, Beijing, China, 1 p.

95-29 NPL (Royaume-Uni). — The N.P.L. Kilogram-monitoring project, by I. A. Robinson and B. P. Kibble, 2 p.

95-30 NRC (Canada), OFMET (Suisse). — Reproducibility of the quantised Hall effect, and the CCE guidelines, by A. D. Inglis, B. Jeckelmann and B. Jeanneret, 6 p.

95-31 PTB (Allemagne). — List of Publications Submitted to the CCE by the Physikalisch-Technische Bundesanstalt (PTB), Braunschweig, Germany, 1 p.

95-32 PTB (Allemagne). — Development of a Hybrid Integrated Josephson Voltage Standard Operated at 10 GHz, by F. X. Hebrank, E. Vollmer, T. Funck, P. Gutmann and J. Niemeyer, 1 p.

95-33 PTB (Allemagne). — Determination of the Fine-Structure Constant by a Precise Measurement of h/m_n, by E. Krüger, W. Nistler and W. Weirauch, *Metrologia*, 1995, **32**, 117-128.

95-34 PTB (Allemagne). — Automated Characterization of Quantum Hall Effect Samples in Compliance with the Technical Guidelines, by B. Schumacher, 5 p.

95-35 PTB (Allemagne). — Intermediate report on the CCE Comparison 92-3 of multijunction ac-dc transfer devices (Euromet Project 274: ac-dc voltage transfer at lowest level of uncertainty), by M. Klonz, 12 p.

95-36 PTB (Allemagne). — International Comparison of 10 mH Inductance Standards, by H. Eckardt, 6 p.

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95-37 NPL (Royaume-Uni). — On the Mutual Recognition of Standards and Measurements between Countries, by B. P. Kibble, 1 p.

95-38 NIST (É.-U. d'Amérique). — Present Status of SI Values of K_J and R_K, by B. N. Taylor and P. J. Mohr, 8 p.

95-39 ETL (Japon). — Lettre de T. Endo du 6 juin 1995 sur "Mercury Battery Supply and Purchase from Panasonic", 2 p.

95-40 BIPM, KRISS (Rép. de Corée), MSL (Nouvelle-Zélande), NML (Australie). — Comparisons of the Josephson Voltage Standard of the BIPM with those of the KRISS, the MSL and the NML, by D. Reymann, K.-T. Kim, L. A. Christian, R. B. Frenkel and T. J. Witt, 7 p.

95-41 BIPM. – Lettre de T. J. Quinn du 22 mai 1995 sur "Equivalence between the primary measurement standards of national metrology institutes", 2 p.

95-42 EUROMET. — Final Summary Report of Comparison "Metrology of ^{192}Ir Brachytherapy Sources", 1 p.

95-43 IEN (Italie). — On the electrometric approach to the comparison of electrical and mechanical power or energy, by F. Cabiati, 3 p.

95-44 International Commission on Non-Ionizing Radiation Protection (Italie). — Guidelines on limits of exposure to static magnetic fields, *Health Physics*, 1994, **66**, 1, 100-106.

95-45 IEN (Italie). — List of Publications Submitted to the CCE by IEN, Torino, Italy, 2 p.

95-46 SP (Suède). — General progress report on electrical metrology at the Swedish National Testing and Research Institute, SP, by H. Nilsson, 5 p.

95-47 CSIRO (Australie). — The 1995 SI determination of R_K in terms of the NML calculable capacitor, by G. W. Small, B. W. Ricketts, P. C. Coogan, B. J. Pritchard and M. M. R. Sovierzoski, 3 p.

95-48 PTB (Allemagne). — Devices for manipulating single electrons, by J. Niemeyer, 8 p.

95-49 PTB (Allemagne). — Technology of the Fabrication and Experimental Investigation of Basic RSFQ Circuits, by R. Dolata, M. I. Khabipov, F.-Im. Buchholz, W. Kessel and J. Niemeyer, 8 p.

95-50 VNIIM (Féd. de Russie). — New link between the national standards of electrical resistance and capacitance at IMM, by A. Ploshinsky and Yu. Semyonov, 4 p.

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95-51 VNIIM (Féd. de Russie). — List of Publications Submitted to the CCE by the D. I. Mendeleyev Institute for Metrology (VNIIM), St. Petersburg (Russia), 1 p.

95-52 VNIIM (Féd. de Russie), KRISS (Rép. de Corée). — Some results of the development of a new system of interrelation between the standards of the farad and the ohm, by Yu. P. Semyonov, T. F. Frudko, A. V. Ploshinsky, B. Ya. Litvinov, I. Ya. Klebanov, M. D. Klionsky, O. A. Shvedov, Rae Duk Lee and Han Jun Kim, 19 p.

95-53 Pennsylvania State University (É.-U. d'Amérique), Petersburg Nuclear Physics Institute, VNIIM (Féd. de Russie). — Corrections of order $\alpha^2(Z\alpha)^5$ to hyperfine splitting and Lamb shift, by M. I. Eides and V. A. Shelyuto, 23 p.

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95-55 BNM-LCIE (France). — Proposal of key measurements for demonstrating equivalence of standards, by L. Érard, 1 p.

95-56 BNM-LCIE (France). — LEP QHE samples, 2 p.

95-57 EUROMET. — Guidance on Accreditation of National Metrology Institutes and Certification of their Quality Systems, 4 p.

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