COMITÉ CONSULTATIF D'ÉLECTRICITÉ

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BUREAU INTERNATIONAL DES POIDS ET MESURES

COMITÉ CONSULTATIF D'ÉLECTRICITÉ

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Liste des sigles utilisés dans le volume

ASMW	Amt für Standardisierung, Messwesen und Warenprüfung, Berlin (Rép. dém. allemande)
BCR	Bureau communautaire de référence de la Communauté économique européenne
BIPM	Bureau international des poids et mesures, Sèvres (France)
BNM	Bureau national de métrologie, Paris (France)
CCE	Comité consultatif d'électricité
CCITT	Comité consultatif international télégraphique et téléphonique
CCPR	Comité consultatif de photométrie et radiométrie
CEI	Commission électrotechnique internationale, Genève (Suisse)
CEN	Comité européen de normalisation
CENELEC	Comité européen de normalisation électrotechnique
CGPM	Conférence générale des poids et mesures
CIPM	Comité international des poids et mesures
CODATA	Committee on Data for Science and Technology
COST	Coopération européenne scientifique et technique
CPEM	Conference on Precision Electromagnetic Measurements
CSELT	Centro Studi Elettronica e Telecommunicazioni, Turin (Italie)
CSIC	Consejo Superior de Investigaciones Cientificas, Madrid (Espagne)
CSIR/DPT	Division of Production Technology, Pretoria (Afrique du Sud) *Voir aussi* NPRL
CSIRO	CSIRO, Division of Applied Physics, Lindfield (Australie)
CSMU	Československý Metrologický Ústav, Bratislava et Prague (Tchécoslovaquie)
ETL	Electrotechnical Laboratory, Tsukuba (Japon)
FFV	Maintenance Division, National Industries Corporation, Arboga (Suède)
FTZ	Fernmelde Technische Zentral Amt, Darmstad (Rép. féd. d'Allemagne)
GT-RF	Groupe de travail pour les grandeurs aux radiofréquences
GU	Gakushuin University, Tokyo (Japon)
IEN	Istituto Elettrotecnico Nazionale Galileo Ferraris, Turin (Italie)
IMM	*Voir* VNIIM
IMS	Institute of Metrological Services, Moscou (URSS)
INM	Institut national de métrologie, Paris (France)

INM	Institut national de métrologie, Bucarest (Roumanie)
INTI	Instituto Nacional de Tecnología Industrial, Buenos Aires (Argentine)
IOM	Instituto de Optica Daza de Valdés, Madrid (Espagne)
IRT	Institut de recherches des télécommunications, Budapest (Hongrie)
LCIE	Laboratoire central des industries électriques, Fontenay-aux-Roses (France)
NBS *	National Bureau of Standards, Gaithersburg (É.-U. d'Amérique)
NIM	Institut national de métrologie, Beijing (Rép. pop. de Chine)
NIST	National Institute of Standards and Technology, Gaithersburg (É.-U. d'Amérique)
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 aussi* CSIR
NRC	Conseil national de recherches du Canada, Ottawa (Canada)
OFMET	Office fédéral de métrologie, Wabern (Suisse)
OMH	Orszagos Mérésügyi Hivatal, Budapest (Hongrie)
PKN	Polski Komitet Normalizaci, Miar i Jacosci, Varsovie (Pologne)
PTB	Physikalisch-Technische Bundesanstalt, Braunschweig (Rép. féd. d'Allemagne)
RIND	Institut de recherches de la défense, Stockholm (Suède)
RSRE	(ancien RRE), Royal Signals and Radar Establishment, Malvern (Royaume-Uni)
SESC	(ancien EQD), Service Electrical Standards Centre, Bromley (Royaume-Uni)
SNIIM	Institut de recherche scientifique sibérien en métrologie, Moscou (URSS)
SNTI	*Voir* SP
SP	Statens Provningsanstalt, Borås (Suède)
TTL	(ancien PTF), Telelutkimuslaitos, Helsinki (Finlande)
TUD	Technical University of Denmark, Lyngby (Danemark)
URSI	Union radioscientifique internationale
VNIIFTRI	Institut des mesures physicotechniques et radiotechniques, Moscou (URSS)
VNIOOFI	Institut de recherche pour les mesures optiques et physiques, Moscou (URSS)
VNIIM	Institut de métrologie V. I. Mendéléev, Leningrad (URSS)
VSL	Van Swinden Laboratorium, Delft (Pays-Bas)

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* Depuis le 23 août 1988, ce laboratoire est devenu le National Institute of Standards and Technology [NIST].

LE BIPM
ET LA CONVENTION DU MÈTRE

Le Bureau international des poids et mesures (BIPM) a été créé par la Convention du Mètre signée à Paris le 20 mai 1875 par dix-sept États, lors de la dernière séance de la Conférence diplomatique du Mètre. Cette convention a été modifiée en 1921.

Le Bureau international a son siège près de Paris, dans le domaine (43 520 m^2) du Pavillon de Breteuil (Parc de Saint-Cloud) mis à sa disposition par le Gouvernement français ; son entretien est assuré à frais communs par les États membres de la Convention du Mètre (¹).

Le Bureau international a pour mission d'assurer l'unification mondiale des mesures physiques ; il est chargé :

— d'établir les étalons fondamentaux et les échelles des principales grandeurs physiques et de conserver les prototypes internationaux ;

— d'effectuer la comparaison des étalons nationaux et internationaux ;

— d'assurer la coordination des techniques de mesure correspondantes ;

— d'effectuer et de coordonner les déterminations relatives aux constantes physiques qui interviennent dans les activités ci-dessus.

Le Bureau international fonctionne sous la surveillance exclusive du Comité international des poids et mesures (CIPM), placé lui-même sous l'autorité de la Conférence générale des poids et mesures (CGPM).

La Conférence générale est formée des délégués de tous les États membres de la Convention du Mètre et se réunit actuellement tous les quatre ans. Elle reçoit à chacune de ses sessions le rapport du Comité international sur les travaux accomplis, et a pour mission :

— de discuter et de provoquer les mesures nécessaires pour assurer la propagation et le perfectionnement du Système international d'unités (SI), forme moderne du Système métrique ;

— de sanctionner les résultats des nouvelles déterminations métrologiques fondamentales et d'adopter les diverses résolutions scientifiques de portée internationale ;

— d'adopter les décisions importantes concernant l'organisation et le développement du Bureau international.

Le Comité international est composé de dix-huit membres appartenant à des États différents ; il se réunit actuellement tous les ans. Le bureau de ce Comité adresse aux Gouvernements des États membres de la Convention du Mètre un rapport annuel sur la situation administrative et financière du Bureau international.

Limitées à l'origine aux mesures de longueur et de masse et aux études métrologiques en relation avec ces grandeurs, les activités du Bureau international ont été étendues aux étalons de mesure électriques (1927), photométriques (1937) et des rayonnements ionisants (1960). Dans ce but, un agrandissement des premiers laboratoires construits en 1876-1878 a eu lieu en 1929 et deux nouveaux bâtiments ont été construits en 1963-1964 pour les laboratoires de la section des rayonnements ionisants.

(¹) Au 31 décembre 1988, quarante-sept États sont membres de cette Convention : Afrique du Sud, Allemagne (Rép. fédérale d'), Allemande (Rép. démocratique), Amérique (É.-U. d'), Argentine (Rép.), Australie, Autriche, Belgique, Brésil, Bulgarie, Cameroun, Canada, Chili, Chine (Rép. pop. de), Corée (Rép. de), Corée (Rép. pop. dém. de), Danemark, Dominicaine (Rép.), Égypte, Espagne, Finlande, France, Hongrie, Inde, Indonésie, Iran, Irlande, Israël, Italie, Japon, Mexique, Norvège, Pakistan, Pays-Bas, Pologne, Portugal, Roumanie, Royaume-Uni, Suède, Suisse, Tchécoslovaquie, Thaïlande, Turquie, U.R.S.S., Uruguay, Venezuela, Yougoslavie.

Une quarantaine de physiciens ou techniciens travaillent dans les laboratoires du Bureau international. Ils y font principalement des recherches métrologiques, des comparaisons internationales des réalisations des unités et des vérifications d'étalons dans les domaines mentionnés ci-dessus. Ces travaux font l'objet d'un rapport annuel détaillé qui est publié avec les procès-verbaux des séances du Comité international. La dotation annuelle du Bureau international est de l'ordre de 17 000 000 francs-or (en 1988), soit environ 31 000 000 de francs français.

Devant l'extension des tâches confiées au Bureau international, le Comité international a institué depuis 1927, sous le nom de comités consultatifs, des organes destinés à le renseigner sur les questions qu'il soumet, pour avis, à leur examen. Ces comités consultatifs, qui peuvent créer des groupes de travail temporaires ou permanents pour l'étude de sujets particuliers, sont chargés de coordonner les travaux internationaux effectués dans leurs domaines respectifs et de proposer des recommandations concernant les unités, en vue des décisions que le Comité international est amené à prendre directement ou à soumettre à la sanction de la Conférence générale pour assurer l'unification mondiale des unités de mesure.

Les comités consultatifs ont un règlement commun (*BIPM Proc.-verb. Com. int. poids et mesures*, **31**, 1963, p. 97). Chaque comité consultatif, dont la présidence est généralement confiée à un membre du Comité international, est composé de délégués de chacun des grands laboratoires de métrologie et des instituts spécialisés dont la liste est établie par le Comité international, de membres individuels désignés également par le Comité international et d'un représentant du Bureau international. Ces comités tiennent leurs sessions à des intervalles irréguliers ; ils sont actuellement au nombre de huit :

1. Le Comité consultatif d'électricité (CCE), créé en 1927.
2. Le Comité consultatif de photométrie et radiométrie (CCPR), nouveau nom donné en 1971 au Comité consultatif de photométrie (CCP) créé en 1933 (de 1930 à 1933 le Comité précédent (CCE) s'est occupé des questions de photométrie).
3. Le Comité consultatif de thermométrie (CCT), créé en 1937.
4. Le Comité consultatif pour la définition du mètre (CCDM), créé en 1952.
5. Le Comité consultatif pour la définition de la seconde (CCDS), créé en 1956.
6. Le Comité consultatif pour les étalons de mesure des rayonnements ionisants (CCEMRI), créé en 1958. En 1969, ce comité consultatif a institué quatre sections : Section I (Rayons X et γ, électrons), Section II (Mesure des radionucléides), Section III (Mesures neutroniques), Section IV (Étalons d'énergie α) ; cette dernière section a été dissoute en 1975, son domaine d'activité étant confié à la Section II.
7. Le Comité consultatif des unités (CCU), créé en 1964 (ce comité consultatif a remplacé la « Commission du système d'unités » instituée par le CIPM en 1954).
8. Le Comité consultatif pour la masse et les grandeurs apparentées (CCM), créé en 1980.

Les travaux de la Conférence générale, du Comité international, des comités consultatifs et du Bureau international sont publiés par les soins de ce dernier dans les collections suivantes :

— *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 ;*

— *Recueil de travaux du Bureau international des poids et mesures* (ce recueil hors commerce rassemble les articles publiés dans des revues et ouvrages scientifiques et techniques, ainsi que certains travaux publiés sous forme de rapports multicopiés).

Le Bureau international publie aussi des monographies sur des sujets métrologiques particuliers et, sous le titre « *Le Système international d'unités (SI)* », une brochure remise à jour périodiquement qui rassemble toutes les décisions et recommandations concernant les unités.

La collection des *Travaux et mémoires du Bureau international des poids et mesures* (22 tomes publiés de 1881 à 1966) a été arrêtée en 1966 par décision du Comité international.

Depuis 1965 la revue internationale *Metrologia*, éditée sous les auspices du Comité international des poids et mesures, publie des articles sur les principaux travaux de métrologie scientifique effectués dans le monde, sur l'amélioration des méthodes de mesure et des étalons, sur les unités, etc., ainsi que des rapports concernant les activités, les décisions et les recommandations des organes de la Convention du Mètre.

Comité international des poids et mesures

Secrétaire	*Président*
J. DE BOER	D. KIND

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Membres

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CSIR, DIVISION OF PRODUCTION TECHNOLOGY, Pretoria.

CSIRO, DIVISION OF APPLIED PHYSICS [CSIRO], Lindfield (Australie).

ELECTROTECHNICAL LABORATORY [ETL], Tsukuba (Japon).

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NATIONAL PHYSICAL LABORATORY [NPL], Teddington (Royaume-Uni).
OFFICE FÉDÉRAL DE MÉTROLOGIE [OFMET], Wabern (Suisse).
PHYSIKALISCH-TECHNISCHE BUNDESANSTALT [PTB], Braunschweig.
VAN SWINDEN LABORATORIUM [VSL], Delft (Pays-Bas).

Le directeur du BIPM (T. J. QUINN).

ORDRE DU JOUR

de la 18^{e} session

I. Nouvelles valeurs des représentations du volt et de l'ohm

A. Effet Josephson

- Présentation du rapport et des recommandations du Groupe de travail sur l'effet Josephson.
- Adoption d'une nouvelle valeur du quotient fréquence/tension à utiliser pour obtenir une représentation matérielle du volt fondée sur l'effet Josephson (première discussion).

B. Effet Hall quantique

- Rapport sur la comparaison internationale restreinte d'étalons de résistance d'un ohm effectuée par le BIPM en 1987.
- Présentation du rapport et des recommandations du Groupe de travail sur l'effet Hall quantique.
- Adoption d'une nouvelle valeur de la résistance de Hall quantifiée à utiliser pour obtenir une représentation matérielle de l'ohm fondée sur l'effet Hall quantique (première discussion).
- Élimination de la dérive des représentations actuelles de l'ohm antérieure au 1er janvier 1990.

C. Incidence de la promulgation de l'Échelle internationale de température de 1990 (EIT-90).

- Situation présente de l'EIT-90.
- Coordination de la mise en application des nouvelles valeurs des représentations matérielles des unités électriques et de la mise en pratique de l'EIT-90 prévue par la Résolution 7 de la 18^{e} Conférence générale des poids et mesures (octobre 1987).

D. Discussions d'ensemble ; préparation des recommandations

- Discussions d'ensemble en vue de l'adoption de valeurs pour le quotient fréquence Josephson/tension et la résistance de Hall quantifiée à utiliser pour obtenir des représentations du volt et de l'ohm fondées sur l'effet Josephson et l'effet Hall quantique.
- Préparation des recommandations à soumettre au CIPM.

E. Diffusion des informations relatives aux nouvelles valeurs des représentations du volt et de l'ohm et à l'EIT-90

- Actions à entreprendre en vue de porter à la connaissance des utilisateurs des services d'étalonnage les informations relatives aux nouvelles valeurs des représentations et à l'EIT-90.

II. Comparaisons internationales

A. Rapports sur l'état d'avancement des comparaisons en cours

- Étalons de transfert ac/dc (Laboratoire pilote : VSL)
- Étalons d'inductance (Laboratoire pilote : PTB).

B. Choix éventuel de nouvelles comparaisons.

III. Rapport du Groupe de travail pour les grandeurs aux radiofréquences.

IV. Rapport sur le travail de la section électricité du BIPM.

V. Travaux futurs du CCE.

VI. Questions diverses.

RAPPORT
DU
COMITÉ CONSULTATIF D'ÉLECTRICITÉ
(18^{e} session — 1988)
AU
COMITÉ INTERNATIONAL DES POIDS ET MESURES

par O. C. Jones, rapporteur

Le Comité consultatif d'électricité (CCE) s'est réuni pour sa dix-huitième session au Bureau international des poids et mesures, Pavillon de Breteuil, à Sèvres, les 27 et 28 septembre 1988.

Étaient présents :

E. Ambler, président du CCE.

Les délégués des laboratoires membres :

Amt für Standardisierung, Messwesen und Warenprüfung [ASMW], Berlin (W. Schlesok).

Conseil national de recherches du Canada [NRC], Ottawa (B. M. Wood, J. Vanier).

CSIR, Division of Production Technology [DPT], Pretoria (W. M. P. Marais).

CSIRO, Division of Applied Physics [CSIRO], Lindfield (I. K. Harvey, W. R. Blevin).

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

Institut de métrologie D. I. Mendéléev [VNIIM], Leningrad (Y. V. Tarbeev, assisté de V. Pudalov *).

Institut national de métrologie [NIM], Beijing (Zhang Zhonghua).

Istituto Elettrotecnico Nazionale Galileo Ferraris [IEN], Turin (F. Cabiati, D. Andreone).

Laboratoire central des industries électriques [LCIE], Fontenay-aux-Roses (H. Lacoste, L. Érard, A. Fau).

National Institute of Standards and Technology [NIST], Gaithersburg (B. N. Taylor).

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* Institut de métrologie, Moscou.

National Physical Laboratory [NPL], Teddington (O. C. JONES, B. P. KIBBLE).
Office fédéral de métrologie [OFMET], Wabern (U. FELLER).
Physikalisch-Technische Bundesanstalt [PTB], Braunschweig (V. KOSE, H. BACHMAIR).
Van Swinden Laboratorium [VSL], Delft (R. KAARLS).

Le directeur du BIPM (T. J. QUINN).

Invité :

Statens Provningsanstalt [SP], Borås (Suède) (H. NILSSON).

Assistaient aussi à la session : P. GIACOMO (BIPM) ; T. ENDO (ETL) ; T. J. WITT, F. DELAHAYE, D. REYMANN (BIPM) ; A. SATRAPINSKY, interprète (BIPM).

Absent :

Institut national de métrologie de la Roumanie [INM], Bucarest.

Le président du CCE et le directeur du BIPM souhaitent la bienvenue aux participants. Mr Jones est nommé rapporteur. L'ordre du jour provisoire révisé est adopté. Il propose de rechercher d'abord un accord sur les valeurs numériques à recommander pour les constantes de l'effet Josephson et de l'effet Hall quantique puis de discuter des modalités d'utilisation de ces valeurs. Ces points de l'ordre du jour définissent la tâche principale de la réunion, conformément aux instructions reçues du Comité international des poids et mesures (CIPM) à l'issue de sa 75^e session en 1986 et de la 18^e Conférence générale des poids et mesures (CGPM) en 1987. Un total de 54 documents, dont la liste est donnée à l'Annexe E 1 (p. E 25), est soumis au CCE.

1. L'effet Josephson

Un projet de recommandation sur la « Représentation du volt au moyen de l'effet Josephson », proposé conjointement par les Groupes de travail sur l'effet Josephson et sur l'effet Hall quantique, est discuté assez longuement. Il est convenu, suivant la suggestion du Groupe de travail sur l'effet Josephson, d'utiliser « constante de Josephson » et K_J comme nom et symbole du quotient de la fréquence par la tension et d'utiliser $K_{J\text{-}90}$ comme symbole de la valeur conventionnelle recommandée pour ce quotient. (*Note :* ces symboles ne sont pas destinés à représenter la combinaison de constantes fondamentales $2e/h$.) Lors de la mise au point du projet de recommandation, il est décidé d'éviter l'usage du mot « représentation » pour désigner l'utilisation conjointe de l'effet

Josephson et d'une valeur conventionnelle du quotient de la fréquence par la tension pour l'établissement d'un étalon de référence de force électromotrice. Il est confirmé que la date de mise en application de la recommandation est le 1er janvier 1990.

Mr Witt résume le rapport du Groupe de travail sur l'effet Josephson (document CCE/88-34, Annexe E 2) en indiquant qu'il est l'aboutissement de cinq versions provisoires. Mr Witt mentionne également que des réunions conjointes du Groupe de travail sur l'effet Josephson et du Groupe de travail sur l'effet Hall quantique ont eu lieu le 26 septembre 1988 au BIPM et le 11 juin 1988, à l'issue de la conférence CPEM 1988, à Tsukuba au Japon ; de plus, des réunions informelles d'experts se sont tenues pendant les conférences CPEM 1988 à Tsukuba, CPEM 1986 à Washington et CPEM 1984 à Delft. Trois projets de recommandations, préparés conjointement par les deux groupes de travail, sont proposés. On estime que le nouvel étalon de référence de force électromotrice aurait les qualités requises de stabilité à long terme et d'accord avec le SI.

Bien que l'on puisse s'attendre à la réduction future de l'incertitude des mesures de K_J, on suggère que la valeur conventionnelle recommandée ne soit pas alors changée. Le CCE pourrait simplement noter la différence entre un étalon de référence fondé sur l'effet Josephson et un étalon fondé sur la définition du volt. Le groupe de travail propose pour K_J la valeur 483 597,9 GHz/V avec une incertitude relative, correspondant à un écart-type, de 4×10^{-7}. Ceci résulte de sept réalisations directes de la définition du volt, ne nécessitant pas l'hypothèse $K_J = 2e/h$, et de trois mesures indirectes pour lesquelles il est nécessaire de supposer que $K_J = 2e/h$. Il n'y a pas de différence significative entre la moyenne de chacun de ces deux groupes de données, et le résultat final est particulièrement peu sensible à l'exclusion des valeurs individuelles les plus précises.

Mr Vanier demande pourquoi la valeur CODATA de 1986 pour $2e/h$ n'a pas été incorporée dans l'ensemble des données. Mr Taylor explique que certains des résultats utilisés par le groupe de travail supplantent des résultats ayant servi à l'évaluation de la valeur CODATA, tandis que d'autres ne sont que la reproduction de résultats déjà pris en compte pour cette évaluation. La valeur CODATA elle-même n'a donc pas été retenue afin d'éviter l'introduction de données redondantes. Mr Taylor ajoute que la valeur recommandée par le groupe de travail pour $K_{J\text{-}90}$ est en accord avec la valeur CODATA de 1986. Mr Tarbeev note que la valeur recommandée s'éloigne déjà sensiblement de la gamme de valeurs examinée par le CCE en 1986. Mr Cabiati souligne le fait qu'un étalon de référence fondé sur l'effet Josephson est hautement reproductible et que, dans le but d'améliorer l'uniformité mondiale des mesures électriques, il importe davantage que tous les laboratoires adoptent pour K_J une même valeur, plutôt qu'une valeur exacte. Mr Quinn fait remarquer que cette considération apparaît dans la

Résolution 6 de la 18e Conférence générale des poids et mesures (CGPM) de 1987.

Les groupes de travail ont également discuté de trois présentations possibles de l'information à fournir aux utilisateurs d'étalonnages en ce qui concerne le changement des étalons de référence. Le problème de l'expression de l'incertitude des mesures réalisées en utilisant l'effet Josephson et la valeur conventionnelle K_{J-90} est important. En effet K_{J-90} est susceptible de différer de $\pm 4 \times 10^{-7}$ en valeur relative (estimation correspondant à un écart-type) de la valeur exacte, K_J, de la constante de Josephson. Cette différence, constante et identique pour tous les laboratoires, n'affectera pas les échanges commerciaux ; cependant, elle pourrait affecter les résultats de certaines expériences scientifiques très précises. Les membres des groupes de travail n'ont pas réussi à adopter une position commune sur ce problème. Ils ne sont donc pas en mesure de recommander une quelconque des trois présentations examinées.

Suite à une discussion approfondie des conséquences de chacune des trois présentations, le président fait remarquer que les considérations théoriques sont bien sûr à prendre en compte mais que la tâche principale du CCE est de proposer une solution pratique et bien fondée qui puisse être introduite dans l'industrie avec un minimum d'inconvénient. On note que le document CCE/88-53, dont l'auteur est Mr Cabiati, propose un mode d'expression des résultats de mesure qui évite les difficultés inhérentes aux présentations mentionnées dans les rapports des groupes de travail, tout en étant suffisamment rigoureux. Le CCE convient de recommander un mode d'expression s'inspirant de celui proposé par Mr Cabiati. Quatre groupes de travail sont formés afin de préparer des projets de déclarations reflétant l'opinion du CCE sur les aspects principaux de l'introduction de nouveaux étalons de référence. Ces déclarations, reproduites ci-dessous, s'appliquent à la mise en œuvre d'un étalon de force électromotrice utilisant l'effet Josephson comme à celle d'un étalon de résistance utilisant l'effet Hall quantique.

2. Conclusions concernant les projets de recommandation

2.1. Les Recommandations 1 (CI-1988) et 2 (CI-1988) * ne constituent pas une redéfinition des unités SI (B. P. Kibble, B. N. Taylor)

Les valeurs conventionnelles K_{J-90} et R_{K-90} ne peuvent pas être utilisées pour la définition du volt et de l'ohm (c'est-à-dire les unités de force électromotrice et de résistance électrique du Système international d'unités). Cette utilisation ferait que la constante μ_0 n'aurait plus une

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* Ces recommandations du CIPM sont des versions légèrement modifiées des projets de recommandation proposés par le CCE.

valeur définie exactement (ce qui rendrait caduque la définition de l'ampère) et que les unités électriques seraient incompatibles avec la définition du kilogramme et des unités qui en dérivent.

2.2. Au sujet de l'utilisation d'indices associés aux symboles des grandeurs ou unités (R. Kaarls, W. R. Blevin, L. Érard)

Le CCE considère que les symboles de force électromotrice (potentiel électrique, différence de potentiel électrique) et de résistance électrique, ainsi que ceux du volt et de l'ohm, ne devraient pas être modifiés par l'adjonction d'indices désignant des laboratoires ou des dates particuliers.

Les raisons principales de cette prise de position, en ce qui concerne les grandeurs physiques, sont que :

— jusqu'à présent, la température étant l'une des rares exceptions, il n'a pas été nécessaire d'introduire explicitement le concept d'un système de grandeurs physiques conventionnelles différant des grandeurs traditionnelles,

— il serait difficile de faire largement comprendre et accepter un tel concept,

— ce concept, s'il était introduit pour la force électromotrice et la résistance électrique, s'étendrait à d'autres grandeurs.

Les raisons principales de cette prise de position, en ce qui concerne les unités, sont que :

— on éviterait ainsi de donner l'impression qu'un système d'unités différent du SI est introduit. Ce risque est d'autant plus grand que l'utilisation d'indices pourrait s'étendre aux unités d'autres grandeurs,

— les nouveaux étalons de référence seront des représentations du volt et de l'ohm entièrement satisfaisantes dans la grande majorité des applications,

— tout désaccord entre des laboratoires qui réalisent les nouveaux étalons de référence pourra être considéré comme négligeable par la grande majorité des utilisateurs,

— de nombreux pays sont de toute façon contraints, de par leur législation concernant les grandeurs physiques et les unités, d'utiliser les noms et symboles du SI.

2.3. Le point de vue du CCE concernant la mise en œuvre pratique des Recommandations 1 et 2 (CI-1988) (O. C. Jones, V. Kose, T. J. Quinn, B. N. Taylor)

Le CCE, ayant examiné attentivement les trois présentations figurant dans les rapports des groupes de travail (documents CCE/88-34 et CCE/88-35, Annexes E 2 et E 3), estime qu'une solution rigoureuse de ce problème a été identifiée et qu'elle évite :

(i) de définir de nouvelles unités « V_{90} » ou « Ω_{90} » ;

(ii) de définir de nouvelles grandeurs physiques « E_{90} » ou « R_{90} » et

(iii) d'utiliser des indices ou tout autre signe distinctif associés aux symboles des unités ou des grandeurs.

La solution retenue est illustrée ci-dessous par un exemple des informations qui peuvent être communiquées aux utilisateurs de certificats d'étalonnage de piles étalons :

La valeur mesurée de la force électromotrice, E, ou de la différence de potentiel électrique, U, d'une source inconnue peut être exprimée rigoureusement en volt, V, de la façon suivante :

$$E = (1{,}018\ \text{xxx xx})\ \ \text{V} \pm \varepsilon.$$

Le symbole ε représente l'incertitude totale, correspondant à un écart-type, et est donné par :

$$\varepsilon = \sqrt{(\Delta E)^2 + (E \times \delta)^2}$$

où ΔE est l'incertitude combinée en volt (un écart-type) associée à l'étalonnage lui-même ainsi qu'à la réalisation par le laboratoire national particulier de l'étalon de référence fondé sur l'effet Josephson et où δ représente l'incertitude relative avec laquelle le rapport $K_{\text{J-90}}/K_{\text{J}}$ est connu. L'estimation présente de δ est de 4×10^{-7} (un écart-type) comme indiqué dans la Recommandation 1 (CI-1988).

Puisque, par consensus international, δ est commun à tous les laboratoires, sa valeur peut être mentionnée séparément et l'expression ci-dessus de E réécrite sous la forme :

$$E = (1{,}018\,\text{xxx xx})\ \text{V} \pm \Delta E$$

pour tous les besoins pratiques de la métrologie électrique de précision ou des échanges commerciaux. Cependant, dans ce cas, la valeur de δ devra être donnée séparément sur le certificat chaque fois que le niveau de précision le nécessite. Lorsque $\Delta E/E$ est nettement plus grand que 4×10^{-7}, la valeur de δ peut être omise.

Le cas des mesures de résistances (Recommandation 2 (CI-1988)) est strictement analogue.

2.4. Exemple de terminologie à employer pour les certificats d'étalonnage

(I. K. Harvey, J. Vanier, T. J. Witt)

Les valeurs de force électromotrice données ci-dessous sont fondées sur ... [une description de la procédure d'étalonnage peut être placée ici] ... en utilisant la nouvelle valeur conventionnelle de la constante de

Josephson adoptée internationalement à dater du 1er janvier 1990 (*voir* Note A) :

pile numéro	force électromotrice V	incertitude ΔE V
1	1,018 123 4	0,000 000 2

[d'autres données relatives à l'étalonnage peuvent être placées ici]

Note A *

La valeur de la constante de Josephson utilisée pour cet étalonnage est $K_{\text{J-90}}$ = 483 597,9 GHz/V, valeur adoptée par consensus international, à partir du 1er janvier 1990, par tous les laboratoires nationaux qui utilisent l'effet Josephson comme étalon de référence de force électromotrice. Tous ces laboratoires utilisent donc maintenant la même valeur de la constante de Josephson, ce qui n'était pas le cas auparavant. Les laboratoires nationaux qui n'utilisent pas l'effet Josephson comme étalon de référence peuvent maintenir leurs propres références en accord avec la valeur de la constante de Josephson mentionnée ci-dessus grâce à des comparaisons périodiques avec des laboratoires qui utilisent l'effet Josephson. On attribue à un étalon de force électromotrice fondé sur l'utilisation de l'effet Josephson et de $K_{\text{J-90}}$ une incertitude (écart-type), par rapport au volt, de 4×10^{-7} en valeur relative (0,4 µV pour une force électromotrice de un volt). Comme cette incertitude est la même pour tous les laboratoires nationaux, elle n'a pas été incluse dans les incertitudes données dans ce tableau. Cependant, son existence doit être reconnue lorsqu'il est de toute importance que des mesures électriques et mécaniques soient cohérentes.

Mr Kose remarque que, en dépit de la prise de position exprimée en 2.2., les laboratoires nationaux auront probablement besoin d'utiliser des indices ou autres signes distinctifs lorsqu'ils échangeront des informations entre eux ou avec le BIPM.

La version finale de la Recommandation « Représentation du volt au moyen de l'effet Josephson » est alors adoptée à l'unanimité.

3. L'effet Hall quantique

Un projet de recommandation sur la « Représentation de l'ohm au moyen de l'effet Hall quantique », proposé conjointement par les groupes de travail, est discuté. Il est convenu d'utiliser « constante de von

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* Note du rapporteur : différentes modifications, portant sur la forme, ont été apportées au texte de la Note A après la réunion.

Klitzing » et R_K comme nom et symbole de la résistance de Hall quantifiée correspondant au plateau de nombre quantique $i = 1$ et d'utiliser R_{K-90} comme symbole de la valeur conventionnelle recommandée pour cette résistance. (*Note :* le symbole R_K n'est pas destiné à représenter la combinaison de constantes fondamentales h/e^2.)

L'objectif est de rendre la rédaction de cette recommandation aussi proche que possible de celle qui concerne le volt. Il est confirmé que la date de mise en application de cette recommandation est le 1^er^ janvier 1990.

Mr Taylor présente le rapport du Groupe de travail sur l'effet Hall quantique qui non seulement recommande une valeur pour la constante de von Klitzing, mais aussi propose un guide concernant les précautions à prendre lors de l'utilisation de l'effet Hall quantique et de la valeur conventionnelle de R_K pour l'établissement d'un étalon de référence de résistance. Ce guide constitue un document séparé (document CCE/88-40) préparé par Mr Delahaye et reproduit dans l'Annexe E 4.

Les recommandations et le rapport du groupe de travail (document CCE/88-35, Annexe E 3) sont présentés d'une manière similaire à celle des documents correspondants du Groupe de travail sur l'effet Josephson. Afin d'inclure des résultats fondés sur des mesures de constantes fondamentales, il a été nécessaire de supposer que $R_K = h/e^2$. Le groupe de travail estime que cette hypothèse peut être faite valablement compte tenu du niveau d'incertitude requis. La valeur recommandée pour R_K est fondée sur de telles mesures indirectes au nombre de quatre et aussi sur sept mesures directes. Une confirmation supplémentaire des mesures directes est obtenue grâce à des mesures de R_K réalisées par deux laboratoires qui, bien que ne disposant pas de condensateurs calculables, rattachent néanmoins leurs résultats à l'ohm à l'aide de comparaisons directes de résistance avec le CSIRO/NML. La détermination de R_K la plus précise est la valeur indirecte déduite d'une mesure de a_e, anomalie du moment magnétique de l'électron.

La dispersion totale des résultats est d'environ 4×10^{-7} en valeur relative et il existe un écart systématique entre les moyennes des mesures directes et indirectes, la première indiquant une valeur $R_K = 25\,812{,}808\ \Omega$ et la seconde une valeur $R_K = 25\,812{,}806\ \Omega$. Le groupe de travail décide en conséquence de proposer la valeur $R_K = 25\,812{,}807\ \Omega$, l'incertitude (un écart-type) étant estimée, de façon large, à 2×10^{-7} en valeur relative (0,005 Ω). Ce résultat est en accord avec la valeur CODATA de 1986 mais inclut des résultats plus récents. Le CCE convient de recommander la valeur $R_{K-90} = 25\,812{,}807\ \Omega$ exactement. La version définitive de la Recommandation sur la « Représentation de l'ohm à l'aide de l'effet Hall quantique » est adoptée à l'unanimité.

Trois présentations possibles de l'information à fournir aux utilisateurs d'étalonnages en ce qui concerne l'utilisation d'un étalon de référence fondé sur l'effet Hall quantique et sur une valeur conventionnelle de R_K sont examinées. Les membres du groupe de travail n'ont pas réussi une fois encore à adopter une position commune, mais ils estiment que l'introduction de « grandeurs physiques conventionnelles » risquerait de désorienter les utilisateurs d'étalonnages.

Le CCE décide d'adopter, pour la mise en œuvre de la recommandation relative à l'étalon de résistance fondé sur l'effet Hall quantique, la même solution que celle retenue pour l'étalon de référence de force électromotrice fondé sur l'effet Josephson. Les conclusions 2.1 à 2.4 doivent être considérées comme s'appliquant également au cas de l'effet Hall quantique.

Mr Delahaye présente le document CCE/88-40 « Technical guidelines for reliable measurements of the quantized Hall resistance » (Annexe E 4). Mr Jones remarque que le document est extrêmement utile mais que Mr Hartland du NPL y a relevé quelques imprécisions de détail et qu'il propose son aide pour la préparation de la version finale de ce document. Mr Quinn pense que de futures mises à jour de ce document seront nécessaires car les techniques sont encore dans une phase d'amélioration rapide.

Le président remercie les membres du Groupe de travail sur l'effet Josephson et ceux du Groupe de travail sur l'effet Hall quantique pour leurs contributions et annonce que ces groupes sont maintenant dissous.

4. Comparaisons internationales

4.1. Comparaison internationale d'étalons de résistance de un ohm

Mr Witt présente le document CCE/88-36 (Annexe E 5) qui décrit les résultats de cette comparaison réalisée au BIPM et souligne l'importance de ces résultats qui démontrent l'accord entre les différentes mesures de R_K en fonction de $\Omega_{69\text{-BI}}$. Douze laboratoires ont participé à cette comparaison. Pour cinq des six laboratoires qui utilisent déjà l'effet Hall quantique pour suivre la dérive de leurs étalons de résistance et annoncent une incertitude relative inférieure ou égale à $3{,}6 \times 10^{-8}$, l'accord entre les mesures de R_K est excellent : la dispersion totale est en valeur relative de $6{,}6 \times 10^{-8}$. Un résultat particulièrement significatif est que la valeur de $\Omega_{69\text{-BI}}$ déduite des résultats de la comparaison coïncide à $5 \times 10^{-9}\ \Omega$ près avec la valeur extrapolée suivant le taux de la dérive déterminé grâce aux comparaisons réalisées depuis 1964 avec le condensateur calculable du CSIRO. Mr Witt remarque également que certaines des résistances de un ohm présentent des résistances de fuite trop faibles, ce qui les rend inutilisables pour des comparaisons de haute précision.

Le président demande si les laboratoires nationaux ont continué à conserver leur représentation de l'ohm à l'aide de groupes de résistances étalons, comme cela avait été demandé par le CCE en 1986. Le but était de maintenir les taux de dérive actuels, qui sont bien établis et permettent de comparer valablement les différentes mesures de R_K. Il est confirmé que cette demande a été satisfaite. Mr Witt ajoute que les comparaisons réalisées au BIPM peuvent fournir des informations supplémentaires concernant les taux de dérive et qu'elles permettent le rattachement au condensateur calculable du CSIRO.

4.2. Comparaison internationale d'étalons de transfert courant alternatif/courant continu

Cette comparaison mondiale, dont le laboratoire pilote est le Van Swinden Laboratorium, porte sur un ensemble de trois éléments thermiques pour des courants de 5 mA, 10 mA et 30 mA associés à un jeu de résistances permettant de couvrir la gamme de tension allant de 10 V à 1 000 V. Les mesures sont effectuées à des fréquences réparties entre 40 Hz et 1 MHz.

Mr Kaarls fait le point sur les boucles de cette comparaison qui se sont déroulées en Europe de l'ouest (organisées par le Bureau communautaire de référence, BCR). Des résultats préliminaires ont été rapportés au CCE en 1983. La seconde boucle de la comparaison a mis en jeu sept laboratoires nationaux et a duré quatre ans et demi.

Les résultats sont résumés dans le tableau 1 :

Tableau 1

fréquence	gamme de tension ou de courant	dispersion totale des différences ca-cc mesurées
40 Hz-100 kHz	10 V-100 V	10^{-4}
< 20 kHz	< 100 V	10^{-5}
1 MHz	10 V	5×10^{-4}
40 Hz-100 kHz	5, 10 et 30 mA	$1{,}5 \times 10^{-5}$
100 kHz	10 mA	4×10^{-5}

En conclusion, bien que des améliorations aient été faites au cours de la comparaison, plusieurs laboratoires doivent réexaminer leur procédure d'étalonnage. Ceci est particulièrement nécessaire pour les laboratoires qui doivent étalonner certains instruments industriels dont l'incertitude relative annoncée est de 2×10^{-5}. La durée particulièrement longue de cette comparaison en réduit considérablement la signification.

Les trois prochaines boucles de cette comparaison sont déjà programmées. Sept autres laboratoires nationaux des différentes régions du globe y participent. Mr Tarbeev souhaite vivement que la boucle impliquant le VNIIM soit programmée bien avant 1990, date suggérée dans le document CCE/88-45. Mr Kaarls est d'accord pour examiner la possibilité de réaliser ce changement. Il ajoute que des comptes rendus détaillés des résultats déjà acquis pourront être obtenus par l'intermédiaire du BIPM.

4.3. Comparaison internationale d'étalons d'inductance

Mr Kose présente le document CCE/88-22 et résume brièvement les résultats de cette comparaison organisée par le BCR et à laquelle six laboratoires européens ont participé.

Les valeurs mesurées des étalons de 1 H et de 10 mH sont en accord à mieux que $\pm 1 \times 10^{-4}$ en valeur relative pour toutes les fréquences de mesure réparties entre 60 Hz et 5 kHz. Pour l'étalon de 100 μH, un accord semblable est observé, sauf pour des fréquences proches des limites de la gamme, à 200 Hz et 5 kHz, où les écarts vont jusqu'à $\pm 6 \times 10^{-4}$ en valeur relative. Ce niveau d'incertitude semble satisfaire les demandes industrielles actuelles.

4.4. Rapport du Groupe de travail pour les grandeurs aux radiofréquences (GT-RF)

Le document CCE/88-29, présenté par le président du groupe de travail, Mr Érard, est discuté. Une comparaison a été terminée depuis 1986 ; elle avait commencé en 1978. Pour trois autres comparaisons, les mesures sont terminées mais les rapports ne sont pas encore disponibles. Quatre comparaisons ont été abandonnées et dix-huit sont en cours. Six propositions pour de futures comparaisons possibles sont examinées. Une comparaison de puissance laser pour des longueurs d'onde de 0,85 μm, 1,3 μm et 1,55 μm sera entreprise sous la responsabilité conjointe du Comité consultatif de photométrie et radiométrie (CCPR) et du GT-RF. Aucune autre proposition n'est envisagée. Mr Érard rappelle les directives du BIPM concernant le déroulement des comparaisons internationales et ajoute qu'elles devront être suivies. Il y aura une réunion commune des membres du GT-RF et du CCPR, au BIPM, le 30 septembre 1988 (*voir* Annexe E 6, p. E 35). Mr Érard suggère que la compétence en matière de métrologie des fibres optiques ne soit pas divisée arbitrairement entre ces comités et que toute proposition dans ce domaine fasse l'objet d'une concertation. L'organisation d'une activité serait de la responsabilité du comité qui l'aurait proposée. Mr Blevin, président du CCPR, suggère qu'avant toute comparaison de grande ampleur on entreprenne une comparaison préliminaire réduite utilisant les étalons de transfert et les méthodes retenues. Il approuve la proposition d'activités communes entre le CCPR et le GT-RF.

5. Travaux futurs

5.1. Les laboratoires sont invités à participer à différentes comparaisons envisagées

R. Kaarls — Étalons de transfert courant alternatif/courant continu : voir ci-dessus en 4.2. Un certain nombre de laboratoires désirent participer à cette comparaison.

W. Schlesok — Étalons d'inductance de 10 mH à mesurer à 1000 Hz. Les laboratoires suivants se déclarent intéressés : VNIIM, VSL, PTB, ASMW, LCIE, NIM, IEN, NIST, NPL, SP. L'ASMW sera le laboratoire pilote.

U. Feller — Comparaison internationale d'étalons de résistance de 1 Ω et de 10 kΩ, suivant la proposition d'EUROMET du document CCE/88-26. Le but est d'aider les laboratoires qui réalisent ou se préparent à réaliser des mesures fondées sur l'effet Hall quantique. Mr Witt indique qu'il est prêt à organiser cette comparaison, qui aura lieu au BIPM, et propose qu'elle commence en septembre 1990. Le BIPM diffusera parmi les laboratoires nationaux un questionnaire afin d'établir la liste des laboratoires participants.

Mr Tarbeev suggère que l'utilisation de résistances de 6,4 kΩ serait préférable à celle de résistances de 10 kΩ. Néanmoins le BIPM indique qu'il ne souhaite pas organiser une comparaison de grande ampleur avec des résistances de cette valeur. Mr Kibble suggère d'utiliser également des résistances de 100 Ω, mais Mr Witt fait remarquer que de telles résistances, déjà mesurées par le BIPM, n'ont pas été suffisamment stables lors des transports.

Mr Pudalov mentionne qu'il a utilisé des jeux de résistances de 100 Ω et de 6,4 kΩ qui possèdent des taux de dérive aussi faibles que 2×10^{-8} en valeur relative par an et qui sont restées stables lors de transports à l'intérieur de l'URSS.

Mr Schlesok fait ressortir les avantages d'échanger des échantillons de Hall plutôt que des résistances. Les boîtiers et embases de type TO-8 sont ceux utilisés de préférence par plusieurs laboratoires dans ce domaine. La généralisation de l'utilisation de ce type de connecteur faciliterait les échanges d'échantillons entre laboratoires. Mr Kose se demande si cela ne devrait pas être mentionné dans le guide concernant les précautions à prendre lors de la mise en œuvre de la résistance de Hall quantifiée.

Le président demande si la date proposée pour le début de la comparaison (septembre 1990) semble convenable. Plusieurs laboratoires répondent qu'ils seront prêts à cette date.

Une courte discussion s'engage sur le problème de la disponibilité des échantillons utilisés pour la mise en œuvre de l'effet Hall quantique. Il apparait que les laboratoires AT&T Bell ne peuvent fournir actuellement des échantillons convenables pour la métrologie. Le Professeur M. Ilegems, de l'Institut fédéral de technologie de Lausanne, a déjà fourni des échantillons à plusieurs laboratoires de métrologie. Mr Feller explique que cet institut, orienté vers l'université et la recherche, ne peut probablement pas être considéré comme un fournisseur à long terme d'échantillons. Mr Witt rapporte que le Professeur von Klitzing est susceptible de fournir des échantillons aux laboratoires qui possèdent un dispositif opérationnel pour l'étude de l'effet Hall quantique et qu'il préfère le faire directement plutôt que, comme cela avait été éventuellement proposé, par l'intermédiaire d'un autre organisme tel que le BIPM.

5.2. Travaux relatifs aux constantes fondamentales

La Recommandation E 3 « Réalisation des unités SI en électricité » a été préparée afin d'attirer l'attention sur le rôle important que jouent les mesures de constantes fondamentales dans la métrologie, en particulier la métrologie électrique, et d'encourager les expérimentateurs engagés dans ce domaine très exigeant à continuer leurs efforts. Il est probable que les incertitudes associées aux valeurs des constantes de Josephson et de von Klitzing pourront être réduites dans le futur proche. Les avantages qui résulteraient de la réduction de l'incertitude avec laquelle les représentations mécanique et électrique du watt peuvent être comparées sont mentionnés. Il existe par exemple maintenant une possibilité réelle d'évaluer la dérive à long terme du kilogramme grâce à une expérience du type « bobine mobile » d'incertitude réduite.

Cette recommandation est également adoptée à l'unanimité (*voir* p. E 17).

5.3. Suivi des conséquences de l'introduction d'étalons de référence fondés sur l'effet Josephson et sur l'effet Hall quantique

Il est convenu que le CCE se réunisse en juin 1991 afin d'examiner les progrès réalisés dans l'adoption des nouveaux étalons de référence et de préparer un rapport sur ce sujet pour la prochaine CGPM qui doit se tenir en octobre 1991. De nouveaux résultats de mesures de K_J et R_K actuellement en cours devraient alors être connus. L'influence du changement des étalons de référence sur l'uniformité internationale des mesures électriques devrait être également examinée.

5.4. Diffusion des travaux du CCE

Trois articles doivent être préparés afin d'être publiés dans *Metrologia* :

- « News from the BIPM », par Mr Quinn, rendant compte de la présente session et reproduisant les trois recommandations.
- Une version sous forme d'article des rapports des deux groupes de travail, par MM. Taylor et Witt.
- « Technical guidelines for reliable measurements of the quantized Hall resistance », par Mr Delahaye.

Mr Quinn annonce que les documents soumis au CCE lors de cette session seront reliés ensemble et publiés comme un complément au rapport. Ils seront distribués aux représentants des laboratoires membres du CCE et disponibles sur demande.

6. Autres questions discutées

6.1. La nouvelle échelle internationale de température

Mr Quinn rend compte de l'avancement de la préparation de l'EIT-90 qui devrait vraisemblablement entrer en vigueur, comme prévu, le 1er janvier 1990. Une figure donnant la différence $\Delta T = T_{90} - T_{68}$ devrait être publiée début 1989. Les changements concernant les températures proches de la température ambiante concernent en particulier la métrologie électrique. Par exemple, à 20 °C, $\Delta T = -5$ mK et à 100 °C, $\Delta T = -25$ mK.

Il y aura, à l'avenir, trois points fixes proches de la température ambiante, permettant la réalisation primaire de T_{90}. Ils utiliseront le point triple du mercure, de l'eau et du gallium.

6.2. Rapport sur les travaux de la section d'électricité du BIPM

Mr Witt fait brièvement référence au document CCE/88-36 (Annexe E 5), décrivant la comparaison récente d'étalons de 1 Ω et au document CCE/88-25 rendant compte du travail du BIPM sur l'effet Hall quantique et en particulier de la mesure de R_K en fonction de $\Omega_{69\text{-BI}}$. Le BIPM dispose maintenant d'un étalon de référence fondé sur l'effet Hall quantique qui peut être utilisé pour conserver un groupe de résistances de 1 Ω, par comparaison avec R_K, avec une incertitude égale à $1{,}5 \times 10^{-8}$ en valeur relative. Des mesures de piles étalons réalisées par rattachement à une tension Josephson de 10 mV délivrée par une double jonction ont été comparées avec des mesures réalisées à l'aide d'un réseau de jonctions délivrant 1 V, don du NIST. L'accord est remarquablement bon : $\pm 2 \times 10^{-8}$.

Des jonctions Josephson à micropont ont été fabriquées avec succès à partir du matériau céramique supraconducteur à haute température critique $YBa_2Cu_3O_7$. Des mesures de $2e/h$ réalisées avec ce matériau à des températures allant jusqu'à 77 K sont en accord à $(5{,}6 \pm 3{,}4) \times 10^{-6}$ près, en valeur relative, avec des mesures réalisées à l'aide de supraconducteurs métalliques. Le fonctionnement d'un SQUID a pu être obtenu pour des températures allant jusqu'à 38 K et un comportement caractéristique de SQUID observé jusqu'à 77 K.

Le président remercie les membres des deux groupes de travail ainsi que les autres participants et clôt la session.

10 octobre 1988

Recommandations
adoptées
par le Comité international des poids et mesures

Représentation du volt au moyen de l'effet Josephson

RECOMMANDATION 1 (CI-1988)*

Le Comité international des poids et mesures,

agissant conformément aux instructions données dans la Résolution 6 de la 18e Conférence générale des poids et mesures concernant l'ajustement prévu des représentations du volt et de l'ohm,

considérant

— qu'une étude approfondie des résultats des déterminations les plus récentes conduit à une valeur de 483 597,9 GHz/V pour la constante de Josephson, K_J, c'est-à-dire pour le quotient de la fréquence par la tension correspondant au palier de rang $n = 1$ dans l'effet Josephson,

— que l'effet Josephson, avec cette valeur de K_J, peut être utilisé pour établir un étalon de référence de force électromotrice dont l'incertitude (écart-type), par rapport au volt, est estimée à 4×10^{-7} en valeur relative et dont la reproductibilité est nettement meilleure,

recommande

— que l'on adopte, par convention, pour la constante de Josephson, K_J, la valeur $K_{J\text{-}90} = 483\,597{,}9$ GHz/V exactement,

— que cette nouvelle valeur soit utilisée à partir du 1er janvier 1990, et non auparavant, pour remplacer les valeurs actuellement en usage,

— que cette nouvelle valeur soit utilisée à partir de cette même date par tous les laboratoires qui fondent sur l'effet Josephson leurs mesures de force électromotrice,

— qu'à partir de cette même date tous les autres laboratoires ajustent la valeur de leurs étalons de référence pour la mettre en accord avec cette nouvelle valeur,

estime

— qu'aucun changement de cette valeur recommandée de la constante de Josephson ne sera nécessaire dans un avenir prévisible,

attire l'attention des laboratoires sur le fait que la nouvelle valeur est supérieure de 3,9 GHz/V, soit approximativement 8×10^{-6} en valeur relative, à la valeur donnée en 1972 par le Comité consultatif d'électricité dans sa Déclaration E-72.

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* Cette recommandation du CIPM est une version légèrement modifiée du projet de recommandation proposé par le CCE.

Représentation de l'ohm au moyen de l'effet Hall quantique

RECOMMANDATION 2 (CI-1988)*

Le Comité international des poids et mesures,

agissant conformément aux instructions données dans la Résolution 6 de la 18^e Conférence générale des poids et mesures concernant l'ajustement prévu des représentations du volt et de l'ohm,

considérant

— que la plupart des étalons actuels de référence de résistance électrique présentent au cours du temps des variations significatives,

— qu'un étalon de référence de résistance électrique fondé sur l'effet Hall quantique serait stable et reproductible,

— qu'une étude approfondie des résultats des déterminations les plus récentes conduit à une valeur de 25 812,807 Ω pour la constante de von Klitzing R_K, c'est-à-dire pour le quotient de la tension de Hall par le courant correspondant au plateau de rang $i = 1$ dans l'effet Hall quantique,

— que l'effet Hall quantique, avec cette valeur de R_K, peut être utilisé pour établir un étalon de référence de résistance dont l'incertitude (écart-type), par rapport à l'ohm, est estimée 2×10^{-7} en valeur relative et dont la reproductibilité est nettement meilleure,

recommande

— que l'on adopte par convention, pour la constante de von Klitzing, R_K, la valeur $R_{K\text{-}90} = 25\,812{,}807\ \Omega$ exactement,

— que cette valeur soit utilisée à partir du 1er janvier 1990, et non auparavant, par tous les laboratoires qui fondent sur l'effet Hall quantique leurs mesures de résistance électrique,

— qu'à partir de cette même date tous les autres laboratoires ajustent la valeur de leurs étalons de référence pour la mettre en accord avec $R_{K\text{-}90}$,

— que, pour établir un étalon de référence de résistance électrique fondé sur l'effet Hall quantique, les laboratoires suivent les conseils pour la mise en œuvre de la résistance de Hall quantifiée élaborés par le Comité consultatif d'électricité et publiés par les soins du Bureau international des poids et mesures, dans leur édition la plus récente,

et estime

— qu'aucun changement de cette valeur recommandée de la constante de von Klitzing ne sera nécessaire dans un avenir prévisible.

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* Cette recommandation du CIPM est une version légèrement modifiée du projet de recommandation proposé par le CCE.

Recommandation
du
Comité consultatif d'électricité

Réalisation des unités SI en électricité

Recommandation E 3 (1988)*

Le Comité consultatif d'électricité,

reconnaissant

— l'importance de l'exactitude des mesures électriques pour la science, le commerce et l'industrie,

— le fait que cette exactitude dépend de l'exactitude des valeurs attribuées aux étalons représentatifs des unités électriques,

— le lien très étroit qui existe actuellement entre la métrologie électrique et les constantes physiques fondamentales,

— la possibilité d'obtenir des représentations des unités électriques d'une plus grande exactitude soit au moyen de réalisations directes de leur définition soit indirectement à partir de mesures de constantes fondamentales, et

— la nécessité constante de comparer des réalisations des unités et des mesures des constantes fondamentales indépendantes entre elles pour vérifier leur exactitude,

recommande

— que les laboratoires poursuivent leurs travaux sur les unités électriques en effectuant des réalisations directes de ces unités et des mesures des constantes fondamentales, et

— qu'ils continuent à perfectionner les moyens permettant d'effectuer des comparaisons internationales des étalons nationaux de tension et de résistance électrique.

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* Le CIPM a pris connaissance de cette recommandation.

Rapport du Groupe de travail pour les grandeurs aux radiofréquences

Le Groupe de travail s'est réuni à l'Electrotechnical Laboratory, Tsukuba, Ibaraki, Japon, les 13 et 14 juin 1988.

Étaient présents : Mr L. Érard, président, MM. L. Brunetti (IEN), R. F. Clark (NRC), R. L. Gallawa (NBS), U. Stumper (PTB), J. P. M. de Vreede (VSL), I. Yokoshima (ETL).

Le directeur du BIPM, P. Giacomo.

Assistait aussi à la réunion : Mr T. J. Witt (BIPM).

Excusés : les représentants du CSIRO et du NPL.

Absents : les représentants de l'ASMW, de l'IRT, du NIM et du VNIIM.

Le Dr M. Sugiura, directeur général de l'ETL, souhaite la bienvenue au groupe de travail au nom de l'ETL, ainsi qu'une réunion fructueuse. Il fait remarquer que les 17 comparaisons internationales auxquelles l'ETL a participé depuis la création du groupe de travail en 1965 sont une preuve suffisante de l'intérêt manifeste de l'ETL pour les mesures de grande précision dans le domaine des radiofréquences.

Le président et le directeur du BIPM remercient l'ETL pour son hospitalité et accueillent les participants du groupe de travail. L'ordre du jour est examiné et adopté.

Mr Clark est nommé rapporteur.

Mr Érard lit un télégramme de l'ancien président : « Meilleurs vœux pour une réunion fructueuse. Regrette de ne pas me trouver avec vous. Arlie Bailey ».

1. Comparaisons internationales terminées depuis la dernière session du groupe de travail (septembre 1986)

Une comparaison est terminée : elle est détaillée dans le tableau I.

2. Comparaisons en cours d'achèvement

Le point sur ces trois comparaisons, terminées mais pour lesquelles les rapports finaux ne sont pas prêts, est donné dans le tableau II.

3. État d'avancement des comparaisons en cours

Le résumé de l'état d'avancement des comparaisons organisées en 1975, 1978, 1983 et 1986 est donné dans le tableau III.

4. Travaux futurs

Aucune proposition formelle pour de nouvelles comparaisons internationales n'est parvenue au groupe de travail.

Les sujets de comparaisons possibles dans l'avenir déjà énumérés (R 1 à R 7) en septembre 1987 ont été réexaminés et récapitulés dans le tableau IV. Une nouvelle comparaison internationale possible a été ajoutée à la liste (R 8).

5. Questions diverses

a) Des copies du document « Commentaires sur l'organisation des comparaisons internationales » de A. Rytz (Rapport BIPM-84/4, avril 1984, révisé août 1984) sont distribuées en séance. Il est également demandé de tenir compte du document « Directives concernant le déroulement des comparaisons internationales » publié par le BIPM dans *BIPM Com. cons. d'électricité,* **16**, 1983, pp. E21-E22.

b) Mr Giacomo rappelle au groupe de travail que si deux pays effectuent une comparaison bilatérale, ils sont invités à présenter leurs résultats au BIPM. Mr Érard a promis d'envoyer une copie du rapport sur les résultats de la comparaison de puissance de bruit, sur coaxial et guide d'ondes, effectuée entre le LCIE et le VNIIFTRI. Ce rapport (1) (document GT-RF/88-15) a été diffusé aux membres après la réunion.

c) À titre d'information générale, le projet « International Comparison of RF and Microwave Standards » préparé par Mr Bailey pour la session de septembre 1986 du groupe de travail est distribué en séance. Des informations complémentaires sont disponibles dans le document « International Organization of Electromagnetic Metrology and International Comparison of RF and Microwave Standards » par A. E. Bailey, H. W. Hellwig, T. Nemoto and S. Okamura, *Proc. IEEE,* **74**, 1986, pp. 9-14.

d) Mr Érard se reporte au questionnaire qu'il envoie chaque année afin de connaître l'état d'avancement des comparaisons. Si le responsable de la comparaison internationale est connu, le questionnaire lui est envoyé ; dans le cas contraire, il est envoyé à la dernière personne représentant le laboratoire pilote au groupe de travail. Enfin, un résumé de l'état d'avancement des comparaisons est envoyé à tous les laboratoires.

e) Mr de Vreede suggère que le groupe de travail examine la manière d'améliorer la précision des mesures de puissance surfacique dans la bande 10 à 300 GHz, la raison principale étant la diminution des valeurs limites d'exposition pour la sécurité des personnes.

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(1) Érard, L. et Petrossian, H. Intercomparaison de mesure de puissance de bruit radioélectrique entre la France et l'URSS, *Bulletin BNM*, **65**, 1986, pp. 27-29.

Le groupe de travail l'invite à rédiger une proposition montrant la portée internationale de ce travail.

f) Une réunion commune du Comité consultatif de photométrie et radiométrie (CCPR) et du Groupe de travail pour les grandeurs aux radiofréquences (GT-RF) du Comité consultatif d'électricité (CCE) aura lieu le 30 septembre 1988 au BIPM (*voir* Annexe E 6 ; p. E 35) ; au cours de cette réunion seront examinés les problèmes métrologiques liés à l'utilisation de fibres optiques. Mr Érard a résumé comme suit la position du Groupe de travail pour les grandeurs aux radiofréquences :

(1) L'activité métrologique dans le domaine des fibres optiques ne devrait pas être partagée entre le CCPR et le GT-RF.

(2) Les comparaisons déjà proposées, ou en cours, devraient être effectuées par le comité ou groupe qui les a proposées (CCPR ou GT-RF), toutefois l'autre comité ou groupe doit être tenu informé de l'état d'avancement de celles-ci.

(3) Toute nouvelle comparaison devrait suivre la procédure exposée ci-dessus en (2) avec au préalable une concertation entre les deux comités.

6. Date de la prochaine réunion

Le groupe de travail, supposant que la prochaine réunion du Comité consultatif d'électricité aura lieu en 1991, fixera la date de sa prochaine réunion dès que celle du CCE sera connue.

23 juin 1988

Le Rapporteur
R. F. CLARK

Le Président
L. ÉRARD

TABLEAU I

Comparaisons terminées depuis la dernière session du groupe de travail (septembre 1986)

78-14 Puissance (1 mW) à 50 MHz sur ligne coaxiale 50 Ω.
(Laboratoire pilote : NRC ; participants : CSIRO, ETL, FFV, IEN, LCIE, NBS, NPL, OMH, PTB, VSL).
Les résultats complets ont été publiés dans *IEEE Trans. Instrum. Meas.*, **IM-37**, 1988, pp. 160-162 (document GT-RF/88-7).

TABLEAU II

Comparaisons en cours d'achèvement

72-1 Déphasage sur guide d'ondes R 100, aux fréquences 9,0, 10,0 et 11,2 GHz.
(Laboratoire pilote : NBS ; participants : CSIRO, ETL, NRC, RSRE).
Ainsi qu'il avait déjà été mentionné en 1978, tous les laboratoires ont terminé les mesures. Il est souhaité que le NBS fournisse rapidement le rapport final.

78-11 Impédance sur ligne coaxiale à 100, 200 et 300 MHz (connecteur GR 900).
(Laboratoire pilote : RSRE ; participants : CSIRO, NBS, PTB, VSL).
Bien que les mesures effectuées par les différents laboratoires aient été considérées comme terminées en 1986, le laboratoire pilote doit encore procéder à de dernières mesures. Le rapport final est prévu pour la fin de l'année 1988.

83-3 Puissance à 94 GHz.
(Laboratoire pilote : ETL ; participants : LCIE, NBS, RSRE).
Tous les laboratoires ont effectué les mesures. Le projet de rapport final a été présenté et commenté.

TABLEAU III

Comparaisons en cours

a. Comparaisons abandonnées

Après examen de leur état d'avancement et de l'intérêt présenté, le groupe de travail décide que les comparaisons suivantes devraient être abandonnées.

75-C3 Temps de montée d'impulsions sur ligne coaxiale 50 Ω.
(Laboratoire pilote : NBS ; participants : ETL, NIM*, NPL).

78-7 Puissance laser à ondes entretenues (10,6 µm).
(Laboratoire pilote : NBS ; participants : ETL, NPL, NRC, PTB).

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* Sujet à confirmation.

78-9 Énergie d'impulsion laser (1,06 μm).
(Laboratoire pilote : NBS ; participants : ETL, NPL, PTB, VSL).

86-7 Puissance sur guide d'ondes à 45 GHz.
(Laboratoire pilote : NBS ; participants : ETL, RSRE).

b. Comparaisons maintenues *

75-A4 Facteur de réflexion à 500 MHz, 3 et 7 GHz sur coaxial 50 Ω.
(Laboratoire pilote : PTB ; participants : VSL, NRC, NBS, CSIRO, ETL, OMH, CSMU, NIM, RSRE, SNIIM).
Les étalons sont actuellement à la PTB pour des mesures intermédiaires, puis ils seront expédiés au NIM.

75-A6 Tension sur ligne coaxiale 50 Ω, 100 V à 30 MHz.
(Laboratoire pilote : PTB ; participants : NBS, NPLI).
Les mesures finales sont en cours au NBS.

75-A7 Tension sur ligne coaxiale 50 Ω, 1 mV à 30 MHz.
(Laboratoire pilote : PTB ; participants : ASMW, NBS, NIM, OMH, TTL, NPLI. Le VSL et le CSIRO se sont retirés de la comparaison).
La PTB possède les étalons. Elle effectuera les mesures finales prochainement et rédigera le rapport final.

75-A11 Puissance sur ligne coaxiale à 12, 14 et 17 GHz : efficacité de montures bolométriques équipées de connecteurs de précision 7 mm (APC-7).
(Laboratoire pilote : PTB ; participants : NRC, NBS, IEN, CSIRO, LCIE, VSL, OMH).
Des mesures intermédiaires sont en cours à la PTB, les étalons de transfert seront envoyés prochainement au LCIE.

75-A14 Affaiblissement à 300 MHz sur ligne coaxiale 75 Ω (connecteur GR 900).
(Laboratoire pilote : PTB ; participants : NPL, VSL, TTL, NRC).
Les étalons voyageurs sont actuellement au NPL en attente d'expédition au VSL qui doit effectuer une nouvelle série de mesures. Les autres laboratoires ont effectué leurs mesures.

75-B3 Facteur de réflexion à 1 GHz sur ligne coaxiale 75 Ω.
(Laboratoire pilote : NRC ; participants : PTB, LCIE, NPL, VSL, TTL, OMH).
La comparaison a débuté en mai 1988. Les étalons voyageurs sont actuellement à la PTB.

78-1 Affaiblissement (60 et 100 dB) à 30 MHz sur ligne coaxiale 50 Ω.
(Laboratoire pilote : PTB ; participants : VSL, LCIE, IEN, NPL, FFV, PKN, OMH, CSIRO, NBS, NIM, VNIIFTRI).
Cette comparaison est organisée sous l'égide du Bureau communautaire de référence (CEE) et du BIPM. La comparaison « BCR » est terminée et un rapport final a été publié par la CEE. Les étalons voyageurs, actuellement à la PTB, seront envoyés prochainement au dernier laboratoire participant, le VNIIFTRI.

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* L'ordre adopté pour les laboratoires participants dans ce tableau est, dans la mesure du possible, l'ordre de circulation des étalons voyageurs.

78-2 Puissance (10 mW) à 500 MHz sur ligne coaxiale 75 Ω (connecteur GR 900).
(Laboratoire pilote : NRC ; participants : PTB, LCIE, NPL, VSL, OMH, TTL).
Il est prévu que la comparaison débute à l'automne 1988.

78-5 Gain d'un cornet et taux de polarisation transversale entre 8 et 12 GHz.
(Laboratoire pilote : NBS ; participants : NPL, TUD, FTZ, IEN, CNET, NRC, CSIRO, ETL, VSL).
Les étalons voyageurs sont actuellement au CSIRO.

78-13 Puissance de bruit sur guide d'ondes R100.
(Laboratoire pilote : RSRE ; participants : NIM, CSIRO, NBS, PTB, LCIE, L'ETL s'est retiré).
Les étalons voyageurs sont actuellement au RSRE pour des mesures intermédiaires, ils seront envoyés à la PTB dès qu'elles seront terminées.

83-4 Mesure des coefficients de dispersion (« S parameters ») à l'aide de système « large bande » dans la bande de fréquence 2-18 GHz. La comparaison débutera prochainement.
(Laboratoire pilote : RSRE ; participants : NBS, CSIRO, PTB, VSL, NIM).

86-1 Puissance surfacique à 2,45 et 10 GHz.
Champ électrique entre 300 et 1000 MHz.
(Laboratoire pilote : NPL ; participants : IEN, LCIE, NBS, VSL, CSIRO, NRC *, PTB *, NIM *). La comparaison est prête à débuter.

86-2 Facteur de surtension jusqu'à 30 MHz.
(Laboratoire pilote : NBS ; participants : SESC, LCIE, NIM, CSIRO, PTB, VSL. L'IEN s'est retiré). Des mesures préliminaires ont été effectuées au SESC.

86-3 Facteur de réflexion (en module et phase) sur guide d'ondes (R320) à 3 fréquences : 27, 35 et 40 GHz.
(Laboratoire pilote : RSRE ; participants : LCIE, NBS, NIM. L'ETL et le NRC se sont retirés).
Les étalons de transfert ont été réalisés et la comparaison devrait commencer en octobre 1988.

86-4 Puissance laser à 0,85 μm, 1,3 μm et 1,55 μm.
(Laboratoire pilote : NBS ; participants : NPL, PTB, CSIRO, NRC, VSL, IEN, INM, CSIC, SNTI, ETL, OMH, NPRL, NIM *).
Les étalons voyageurs ont été contrôlés et envoyés pour des mesures préliminaires (1re partie de la comparaison) au NPL, à la PTB et au CSIRO. Le CCPR est tenu informé du déroulement de la comparaison.

86-5 Affaiblissement de fibre optique (< 50 dB).
(Laboratoire pilote : ETL ; participants : LCIE, CSELT, VSL, PTB).
L'étalon voyageur est prêt et la comparaison débutera en septembre 1988.

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* Sujet à confirmation.

86-6 Puissance à 20 GHz sur guide d'ondes R220, efficacité de montures bolométriques.
(Laboratoire pilote : LCIE ; participants : NRC, NBS, PTB, RSRE, VNIIFTRI).
Les étalons voyageurs sont actuellement au NRC pour y être mesurés.

86-8 Affaiblissement (< 25 dB) sur guide d'ondes R320 à 27, 35 et 40 GHz.
(Laboratoire pilote : RSRE ; participants : PTB, LCIE, NRC, NBS, NIM).
Les étalons voyageurs sont prêts et la comparaison doit débuter en septembre 1988.

TABLEAU IV

Sujets éventuels de comparaisons futures

R1 Gain d'antennes cornet dans les bandes millimétriques.
Le NBS et le NPL sont toujours intéressés.

R2 Dispersion chromatique d'une fibre optique (1,2 à 1,6 μm). Abandonné pour manque d'intérêt.

R3 Puissance de bruit sur ligne coaxiale dans la bande de fréquence 2-18 GHz et sur guide d'ondes pour les fréquences supérieures à 12 GHz.
Les laboratoires suivants sont intéressés : LCIE, NBS, NRC, PTB, RSRE. Le NBS pourrait être le laboratoire pilote.

R4 Impédance dans la bande de fréquence 0,1-1 000 MHz. Ce sujet intéresse toujours plusieurs participants, mais aucune proposition concrète n'a été faite.

R5 Mesures dans les bandes millimétriques et sub-millimétriques ($f > 100$ GHz).
Le groupe de travail ne se fixe pas de limite de fréquence de travail. Il examinera toutes les propositions qui lui seront transmises et prend note que des comparaisons de mesure de puissance et de caractéristiques d'équipement en transmission entre 100 et 300 GHz pourraient être organisées.

R6 Mesure des coefficients de dispersion (« S parameters ») à l'aide de système « large bande » dans la bande de fréquence 2-18 GHz (pour éléments munis de connecteurs type N). Abandonné pour manque d'intérêt.

R7 Facteur de réflexion entre 75 et 105 GHz (fréquences préférentielles : 94-95 GHz).

R8 Puissance sur guide d'ondes R320 à 35 GHz.
L'IEN souhaite être le laboratoire pilote de cette comparaison. Le groupe de travail l'incite à s'y préparer et à faire une proposition dans ce sens lors de la prochaine réunion du groupe de travail. Les laboratoires intéressés sont : LCIE, NBS, NRC, PTB et VSL. L'IEN est chargé de contacter tous les laboratoires du groupe de travail afin de connaître leur intention au sujet de cette comparaison.

ANNEXE E 1

Documents de travail présentés à la 18e session du CCE

Ces documents de travail, qu'ils soient ou non publiés dans ce volume, peuvent être obtenus dans leur langue originale sur demande adressée au BIPM.

Document CCE/	
88-1a	CSIRO (Australie). — A determination of $2e/h$ with improved accuracy, by G. J. Sloggett, M. F. Currey and D. J. Benjamin, 4 pages.
88-1b	CSIRO (Australie). — Addendum to « a determination of $2e/h$ with improved accurracy », by G. J. Sloggett *et al.*, 2 pages.
88-2	Institute of Metrological Service (URSS). — La référence de la résistance quantique et le contrôle de la stabilité de la résistance des standards (publié en russe dans « Metrological Service in the USSR », N° 10, 1987, pp. 29-33, résumés en anglais et en français), par V. M. Pudalov et S. G. Semenchinsky.
88-3	Institute of Metrological Service et IMM (URSS). — Measurement of h/e^2 at IMS and IMM, by V. A. Kuznetsov *et al.*, 4 pages.
88-4	Institute of Metrological Service (URSS). — High-precision measuring apparatus for quantum-Hall-effect resistance standard, by V. P. Bootz *et al.*, 3 pages.
88-5	Institute of Metrological Service (URSS). — Performance of the quantum Hall effect resistance standard at IMS, by I. Ya. Krasnopolin *et al.*, 4 pages.
88-6	Institute of Metrological Service (URSS). — Physical resistance reference based on the quantum Hall effect (publié en russe dans *Pribory i Technika Experimenta*, N° 6, 1987, pp. 5-24, résumés en anglais et en français), by I. Ya. Krasnopolin.
88-7	NIM (Rép. pop. de Chine). — The absolute measurement of the ohm based on a calculable cross capacitor at NIM, by Ruan Yongshun *et al.*, 4 pages.
88-8	NIM et Physics Institute, Academy of China (Rép. pop. de Chine). — A precise measurement of QHR, by Zhang Zhonghua *et al.*, 13 pages.

88-9 NPL (Royaume-Uni). — An NPL re-determination of the quantized Hall resistance in SI units, by A. Hartland, R. G. Jones and D. J. Legg, 14 pages.

88-10 ETL (Japon). — Articles de référence :

A. Détermination des valeurs de référence :

1. K. Shida, T. Wada, H. Nishinaka, M. Kobayashi, G. Yonezaki, T. Igarashi and T. Nemoto. Determination of the Quantized Hall Resistance Value by Using a Calculable Capacitor at ETL. *IEEE Trans. Instrum. Meas.*, **IM-36**, 1987, pp. 214-217.
2. H. Nakamura, N. Kasai and H. Sasaki. The Low-Field Proton Gyromagnetic Ratio Experiment at the ETL. *IEEE Trans. Instrum. Meas.*, **IM-36**, 1987, pp. 196-200.
3. F. Shiota and K. Hara. A Study of a Superconducting Magnetic Levitation System for an Absolute Determination of the Magnetic Flux Quantum. *IEEE Trans. Instrum. Meas.*, **IM-36**, 1987, pp. 271-274.

B. Techniques d'étalonnage :

4. K. Shida. Circumstances in Japan for the Proposed Changes in the Electrical Units. *IEEE Trans. Instrum. Meas.*, **IM-36**, 1987, pp. 668-669.
5. H. Sasaki, H. Nishinaka and K. Shida. A Modified Wheatstone Bridge for High-Precision Automated Resistance Measurement. *Japan. J. Appl. Phys.*, **26**, 1987, pp. L1947-L1949.
6. H. Sasaki, A. Miyajima, N. Kasai and H. Nakamura. High-Stability DC-Current Source Using NMR Lock Technique. *IEEE Trans. Instrum. Meas.*, **IM-35**, 1986, pp. 642-643.
7. Y. Murayama, T. Endo, and M. Koyanagi. Squid Galvanometer for Measurements of the Quantized Hall Resistance. *Japan. J. Appl. Phys.*, **26**, 1987, pp. 1159-1163.
8. J. Kinoshita, K. Inagaki, Y. Murayama, T. Endo, C. Yamanouchi, K. Yoshihiro, J.-I. Wakabayashi and S. Kawaji. An Improved Josephson Potentiometer System for the Measurement of the Quantum Hall Effect. *IEEE Trans. Instrum. Meas.*, **IM-36**, 1987, pp. 230-233.

C. Autres :

9. K. Yoshihiro, J. Kinoshita, K. Inagaki and C. Yamanouchi. Observation of a New Macroscopic Quantum Effect in a Two-Dimensional Cluster of Extremely Small Josephson Junctions. *In* Proc. 2nd Int. Symp. Foundations of Quantum Mechanics, 1986, pp. 298-306.
10. K. Yoshihiro, J. Kinoshita, K. Inagaki, C. Yamanouchi, S. Kobayashi and T. Karasawa. Observation of the « Bloch Oscillations » in Granular Films of Oxidized Tin Particles. *Japan. J. Appl. Phys.*, **26**, 1987, pp. 1379-1380.

88-11 NIM (Rép. pop. de Chine). — A recent determination of SI ampere at NIM, by Liu Hengji *et al.*, 8 pages.

88-12 NIST (États-Unis d'Amérique). — SI value of Josephson frequency to voltage quotient based on past NBS fundamental constants and ohm realization experiments, by B. N. Taylor, 4 pages.

88-13 LCIE (France). — Étalonnage jusqu'à 100 kHz des condensateurs à 5 bornes de 1 pF à 1 µF, par R. Soucek et L. Érard, 10 pages.

88-14 LCIE (France). — Détermination absolue de l'unité de capacité, par A. Fau, M. Bellon et L. Érard, 6 pages.

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88-26 OFMET (Suisse) et EUROMET. — Proposal for an intercomparison of standard resistors, 1 page.

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88-34 Report to the CCE from the Working Group on the Josephson Effect, by R. Kaarls, B. P. Kibble, B. N. Taylor and T. J. Witt (Rapport BIPM-88/7, August 1988) (*voir* Appendix E 2, p. E 76).

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ANNEXE E 2

Rapport du Groupe de travail sur l'effet Josephson

(Document CCE/88-34, *voir* Appendix E 2, page E 76)

ANNEXE E 3

Rapport du Groupe de travail sur l'effet Hall quantique

(Document CCE/88-35, *voir* Appendix E 3, page E 97)

ANNEXE E 4

Guide concernant les précautions à prendre lors de la mise en œuvre de la résistance de Hall quantifiée

par F. Delahaye, T. Endo, O. C. Jones, V. Kose, B. N. Taylor et B. M. Wood

(Document CCE/88-40, *voir* Appendix E 4, page E 119)

ANNEXE E 5

Rapport sur la comparaison internationale (1987) d'étalons de résistance de un ohm et accord entre les déterminations de R_H

par T. J. Witt, F. Delahaye et D. Bournaud
Bureau international des poids et mesures

(Document CCE/88-36)

Résumé. — C'est lors de sa 17ᵉ session (septembre 1986) que le Comité consultatif d'électricité a demandé au BIPM d'organiser une comparaison internationale d'étalons de résistance de 1 Ω, limitée aux laboratoires qui mesurent la résistance de Hall quantifiée R_H ou qui réalisent des déterminations absolues de l'ohm. Le but principal de cette comparaison était d'évaluer l'accord existant entre les mesures de R_H réalisées par les différents laboratoires en fonction de leur représentation de l'ohm, Ω_{LAB}.

Onze laboratoires nationaux (CSIRO, ETL, IMM, LCIE, NBS, NIM, NPL, NRC, OFMET, PTB, VSL) ainsi que le BIPM ont participé à cette comparaison. Chaque laboratoire a fait parvenir au Bureau deux ou trois étalons voyageurs de 1 Ω (31 étalons au total). Ces 31 étalons, ainsi que les 6 étalons du Bureau qui matérialisent la représentation de l'ohm du BIPM ($\Omega_{69\text{-}BI}$) ont été comparés à deux étalons de transfert du BIPM, fabriqués par le CSIRO et ayant de très faibles coefficients de température et de pression. Ces comparaisons ont été réalisées à l'aide d'un comparateur cryogénique de courants continus. Le même dispositif de mesure a été utilisé pour rattacher les deux étalons de transfert à R_H, immédiatement avant et après la comparaison.

Les différences $\Omega_{LAB} - \Omega_{69\text{-}BI}$ ont été évaluées à la date centrale de la comparaison (20 octobre 1987) avec une incertitude totale qui, à une exception près, est de l'ordre de 0,03 μΩ. La valeur de $\Omega_{69\text{-}BI}$ en Ω, déduite de la comparaison avec le CSIRO et de la détermination de l'ohm réalisée par ce laboratoire, diffère de moins de 0,01 μΩ de la valeur attendue, calculée par extrapolation des résultats des comparaisons précédentes. Cela confirme le fait que $\Omega_{69\text{-}BI}$ dérive linéairement et indique également un bon accord entre l'ancien et le nouveau dispositif de mesure du BIPM.

La moyenne et l'écart-type pondérés des valeurs de R_H en $\Omega_{69\text{-}BI}$, déduites des mesures de R_H en Ω_{LAB} et en $\Omega_{69\text{-}BI}$ réalisées dans les onze laboratoires nationaux et au BIPM, sont :

$$R_H = 25\,812{,}8\,[1 + (2{,}059 \pm 0{,}021) \times 10^{-6}]\,\Omega_{69\text{-}BI} \quad (1987\text{-}10\text{-}20).$$

Les valeurs de R_H en $\Omega_{69\text{-BI}}$, correspondant à cinq des six laboratoires qui annoncent une incertitude relative inférieure ou égale à 3,6 × 10^{-8} sur la mesure de R_H en fonction de leur représentation de l'ohm, ainsi que la valeur extrapolée de la moyenne pondérée de mesures de R_H en $\Omega_{69\text{-BI}}$ rapportées au 1er janvier 1986, sont toutes incluses dans un intervalle de 6,6 × 10^{-8}. Cet accord excellent démontre qu'il est maintenant possible d'utiliser l'effet Hall quantique pour réaliser une représentation de l'ohm invariable et reproductible à quelques 10^{-8} près.

ANNEXE E 6

Compte rendu de la réunion d'information sur les fibres optiques

(Réunion commune au CCPR et au GT-RF du CCE)

par J. Bastie, rapporteur

Une réunion d'information sur les fibres optiques, commune au Comité consultatif de photométrie et radiométrie (CCPR) et au Groupe de travail pour les grandeurs aux radiofréquences (GT-RF) du Comité consultatif d'électricité (CCE), s'est tenue au Bureau international des poids et mesures (BIPM), à Sèvres, le vendredi 30 septembre 1988.

Étaient présents :

W. R. Blevin, président.

Les délégués des laboratoires membres :

Amt für Standardisierung, Messwesen und Warenprüfung [ASMW], Berlin (W. Schlesok).

Bureau national de métrologie [BNM], Paris : Institut national de métrologie [INM] du Conservatoire national des arts et métiers (J. Bastie).

Conseil national de recherches [NRC], Ottawa (J. Vanier).

CSIR, Division of Production Technology [CSIR], Pretoria (M. L. du Preez).

CSIRO, Division of Applied Physics [CSIRO], Lindfield (W. R. Blevin, membre du CIPM, président du CCPR).

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

Institut national de métrologie [NIM] Beijing (J. M. Zhang).

Instituto de Optica Daza de Valdés [IOM], Madrid (A. Pons).

Laboratoire central des industries électriques [LCIE], Fontenay-aux-Roses (L. Érard, président du Groupe de travail pour les grandeurs aux radiofréquences).

National Institute of Standards and Technology [NIST], Gaithersburg (E. Ambler, membre du CIPM, président du CCE).

National Physical Laboratory [NPL], Teddington (D. H. Nettleton, O. C. Jones).

Orszagos Mérésügyi Hivatal [OMH], Budapest (G. DEZSI).
Physikalisch-Technische Bundesanstalt [PTB], Braunschweig (K. MÖSTL, W. MÖLLER).
Statens Provningsanstalt [SP], Borås (L. LIEDQUIST).
Van Swinden Laboratorium [VSL], Delft (J. de VREEDE).

J. SCHANDA, Research Institute for Technical Physics, Budapest.
Le directeur du BIPM (T. J. QUINN).

Assistaient aussi à la réunion : P. GIACOMO, directeur honoraire ; J. BONHOURE et T. J. WITT, adjoints au directeur ; R. KÖHLER (BIPM).

Excusé :

Instituto Nacional de Tecnología Industrial [INTI], Buenos Aires (R. D. LOZANO).

Absents :

Institut de recherche pour les mesures optiques et physiques [VNIIOFI], Moscou.
Institut des télécommunications [IRT], Budapest.
Istituto Elettrotecnico Nazionale Galileo Ferraris [IEN], Turin.
Office fédéral de métrologie [OFMET], Wabern/World Radiation Center, Davos Dorf.
Union radioscientifique internationale [URSI].
A. E. BAILEY, Milford-on-Sea.

Le président ouvre la séance et souhaite la bienvenue à tous ceux qui y assistent. Après la présentation de chacun des participants, Mr Bastie est désigné comme rapporteur.

L'ordre du jour est approuvé après avoir été complété par un point 7 : publication des travaux de la réunion.

1. Rapport sur les travaux métrologiques des laboratoires nationaux qui se rattachent spécifiquement ou servent d'appui à la technologie des fibres optiques

Ce point de l'ordre du jour a fait l'objet de réponses écrites, reproduites dans le document de travail RFO/88-1-R, aux questions 1 et 2 du questionnaire préliminaire (document RFO/88-1).

En pratique, la plupart des laboratoires disposent des installations nécessaires à la mesure des caractéristiques des sources (flux énergétique, répartition spectrale, etc.) et des détecteurs (sensibilité spectrale, linéarité, etc.) ; certains, seulement, sont équipés pour la mesure des caractéristiques des fibres monomodes et multimodes (atténuation par exemple). Toutes ces installations doivent être complétées à l'avenir en fonction des besoins des utilisateurs.

2. Identification des organisations nationales et internationales, autres que la Convention du Mètre et le BIPM, qui fournissent dès à présent des occasions de collaboration dans la métrologie des fibres optiques

2.1. Organisations nationales

Cette question a fait l'objet d'une réponse écrite (document RFO/88-1-R) de la plupart des participants. On constate que les laboratoires nationaux jouent généralement un rôle important, mais il existe d'autres organisations : ASMW et Kammer der Technik en Rép. dém. allemande, BNM et Union technique de l'électricité en France, National Calibration Service en Afrique du Sud, ETL, Japan Machinery and Metals Inspection Institute et Optoelectronic Industry and Technology Development Association au Japon, NIST et Electronics Industries Association aux États-Unis, NPL, Optical Fibre Measurement Club et British Standards Institution au Royaume-Uni, Deutscher Kalibrierdienst et Comité d'étalonnage DIN DKE en Rép. féd. d'Allemagne, SP en Suède.

On demande ensuite à Mr Schanda de préciser la situation dans son pays. En Hongrie, l'OMH est chargé de la métrologie fondamentale des rayonnements optiques. Les mesures pratiques sont effectuées au Research Institute for Technical Physics qui est actif dans pratiquement toutes les mesures énumérées dans le questionnaire.

2.2. Organisations internationales

Dans les réponses reçues, les deux organismes les plus souvent cités sont le Comité consultatif international télégraphique et téléphonique (CCITT) et la Commission électrotechnique internationale (CEI).

Des informations apportées principalement par MM. Jones, Nettleton, Nemoto, Ambler, Vanier et Quinn, il ressort que le CCITT, organe permanent de l'Union internationale des télécommunications, a publié un livre de spécifications pour assurer un usage cohérent des fibres optiques en télécommunications et a développé un certain nombre de méthodes de référence pour effectuer des tests. De nombreux paramètres caractéristiques des fibres optiques ont des méthodes de référence « CCITT » et beaucoup de pays utilisent les recommandations du CCITT pour passer leurs commandes de matériel de télécommunications. Bien que certains laboratoires de métrologie participent aux activités du CCITT, il ne semble pas que ses préoccupations soient métrologiques.

Le rôle de la CEI est d'établir des normes. Mr Nettleton indique que cet organisme a actuellement en préparation des normes sur les méthodes d'étalonnage dans le domaine des fibres optiques et, en particulier, sur les mesures de puissance. Mr Jones complète ces informations en indiquant que le CCITT adopterait probablement les normes CEI si elles étaient prêtes plus rapidement.

Mr Schanda indique que la Commission internationale de l'éclairage (CIE) n'a pas de comité technique spécifique des fibres optiques ; elle effectue des travaux seulement sur la radiométrie.

En Europe, un certain nombre d'organismes s'intéressent au problème des fibres optiques d'une manière plus ou moins active. On peut citer le Comité européen de normalisation (CEN), le Comité européen de normalisation électrotechnique (CENELEC), la Coopération européenne scientifique et technologique (COST), le Bureau communautaire de référence (BCR) et EUROMET.

Le président conclut la discussion sur ce point en indiquant que l'organisme international qui semble actuellement le plus actif est le CCITT ; ce dernier fournit des méthodes d'évaluation couvrant la plupart des besoins industriels pour la caractérisation des fibres optiques.

3. Discussion sur l'opportunité pour le BIPM et la Convention du Mètre de fournir des occasions supplémentaires de collaboration dans la métrologie des fibres optiques, particulièrement entre les laboratoires nationaux de métrologie

La plupart des réponses au questionnaire préliminaire montrent que les laboratoires souhaitent que le rôle du CIPM soit limité aux mesures fondamentales. Seuls, l'ASMW et le CSIR verraient une activité beaucoup plus large pour le CIPM ; ils sont toutefois d'accord pour reconnaître que les points fondamentaux sont les sources et les détecteurs, et plus particulièrement les mesures de puissance. Il ressort donc de cette première approche du problème que le CIPM doit s'intéresser aux mesures faites sur les fibres optiques dans les domaines qui relèvent des étalons, mais ne doit pas intervenir en ce qui concerne la technologie des fibres optiques.

Mr Nettleton pose alors le problème des mesures dimensionnelles de grande précision pour de très petites valeurs ; Mr Érard fait ensuite remarquer qu'en plus des mesures sur les sources et les détecteurs, il serait tout aussi souhaitable de prendre en considération le problème de l'atténuation.

Après cette discussion d'ordre général, on passe à l'étude du tableau des réponses liées à la question 6 (document RFO/88-1-R) pour déterminer plus précisément le rôle du CIPM dans le domaine des fibres optiques.

Sources : les deux premiers points, puissance rayonnante et répartition spectrale, sont du domaine de compétence du CIPM. Par contre le troisième point, caractéristiques de modulation, semble être davantage du ressort des laboratoires nationaux ou de l'industrie.

Détecteurs : la sensibilité spectrale, la linéarité, la réponse en fréquence et l'uniformité spatiale rentrent dans le domaine d'activité du CIPM.

Fibres en général: le diamètre de cœur et le diamètre de gaine sont des points importants pour l'industrie ; ils posent le problème de la métrologie dimensionnelle des objets très petits. Mr Quinn fait remarquer que ce problème dépasse largement le cadre des fibres optiques et couvre tout le domaine des « nanotechnologies ». Cela peut intéresser le CIPM.

Fibres monomodes : l'ensemble des problèmes posés par les fibres monomodes ne semble pas relever du domaine de compétence du CIPM.

Fibres multimodes : le GT-RF a actuellement en préparation une comparaison dans le domaine de l'atténuation pour ce type de fibre, avec l'ETL comme laboratoire pilote et cinq laboratoires participants (comparaison GT-RF/86-5). C'est donc un domaine dans lequel le CIPM a déjà une activité.

Caractéristiques des autres appareils : c'est un point très important pour l'industrie, qui pose le problème des étalonnages et de la traçabilité mais ne relève pas directement du CIPM.

De l'ensemble de cette discussion, il ressort que les membres du CCPR sont beaucoup plus orientés vers le rôle fondamental du CIPM et vers les références de base, alors que le GT-RF est beaucoup plus tourné vers les aspects industriels. Mr Ambler explique que cette orientation est due à des raisons historiques.

Pour le président, le point le plus important est de s'assurer que les laboratoires nationaux sont en bon accord entre eux avant d'entreprendre des actions à caractère plus industriel. Mr Quinn fait de plus remarquer qu'il serait important de savoir quelle marge subsiste entre les besoins des utilisateurs et les possibilités offertes par les meilleurs étalons et techniques de mesure disponibles actuellement.

Pour compléter les informations sur ce point de l'ordre du jour, le président demande à Mr Nemoto de faire un bref exposé sur l'avancement des travaux de la comparaison GT-RF/86-5. Mr Nemoto précise que la première phase de la comparaison avec une fibre multimode (diode électroluminescente, 0,85 μm) commence maintenant ; une deuxième phase est envisagée en 1989 avec une fibre monomode (diode laser, 1,3 μm).

De cette discussion il ressort que, pour le moment, les activités du CIPM, dans le domaine des fibres optiques, doivent être limitées aux sources, aux détecteurs et à l'atténuation ; pour les autres caractéristiques, la question reste ouverte.

En ce qui concerne la répartition de ces activités entre les différents comités consultatifs, il apparaît qu'une étroite collaboration entre le CCPR et le GT-RF est tout à fait souhaitable. Il est donc proposé que les mesures de puissance et des grandeurs associées soient du domaine de compétence du CCPR et que le GT-RF soit consulté et invité à participer aux travaux. Quant aux mesures d'atténuation, elles intéressent principalement le GT-RF ; elles sont donc de son ressort et, là encore, les membres du CCPR devraient être consultés et pourraient, s'ils le désiraient, participer aux comparaisons proposées.

Le problème des mesures dimensionnelles (nanotechnologies) n'étant pas de la compétence du CCPR ni du GT-RF, il sera transmis au CIPM.

4. Rapport d'avancement de la comparaison internationale de puissance optique associée aux fibres optiques (laboratoire pilote NIST)

En l'absence de Mr Gallawa, c'est Mr Nettleton qui donne le rapport d'avancement de la comparaison. Une première réunion préparatoire a eu lieu le 18 septembre 1987 à Braunschweig (Rép. féd. d'Allemagne). Cette comparaison se divise en deux parties : la première, destinée à préparer les détecteurs ; la seconde, constituée par la comparaison qui s'effectuera suivant trois branches parallèles pour diminuer les délais. Quatre laboratoires, le NIST, le NPL, la PTB et le CSIRO, sont concernés par la première partie et 14 par la seconde. Les travaux de la première partie sont en cours et les détecteurs devraient être prêts vers le mois d'avril 1989. La durée prévue pour la circulation des étalons est d'un an environ.

Le président remercie Mr Nettleton pour son rapport, ainsi que le NIST, le NPL et la PTB pour le travail déjà effectué. La discussion des résultats se fera en commun par le CCPR et le GT-RF.

À la suite de cet exposé, une brève discussion s'engage sur les problèmes pratiques liés au transport des détecteurs et aux formalités douanières. Comme dans le cas d'autres comparaisons, le BIPM conseille vivement l'utilisation du carnet ATA, document douanier qui facilite l'importation temporaire du matériel.

5. Responsabilité pour les futures comparaisons de mesures radiométriques sur les lasers

Mr Jones propose que les lasers pulsés ou de forte puissance soient du domaine de compétence du CCE et que les lasers continus de faible puissance relèvent du CCPR. En cas de doute, une discussion entre les présidents des deux comités consultatifs devrait permettre de résoudre le problème. Cette solution est satisfaisante pour l'ensemble des participants.

6. Sujets divers

Sur proposition de l'ETL, on étudie la possibilité de créer un groupe de travail commun, CCPR et CCE, sur les composants opto-électroniques. Le président demande s'il y aurait assez d'activité pour justifier la création d'un tel groupe de travail. Pour Mr Nettleton, il semble qu'une instance pour discuter ces problèmes serait probablement intéressante ; une autre solution consisterait à créer un petit groupe de travail pour chaque sujet ponctuel tel qu'une comparaison. Quant aux documents à mettre au point, la concertation pourrait se faire par écrit, sans nécessairement avoir recours à une réunion internationale.

Mr Schanda fait mention d'une comparaison internationale organisée par la CIE, portant sur les caractéristiques photométriques et radiométriques de diodes électroluminescentes. Des diodes maintenues à température constante ont circulé entre différents laboratoires qui devaient mesurer l'intensité lumineuse, le flux lumineux, la répartition spectrale et les coordonnées trichromatiques des diodes. Les résultats obtenus n'ont pas été très satisfaisants et, actuellement, deux des laboratoires participants ont repris les mesures dans de meilleures conditions pour essayer de lever les ambiguités constatées. Une future comparaison est prévue, sur une plus grande échelle, avec de nouvelles diodes. Une telle comparaison étendue à l'infrarouge intéresserait-elle les membres du CCPR et du GT-RF ?

7. Publication des travaux de la réunion

Les participants souhaitent que ce compte rendu soit publié en annexe du rapport de la session de 1988 du CCE, ainsi qu'en annexe du rapport de la session de 1990 du CCPR.

Le président remercie tous les participants pour le travail accompli et clôt la séance.

Notice for the reader of the English version

In order to make the reports of the various Comités Consultatifs more accessible to the many readers who are more familiar with the English language than with the French, the Comité International des Poids et Mesures has decided to publish an English version of these reports. The reader must however be aware that the official report is always the French one. The English version is published for convenience only. If any matter gives rise to controversy, or if an authoritative reference is needed, the French text must be used. This applies especially to the text of the recommendations submitted to the Comité International des Poids et Mesures.

Avertissement au lecteur de la version anglaise

Afin de rendre plus facile l'accès aux rapports des divers comités consultatifs pour de nombreux lecteurs qui sont plus familiers avec la langue anglaise qu'avec la langue française, le Comité international des poids et mesures a décidé de publier une version en anglais de ces rapports. Le lecteur doit cependant prendre garde au fait que le rapport officiel est toujours celui qui est rédigé en français. La version anglaise n'est publiée que pour faciliter la lecture. Si un point quelconque soulève une discussion, ou si une référence autorisée est nécessaire, c'est toujours le texte français qui doit être utilisé. Ceci s'applique particulièrement au texte des recommandations proposées au Comité international des poids et mesures.

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 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 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 for electricity (1927), photometry (1937), and ionizing radiations (1960). To this end the original laboratories, built in 1876-1878, were enlarged in 1929 and two new buildings were constructed in 1963-1964 for the ionizing radiation laboratories.

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* As of 31 December 1988 forty-seven States were members of this Convention: Argentina (Rep. of), Australia, Austria, Belgium, Brazil, Bulgaria, Cameroon, Canada, Chile, China (People's Rep. of), Czechoslovakia, Denmark, Dominican Republic, Egypt, Finland, France, German Democratic Rep., Germany (Federal Rep. of), Hungary, India, Indonesia, Iran, Ireland, Israel, Italy, Japan, Korea (Dem. People's Rep.), Korea (Rep. of), Mexico, Netherlands, Norway, Pakistan, Poland, Portugal, Romania, Spain, South Africa, Sweden, Switzerland, Thailand, Turkey, U.S.S.R., United Kingdom, U.S.A., Uruguay, Venezuela, Yugoslavia.

Some forty physicists or technicians are working in the BIPM laboratories. They are mainly conducting metrological research, international comparisons of realizations of units and the checking of standards used in the above-mentioned areas. An annual report published in Procès-Verbaux des séances du Comité International gives the details of the work in progress. BIPM's annual appropriation is of the order of 17 000 000 gold francs, approximately 31 000 000 French francs (in 1988).

In view of the extension of the work entrusted to BIPM, 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,* **31,** 1963, p. 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 eight 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 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 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.

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 ;*

— *Recueil de Travaux du Bureau International des Poids et Mesures* (this collection for private distribution brings together articles published in scientific and technical journals and books, as well as certain work published in the form of duplicated reports).

The Bureau International also publishes monographs on special metrological subjects and, under the title « Le Système International d'Unités (SI) », a booklet, periodically up-dated, 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 in 1966 by a decision of CIPM.

Since 1965 the international journal *Metrologia,* edited under the auspices of 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.

AGENDA

for the 18th Meeting

I. New representations of the volt and the ohm

A. Josephson effect

- — Review of the report and recommendations of the CCE Working Group on the Josephson effect.
- — Preliminary discussion of the adoption of a new value of the quotient frequency to voltage for use in basing a practical representation of the volt on the Josephson effect.

B. Quantum Hall effect

- — Report on the BIPM 1987 limited international comparison of one-ohm resistance standards.
- — Review of the report and recommendations of the CCE Working Group on the Quantum Hall Effect.
- — Preliminary discussion of the adoption of a value of the quantized Hall resistance for use in basing a practical representation of the ohm on the quantum Hall effect.
- — Discussion of the elimination of the drift rate of present-day ohm representations prior to lst January 1990.

C. Establishment of the International Temperature Scale of 1990 (ITS-90) and its effects

- — Report on the status of ITS-90.
- — Coordination of the implementation of the new practical representations of the volt and ohm with that of ITS-90 following the instructions of the Resolution 7 of the 18th meeting of the CGPM (October 1987).

D. Final discussion and preparation of recommendations

- — Final discussion of the adoption of values for the Josephson frequency to voltage quotient and quantized Hall resistance for use in basing representations of the volt and ohm on the Josephson and quantum Hall effects, respectively.
- — Preparation of the Recommendations to be submitted to the CIPM.

- E. Publicity for the new volt and ohm representations and ITS-90
  - — Possible actions to coordinate publicity about the new representations and about ITS-90 for users of calibration services.

II. International comparisons

- A. Progress reports and comparisons currently under way
  - — ac/dc transfer standards (VSL Pilot Laboratory)
  - — Inductance standards (PTB Pilot Laboratory)
- B. Discussion of possible new comparisons

III. Report of the CCE Working Group on Radiofrequency Quantities.

IV. Report on the work of the BIPM electricity section.

V. Discussion of the future tasks of the CCE.

VI. Miscellaneous questions.

REPORT
OF THE
COMITÉ CONSULTATIF D'ÉLECTRICITÉ
(18th Meeting — 1988)
TO THE
COMITÉ INTERNATIONAL DES POIDS ET MESURES

by O. C. Jones, Rapporteur

The Comité Consultatif d'Électricité (CCE) held its eighteenth meeting on the 27th and 28th of September 1988 at the Bureau International des Poids et Mesures, Pavillon de Breteuil, at Sèvres.

The following persons were present:

E. AMBLER, President of the CCE.

The delegates from the member laboratories:

Amt für Standardisierung, Messwesen und Warenprüfung [ASMW], Berlin (W. SCHLESOK).
CSIR, Division of Production Technology [DPT], Pretoria (W. M. P. MARAIS).
CSIRO, Division of Applied Physics [CSIRO], Lindfield (I. K. HARVEY, W. R. BLEVIN).
Electrotechnical Laboratory [ETL], Tsukuba (T. NEMOTO).
Institut de Métrologie D. I. Mendéléev [VNIIM], Leningrad (Y. V. TARBEEV, assisted by V. PUDALOV*).
Istituto Elettrotecnico Nazionale Galileo Ferraris [IEN], Turin (F. CABIATI, D. ANDREONE).
Laboratoire Central des Industries Électriques [LCIE], Fontenay-aux-Roses (H. LACOSTE, L. ÉRARD, A. FAU).
National Institute of Metrology [NIM], Beijing (ZHANG ZHONGHUA).
National Institute of Standards and Technology [NIST], Gaithersburg (B. N. TAYLOR).
National Physical Laboratory [NPL], Teddington (O. C. JONES, B. P. KIBBLE).

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* Institute of Metrological Service, Moscow.

National Research Council of Canada [NRC], Ottawa (B. M. Wood, J. Vanier).
Office Fédéral de Métrologie [OFMET], Wabern (U. Feller).
Physikalisch-Technische Bundesanstalt [PTB], Braunschweig (V. Kose, H. Bachmair).
Van Swinden Laboratorium [VSL], Delft (R. Kaarls).

The Director of the BIPM (T. J. Quinn).

Invited guest :

Statens Provningsanstalt [SP], Borås (Sweden) (H. Nilsson).

Also attending the meeting : P. Giacomo (BIPM) ; T. Endo (ETL) ; T. J. Witt, F. Delahaye, D. Reymann (BIPM) ; A. Satrapinsky, interpreter (BIPM).

Absent :

Institut National de Métrologie de la Roumanie [INM], Bucarest.

The President of the CCE and the Director of the BIPM welcomed the participants. Mr. Jones was appointed rapporteur. A revised agenda was adopted, in which it was proposed first to agree on the numerical values to be recommended for the Josephson and quantum-Hall-effect constants, and then to discuss the method of implementation of these values. These topics comprised the main business of the meeting, in response to the instructions received from the Comité International des Poids et Mesures (CIPM) following its 75th meeting in 1986 and from the Conférence Générale des Poids et Mesures (CGPM) in its 18th meeting in 1987. A total of 54 documents were presented for consideration by the CCE. A list is given in Appendix E1 (p. E 25).

1. The Josephson effect

A draft of Recommendation « Representation of the volt by means of the Josephson effect », proposed jointly by the Working Groups on the Josephson and quantum Hall effects, was discussed at some length. It was agreed to follow the suggestion of the Working Group on the Josephson effect and to use the term « Josephson constant » with symbol K_J to denote the frequency-to-voltage quotient and to use the symbol $K_{J\text{-}90}$ to denote its recommended conventional value. (*Note :* These symbols are not intended to represent the combination of fundamental constants $2e/h$.) In revising the draft Recommendation, it was decided to avoid the use of the word « representation » to describe the specification of the use of the Josephson effect together with a conventional value of the frequency-to-voltage quotient as a means of providing a laboratory reference standard of emf. The date for the implementation of the Recommendation, 1st January 1990, was confirmed.

Mr. Witt summarized the report of the Working Group on the Josephson effect (document CEE/88-34, Appendix E 2), mentioning that is was now in the 6th draft and that formal joint meetings of the Working Group on the Josephson effect and the Working Group on the quantum Hall effect had been held on 26th September 1988 at the BIPM and on 11th June 1988 after CPEM 88 in Tsukuba, Japan; furthermore, informal meetings of experts had been held at CPEM 88 in Tsukuba, at CPEM 86 in Washington, and CPEM 84 in Delft. Three draft recommendations, prepared jointly by the two Working Groups, were proposed. It was believed that the new reference standard of emf would provide both long-term stability and consistency with the SI.

In the future some reduction in the uncertainty of measurements of K_J can be expected but it is suggested that no change should be made in the recommended conventional value. The CCE could simply note the difference between a reference standard based on the Josephson effect and one based on the definition of the volt in the SI. The Working Group had proposed a value $K_J = 483\,597.9$ GHz/V with an estimated fractional one-standard-deviation uncertainty of 4×10^{-7}. This was derived from seven direct realizations of the SI definition not requiring the assumption $K_J = 2e/h$ and three indirect measurements in which it was necessary to assume that $K_J = 2e/h$. There was no significant difference between the means of these two types of data, nor was the final result particularly sensitive to the exclusion of any of the more precise values.

Mr. Vanier enquired why the 1986 CODATA value for $2e/h$ had not been incorporated in the data. Mr. Taylor explained that some of the results used by the Working Group superseded the results on which the CODATA value was based while others duplicated results incorporated in the CODATA value which was itself omitted in order to avoid « double-counting ». Mr. Taylor added that the value for $K_{J\text{-}90}$ recommended by the Working Group was consistent with the 1986 CODATA value. Mr. Tarbeev noted that the value was already appreciably different from the range of values discussed by the CCE in 1986. Mr. Cabiati stressed that a reference standard based on the Josephson effect is highly reproducible and that it was more important that all laboratories should adopt the same value for K_J than that the value itself should be exact, since the first condition would improve the consistency of electrical measurements world-wide. Mr. Quinn pointed out that this consideration appears in Resolution 6 of the 1987 Conférence Générale des Poids et Mesures (CGPM).

The Working Groups had also discussed three approaches to the problem of informing the users of calibration services about the change of reference standards. The question of the statement of uncertainty was important because the use of the Josephson-effect reference standard could cause calibration results to differ in fractional value by up to ± 4×10^{-7} (estimated one standard deviation) from results referred to the definition of the volt. This offset would be constant and common to all laboratories, and it would thus not affect trade; however, it could affect some very precise scientific experiments. The members of the Working Groups were unable to reach a consensus on this issue and were thus unable to recommend the use of any of the three approaches mentioned in their reports.

Following a detailed discussion of the implications of the three approaches, the chairman remarked that the theoretical contributions provided valuable guidance but that the main task of the CCE was to provide a soundly-based practical solution that could be introduced with the minimum inconvenience to industry. It was pointed out that Mr. Cabiati's paper (document CCE/88-53) contained a method of stating measurement results which avoided the difficulties raised by the approaches in the reports of the Working Groups and which exhibited the necessary degree of rigour. The CCE agreed that this approach should be recommended. Four working groups were formed to draft statements of the CCE's views on the major issues involved in the introduction of the new reference standards. These statements appear below. They are intended to apply to the implementation of both the Josephson-effect standard of emf and the quantum-Hall-effect standard of resistance.

2. Conclusions concerning the draft recommendations

2.1. Recommendations 1 (CI-1988) and 2 (CI-1988) * do not constitute a redefinition of SI units (B. P. Kibble, B. N. Taylor)

The conventional values $K_{J\text{-}90}$ and $R_{K\text{-}90}$ cannot be used as bases for defining the volt and ohm (meaning the present units of electromotive force and electrical resistance in the Système International d'Unités). To do so would change the status of μ_0 from that of a constant having an exactly defined value (and would therefore abrogate the definition of the ampere) and would also produce electrical units which would be incompatible with the definition of the kilogram and units derived from it.

2.2. Concerning the use of subscripts on symbols for quantities or units (R. Kaarls, W. R. Blevin, L. Érard)

The CCE considers that symbols for electromotive force (electric potential, electric potential difference) and electric resistance, and for the volt and the ohm, should not be modified by adding subscripts to denote particular laboratories or dates.

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* These CIPM recommendations are slightly modified versions of the draft recommendations submitted by the CCE.

The principal reasons for this viewpoint with respect to the physical quantities are that :

— until now, temperature being one of the very few exceptions, it has not been necessary to introduce explicitly the concept of a system of conventional physical quantities differing from the traditional quantities,

— it would be difficult to make such a concept widely understood and accepted,

— the concept, if introduced for electromotive force and electrical resistance, would propagate to other quantities.

The principal reasons for this viewpoint with respect to the units are that :

— the appearance of creating a unit system other than SI should be avoided, particularly as this would propagate to units for other quantities,

— the new reference standards will be completely satisfactory representations of the volt and the ohm for the great majority of applications,

— any disagreement between those laboratories that realize the new reference standards will be negligible from the point of view of the great majority of users,

— many countries are in any case constrained by their existing legislation concerning physical quantities and units to use the SI names and symbols.

2.3. Statement of the CCE view concerning the practical implementation of Recommendations 1 and 2 (CI-1988) (O. C. Jones, V. Kose, T. J. Quinn, B. N. Taylor)

The CCE, having carefully considered the three approaches listed in the reports of the Working Groups (documents CCE/88-34 and CCE/88-35, Appendices E 2 and E 3), is of the opinion that a rigorous solution to this problem has been identified which avoids

(i) defining new units « V_{90} » or « Ω_{90} »

(ii) defining new physical quantities « E_{90} » or « R_{90} » ; and

(iii) the use of subscripts or other distinguishing symbols of any sort on either unit symbols or quantity symbols.

The preferred approach is indicated in the following example of a statement that may be communicated to users of standard-cell calibration certificates :

The measured emf, E, or electric potential difference, U, of an unknown source may be rigorously expressed in terms of the volt, V, as :

$$E = (1.018\ \mathrm{xxx\ xx})\ \mathrm{V} \pm \varepsilon.$$

The symbol ε represents the total uncertainty, at the level of one standard deviation, and is given by

$$\varepsilon = \sqrt{(\Delta E)^2 + (E \times \delta)^2}$$

where ΔE is the combined uncertainty in volts (at one standard deviation) associated with the calibration itself and with the realization of the Josephson-effect reference standard at the particular national standards laboratory, and δ represents the relative uncertainty with which the ratio $K_{J\text{-}90}/K_J$ is known. At present δ is estimated to be 4×10^{-7} (one standard deviation) according to Recommendation 1 (CI-1988).

Since, by international agreement, δ is common to all laboratories, it may be indicated separately and the above expression for E may be re-written

$$E = (1.018\ \text{xxx xx})\ \text{V} \pm \Delta E$$

for all practical purposes of precision electrical metrology and trade. However, when this is done, δ should appear separately on the certificate where the precision is such as to require it. When $\Delta E/E$ is significantly greater than 4×10^{-7}, δ may be omitted.

The treatment of resistance measurements (Recommendation 2 (CI-1988)) is strictly analogous.

2.4. Example of the wording to be used on calibration certificates

(I. K. Harvey, J. Vanier, T. J. Witt)

The values of emf below are based on ... [a description of the calibration procedure may be placed here] ... using the new conventional value of the Josephson constant internationally adopted for use on and after January lst 1990 (*see* Note A) :

cell number	emf V	uncertainty, ΔE V
1	1.018 123 4	0.000 000 2

[other data related to the calibration may be placed here]

...

Note A *

The value of the Josephson constant used in this calibration is $K_{J\text{-}90} = 483\ 597.9$ GHz/V and is that adopted, by international agreement, for implementation on January lst, 1990 by all national standards

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* Editorial note. Some editorial changes were made to the wording of Note A after the meeting.

laboratories that use the Josephson effect as a reference standard of electromotive force. By international agreement, all such laboratories now use the same value of the Josephson constant whereas prior to the above date they did not. National standards laboratories of those countries that do not use the Josephson effect as a reference standard can maintain their own reference standards so as to be consistent with the above value of the Josephson constant, by periodic comparisons with a laboratory that does use the Josephson effect. An ideal reference standard of emf based on the Josephson effect and $K_{J\text{-}90}$ is consistent with the volt as defined in the SI within an assigned fractional one-standard-deviation uncertainty of 4×10^{-7} (0.4 μV for an emf of one volt). Because this uncertainty is the same for all national standards laboratories, it has not been formally included in the uncertainties given in the table. However, its existence must be recognized when the utmost consistency between electrical and mechanical measurements is required.

Mr. Kose commented that, notwithstanding the statement in 2.2. above, the national laboratories would probably need to use subscripts etc., when communicating with each other and with the BIPM.

The final revision of the Recommendation « Representation of the volt by means of the Josephson effect » was then adopted unanimously.

3. The quantum Hall effect

A draft of the Recommendation « Representation of the ohm by means of the quantum Hall effect » jointly proposed by the Working Groups was discussed. It was agreed to use the term « von Klitzing constant » with symbol R_K to denote the quantized Hall resistance of the plateau corresponding to $i = 1$, to which a conventional value, denoted by the symbol $R_{K\text{-}90}$ would be assigned. (*Note :* The symbol R_K is not intended to represent the combination of fundamental constants h/e^2.) The intention was to align the wording of this Recommendation with that concerning the volt, as far as possible. The date for the implementation of this Recommendation, 1st January 1990, was confirmed.

Mr. Taylor presented the report of the Working Group on the quantum Hall effect, which not only recommends a value for the von Klitzing constant, but also provides guidance as to the precautions to be taken when using the quantum Hall effect and associated conventional value for R_K to establish a reference standard of resistance. The guidance was incorporated in a separate document (document CCE/88-40) edited by Mr. Delahaye and is included as Appendix E 4.

The Recommendation and the Working Group's report (document CCE/88-35, Appendix E 3) were presented in a manner similar to those of the Working Group on the Josephson effect. In order to incorporate results based upon measurements of fundamental constants it was necessary to assume that $R_K = h/e^2$. The Working Group was confident that this assumption could be made to the level of uncertainty required. The value recommended for R_K was based upon four such indirect measurements and seven direct measurements. Additional confirmation of the direct measurements was provided by values of R_K from two laboratories which, although not equipped with calculable capacitors, related their results to the ohm by direct resistance comparisons with the CSIRO/NML. The most precise determination of R_K was the indirect value obtained from measurement of a_e, the magnetic moment anomaly of the electron.

The overall fractional spread of results was about 4 parts in 10^7 and there was a systematic difference between the means of the direct and indirect measurements, the former suggesting a value of $R_K = 25\,812.808\ \Omega$ and the latter a value of $R_K = 25\,812.806\ \Omega$. The Working Group had therefore decided to propose the value of $R_K = 25\,812.807\ \Omega$, with a conservative estimate of the one-standard-deviation fractional uncertainty of 2×10^{-7} (0.005 Ω). This result is consistent with the 1986 CODATA value but includes more recently reported results. The CCE agreed to recommend the value $R_{K\text{-}90} = 25\,812.807\ \Omega$ exactly. The final wording for the Recommendation « Representation of the ohm by means of the quantum Hall effect » was adopted unanimously.

Three possible approaches to informing the users of calibration services about the consequences of using a reference standard based upon the quantum Hall effect and associated conventional value of R_K were considered. The members of the Working Groups were again unable to agree upon a preferred approach, but suggested that the introduction of « conventional physical quantities » could lead to confusion among users of calibration services.

The CCE decided to adopt the same approach to the implementation of the Recommendation relating to the quantum Hall effect reference standard of resistance as the one which had been adopted in the case of the Josephson effect reference standard of electromotive force. The statements in 2.1 to 2.4 were considered to be equally relevant to the case of the quantum Hall effect.

Mr. Delahaye introduced document CCE/88-40 « Technical guidelines for reliable measurements of the quantized Hall resistance » (Appendix E 4). Mr. Jones said that the document was extremely helpful but that Mr. Hartland of NPL had noted some minor inconsistencies and had offered to assist with the preparation of the final version of this document. Mr. Quinn thought that this useful document would need to be updated in the future, as the techniques are still being improved quite rapidly.

The Chairman thanked the members of the Working Group on the Josephson effect and the Working Group on the quantum Hall effect for their contributions and announced that these groups were now disbanded.

4. International comparisons

4.1. International comparison of one-ohm resistance standards

Mr. Witt introduced document CCE/88-36 (Appendix E 5) describing the results of this comparison carried out at the BIPM and stressing the importance of these results in demonstrating the agreement between measurements of R_K in terms of $\Omega_{69\text{-BI}}$. Twelve laboratories had participated and there had been excellent agreement between values of R_K from five of the six laboratories that already used the quantum Hall effect to monitor their resistance standards and claim relative uncertainties of 3.6×10^{-8} or less ; the total spread, expressed as fractional values of R_K was 6.6×10^{-8}. One result of special significance was that the value of $\Omega_{69\text{-BI}}$ deduced from the comparison results agreed to within 5×10^{-9} Ω with the value predicted from the well-established drift curve based upon comparisons with the CSIRO calculable capacitor since 1964. Mr. Witt also remarked that some 1 Ω resistors possess leakage resistances that are too low, so that they are unsuitable for use in high-precision comparisons.

The Chairman enquired whether national laboratories had continued to maintain their representations of the ohm based on sets of standard resistors, since this had been requested by the CCE in 1986. The intention was to maintain the historical records of drift rates in order to ensure that measurements of R_K were soundly based. It was confirmed that this request had been met. Mr. Witt added that additional information on drift rates could be deduced by using BIPM comparisons to obtain traceability to the CSIRO calculable capacitor.

4.2. International comparison of ac/dc transfer standards

Mr. Kaarls reported progress with the Western European loops (arranged by the European Community Reference Bureau, BCR) of this world-wide comparison undertaken by the Van Swinden Laboratorium, using a set of three thermal elements with currents of 5 mA, 10 mA and 30 mA together with a set of resistors covering the range 10 V to 1 000 V. Measurements were carried out at frequencies from 40 Hz to 1 MHz. Preliminary results were reported to the CCE in 1983. The second round of the comparison involved seven national laboratories and took four and a half years to complete.

The results are summarized in Table 1 :

TABLE 1

frequency	voltage or current range	peak-to-peak range of measured ac-dc differences
40 Hz-100 kHz	10 V-100 V	10^{-4}
< 20 kHz	< 100 V	10^{-5}
1 MHz	10 V	5×10^{-4}
40 Hz-100 kHz	5, 10 and 30 mA	1.5×10^{-5}
100 kHz	10 mA	4×10^{-5}

It was concluded that, despite improvements made during the comparison, several laboratories needed to investigate their procedures. This is especially necessary if laboratories are to match the fractional uncertainty of 2 parts in 10^5 claimed for some industrial instruments. The long duration of this exercise considerably reduced its overall value.

Three further rounds of this comparison are already planned, involving an additional seven national laboratories from all parts of the world. Mr. Tarbeev expressed a strong wish for the comparison involving the VNIIM to be scheduled for a much earlier date than 1990 as suggested in document CCE/88-45. Mr. Kaarls agreed to look into the possibility of making this change. He said that detailed reports of the results of the comparisons to date would be made available via the BIPM.

4.3. International comparison of inductance standards

Mr. Kose introduced document CCE/88-22 and briefly indicated the outcome of this BCR-sponsored comparison involving six European laboratories.

The measured values for 1 H and 10 mH standards agreed at all test frequencies from 60 Hz to 5 kHz to within ± 1 part in 10^4. For the 100 μH standard similar agreement was observed, except at frequencies near the limits of the range, at 200 Hz and 5 kHz, where the deviations increased to ± 6 parts in 10^4. These uncertainties appear to meet present industrial requirements.

4.4. Report of the Working Group on Radiofrequency Quantities (GT-RF)

Document CCE/88-29, presented by the Working Group chairman, Mr. Érard, was discussed. One comparison had been completed since 1986 ; this had started in 1978. In three other comparisons the measurements had been completed but the reports were not yet available. Four comparisons had been abandoned and eighteen were in progress.

Six proposals for possible future comparisons are under consideration. A comparison of laser power at wavelengths of 0.85 µm, 1.3 µm and 1.55 µm will be the joint responsibility of the Comité Consultatif de Photométrie et Radiométrie (CCPR) and the GT-RF. No additional proposals were envisaged. Mr. Érard reviewed the BIPM Guidelines for the conduct of international comparisons and said that these would be followed. There would be a joint meeting of members of the GT-RF and the CCPR at the BIPM on 30 September 1988 (*see* Appendix E 6, p. E 143). Mr. Érard suggested that fibre-optics metrology should not be arbitrarily divided between these committees but that there should be intercommunication regarding all future proposals on this subject. The organization of an activity would be the responsibility of the committee which originated the proposal. Mr. Blevin, President of the CCPR, advocated the practice of performing a small preliminary comparison, using the agreed transfer standards and methods, before any large-scale comparison was embarked upon. He approved of the proposal for joint activities between the CCPR and the GT-RF.

5. Future activities

5.1. Participants were invited to join in a number of proposed future comparisons, as follows

R. Kaarls — ac/dc transfer standards as in 4.2 above. A number of laboratories wished to be included in this comparison.

W. Schlesok — 10 mH transfer standards to be measured at 1 000 Hz. Laboratories expressing interest were VNIIM, VSL, PTB, ASMW, LCIE, NIM, IEN, NIST, NPL, SP. The ASMW will act as pilot laboratory.

U. Feller — international comparison of standard resistors of 1 Ω and 10 kΩ as suggested by EUROMET in document CCE/88-26. This was intended to assist laboratories now making, or preparing to make, measurements based on the quantum Hall effect. Mr. Witt said that he was prepared to organize this comparison, which will be carried out at the BIPM, and proposed September 1990 as a tentative starting date. The BIPM will circulate a questionnaire among national laboratories to establish a list of those desiring to participate.

Mr. Tarbeev suggested that 6.4 kΩ resistors would be preferable to ones of 10 kΩ, but the BIPM was unwilling to carry out a large-scale comparison at this value. Mr. Kibble suggested the addition of 100 Ω resistors, but Mr. Witt said that such resistors previously measured by the BIPM had not been sufficiently stable during transportation.

Mr. Pudalov said that he had experience with sets of resistors of 100 Ω and 6.4 kΩ which had drift rates, expressed as fractional parts of the total resistance, as low as 2×10^{-8} per annum and which had been stable when transported within the USSR.

Mr. Schlesok pointed out the advantages of exchanging QHE samples rather than resistors. The socket type TO-8 was the specified standard type preferred by a number of laboratories in this field. Its wider adoption would facilitate exchanges of devices between laboratories. Mr. Kose wondered whether this should be mentioned in the QHE Guidelines document.

The Chairman queried the proposed starting date of September 1990 ; several laboratories said that they would be ready by that time.

A short discussion ensued on the availability of quantum-Hall-effect samples. It appears that AT & T Bell Laboratories cannot supply metrological-grade samples at this time. Prof. M. Ilegems of the Swiss Federal Institute of Technology, Lausanne, had provided samples to several metrology laboratories. Mr. Feller said that this institute, being a university and research oriented, would probably not be a long-term source of samples. Mr. Witt reported that Prof. von Klitzing is willing to provide samples to laboratories possessing operational quantum-Hall-effect facilities and that he prefers to dispense samples directly from his laboratory and not, as had been informally proposed, through another party such as the BIPM.

5.2. Research on fundamental constants

Recommendation E 3 « Realization of the electrical SI units » was prepared in order to draw attention to the important rôle that measurements of fundamental constants play in underpinning metrology, and electrical metrology in particular, and to encourage workers in this very demanding field to continue their efforts. It was foreseen that the uncertainties associated with the Josephson and von Klitzing constants could with advantage be reduced in the near future. Reference was also made to the advantages to be derived from improving the accuracy with which the mechanical and electrical representations of the watt could be compared. For example, there is now a real possibility that the long-term drift of the kilogram could be monitored by moving-coil experiments with reduced uncertainties.

This Recommendation was also adopted unanimously (*see* p. E 67).

5.3. Review of the result of introducing reference standards utilizing the Josephson effect and the quantum Hall effect

It was agreed that a meeting of the CCE in June 1991 should be held to review progress in adopting these new reference standards so that a report could be prepared for the next CGPM expected to be held in October 1991. New results should be available from measurements of K_J and R_K that are already in progress. The effect of the changes upon the international consistency of electrical measurements should also be studied.

5.4. Publicizing the work of the CCE

Three articles are to be prepared for publication in *Metrologia*

- « News from the BIPM », by Mr. Quinn, reporting the present meeting and quoting the three Recommendations.
- An edited version of the reports of the two Working Groups, by Messrs. Taylor and Witt.
- « Technical guidelines for reliable measurements of the quantized Hall resistance », by Mr. Delahaye.

Mr. Quinn said that documents submitted to the meeting would be bound together and issued as a supplement to the Report. This would be distributed to the representatives of the member laboratories of the CEE and made available to others on request.

6. Other matters discussed

6.1. The new international temperature scale

Mr. Quinn reported progress in preparing the ITS-90, which was likely to be implemented on lst January 1990, as planned. A graph of $\Delta T = T_{90} - T_{68}$ would be published in the beginning of 1989. Of special interest to electrical metrologists were the changes near room temperature. For example, at 20 °C, $\Delta T = -5$ mK and at 100 °C, $\Delta T = -25$ mK.

In the future there will be three fixed points near room temperature, providing primary realisations of T_{90}. These would use the triple points of mercury, water and gallium.

6.2. BIPM progress report

Mr. Witt briefly referred to document CCE/88-36 (Appendix E 5), describing the recent comparison of 1 Ω standards, and document CCE/88-25 reporting the BIPM's work on the quantum Hall effect, including the determination of R_K in terms of $\Omega_{69\text{-BI}}$. The BIPM now has a quantum-Hall-effect reference standard which can be used to maintain a group of one-ohm resistors with respect to R_K with a fractional uncertainty of 1.5×10^{-8}. Measurements of standard cells using the BIPM's 10 mV double-junction Josephson-effect reference standard have been compared with measurements using a 1 volt array donated by the NIST. Agreement is remarkably good at ± 2 parts in 10^8.

Some success has been achieved in producing weak-link Josephson junctions fabricated from the high-T_c ceramic material $YBa_2Cu_3O_7$. Measurements of $2e/h$ using this material at temperatures up to 77 K agree to within $(5.6 \pm 3.4) \times 10^{-6}$ in fractional value with the values found when using metallic superconductors. SQUID operation at temperatures up to 38 K and SQUID-like behaviour up to 77 K have also been demonstrated.

In closing the meeting, the chairman thanked the members of the two working groups and the other members of the CCE.

10 October 1988

Recommendations
adopted
by the Comité International des Poids et Mesures

Representation of the volt by means of the Josephson effect

RECOMMENDATION 1 (CI-1988)*

The Comité International des Poids et Mesures

acting in accordance with instructions given in Resolution 6 of the 18th Conférence Générale des Poids et Mesures concerning the forthcoming adjustment of the representations of the volt and the ohm,

considering

— that a detailed study of the results of the most recent determinations leads to a value of 483 597.9 GHz/V for the Josephson constant, K_J, that is to say, for the quotient of frequency divided by the potential difference corresponding to the $n = 1$ step in the Josephson effect,

— that the Josephson effect together with this value of K_J can be used to establish a reference standard of electromotive force having a one-standard-deviation uncertainty with respect to the volt estimated to be 4 parts in 10^7, and a reproducibility which is significantly better,

recommends

— that 483 597.9 GHz/V exactly be adopted as a conventional value, denoted by K_{J-90}, for the Josephson constant, K_J,

— that this new value be used from 1st January 1990, and not before, to replace the values currently in use,

— that this new value be used from this same date by all laboratories which base their measurements of electromotive force on the Josephson effect, and

— that from this same date all other laboratories adjust the value of their laboratory reference standards to agree with the new adopted value,

is of the opinion

— that no change in this recommended value of the Josephson constant will be necessary in the foreseeable future, and

draws the attention of laboratories to the fact that the new value is greater by 3.9 GHz/V, or about 8 parts in 10^6, than the value given in 1972 by the Comité Consultatif d'Électricité in its Declaration E-72.

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* This CIPM recommendation is a slightly modified version of the draft recommendation submitted by the CCE.

Representation of the ohm by means of the quantum Hall effect

RECOMMENDATION 2 (CI-1988)*

The Comité International des Poids et Mesures,

acting in accordance with instructions given in Resolution 6 of the 18th Conférence Générale des Poids et Mesures concerning the forthcoming adjustment of the representations of the volt and the ohm,

considering

— that most existing laboratory reference standards of resistance change significantly with time,

— that a laboratory reference standard of resistance based on the quantum Hall effect would be stable and reproducible,

— that a detailed study of the results of the most recent determinations leads to a value of 25 812.807 Ω for the von Klitzing constant, R_K, that is to say, for the quotient of the Hall potential difference divided by current corresponding to the plateau $i = 1$ in the quantum Hall effect,

— that the quantum Hall effect, together with this value of R_K, can be used to establish a reference standard of resistance having a one-standard-deviation uncertainty with respect to the ohm estimated to be 2 parts in 10^7, and a reproducibility which is significantly better,

recommends

— that 25 812.807 Ω exactly be adopted as a conventional value, denoted by R_{K-90}, for the von Klitzing constant, R_K,

— that this value be used from lst January 1990, and not before, by all laboratories which base their measurements of resistance on the quantum Hall effect,

— that from this same date all other laboratories adjust the value of their laboratory reference standards to agree with R_{K-90},

— that in the use of the quantum Hall effect to establish a laboratory reference standard of resistance, laboratories follow the most recent edition of the technical guidelines for reliable measurements of the quantized Hall resistance drawn up by the Comité Consultatif d'Électricité and published by the Bureau International des Poids et Mesures,

and *is of the opinion*

— that no change in this recommended value of the von Klitzing constant will be necessary in the foreseeable future.

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* This CIPM recommendation is a slightly modified version of the draft recommendation submitted by the CCE.

Recommendation of the Comité Consultatif d'Électricité

Realization of the electrical SI units

Recommendation E 3 (1988)*

The Comité Consultatif d'Électricité

recognizing

— the importance to science, commerce and industry of accuracy in electrical measurements,

— the fact that this accuracy depends on the accuracy of the reference standards of the electrical units,

— the very close ties that now exist between electrical metrology and fundamental physical constants,

— the possibility of obtaining more accurate reference standards of the electrical units either directly from the realizations of their definitions or indirectly from measurements of fundamental constants, and

— the continuing need to compare among themselves independent realizations of the units and independent measurements of fundamental constants to verify their accuracy,

recommends

— that laboratories continue their work on the electrical units by undertaking direct realizations of these units and measurements of the fundamental constants, and

— that laboratories pursue the improvement of the means for the international comparison of national standards of electromotive force and electrical resistance.

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* The CIPM took note of this recommendation.

Report of the Working Group on Radiofrequency Quantities

The Working Group met at the Electrotechnical Laboratory, Tsukuba, Ibaraki, Japan on the 13th and 14th June 1988.

Present: Mr. L. ÉRARD, Chairman, Messrs. L. BRUNETTI (IEN), R. F. CLARK (NRC), R. L. GALLAWA (NBS), U. STUMPER (PTB), J. P. M. DE VREEDE (VSL), I. YOKOSHIMA (ETL).

The Director of the BIPM, Mr. P. GIACOMO.

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

Apologies for absence were received from CSIRO, NPL.

Absent: the representatives of ASMW, IRT, NIM, VNIIM.

Dr. M. Sugiura, Director-general of the Electrotechnical Laboratory extended the welcome of the ETL and wished the GT-RF a successful meeting. He suggested that the 17 international comparisons in which ETL has been involved since the founding of the GT-RF in 1965 give ample proof of the ETL's great interest in and support of world-wide high-accuracy measurement of radiofrequency quantities.

The chairman and the director of the BIPM expressed their appreciation of the ETL's hospitality and welcomed the members of the Working Group. The agenda was considered and approved.

Mr. Clark was appointed as rapporteur.

Mr. Érard read a telegram to the meeting from the former chairman: « Best wishes for a successful meeting. Regret I cannot be with you. Arlie Bailey ».

1. International comparisons completed since the last meeting of the Working Group (September, 1986)

One comparison has been completed: details are given in Table I.

2. Comparisons almost completed

The status of three comparisons which were completed except for preparation of the final reports is given in Table II.

3. Progress on continuing comparisons

A summary of the state of progress of comparisons arranged in 1975, 1978, 1983 and 1986 which are still active is given in Table III.

4. Future work

No formal proposals for future new international comparisons were made.

The possible subjects for future comparisons listed (R 1 to R 7) in September, 1986 were considered. These are summarized in Table IV. One new possible comparison was added (R 8).

5. Other business

a) Copies of « Comments on the organization of international comparisons » by A. Rytz (BIPM Report BIPM-84/4, April 1984, revised August 1984) were distributed. Attention was called to « Guidelines for the conduct of RF intercomparisons » published in *BIPM Com. Cons. d'Électricité,* **16**, 1983, pp. E 126-128.

b) Mr. Giacomo reminded the Working Group that when two national laboratories arrange a bilateral comparison they should submit the results to the BIPM. Mr. Érard promised to distribute a copy of the results of the LCIE-VNIIFTRI comparison on waveguide and coaxial noise standards. This report (1) was distributed to members after the meeting.

c) For general information, the draft of « International Comparisons of RF and Microwave Standards » prepared by Mr. Bailey for the September, 1986 GT-RF meeting was distributed. Further information is available in « International Organization of Electromagnetic Metrology and International Comparison of RF and Microwave Standards » by A. E. Bailey, H. W. Hellwig, T. Nemoto and S. Okamura, *Proc. IEEE,* **74**, 1986, pp. 9-14.

d) Mr. Érard referred to the questionnaires he sends out annually on the progress of each comparison. If the name of the person in charge is known, Mr. Érard sends it to that person; otherwise the questionnaire goes to the last person to represent the pilot laboratory at the GT-RF. Finally, a summary of the state of progress of the comparisons is sent to each laboratory.

e) Mr. de Vreede suggested that the GT-RF investigate the accuracy of power-flux-density measurement over the frequency range 10 to 300 GHz because of the continued tightening of exposure limits for safety. The Working Group encouraged him to write a proposal for this, bearing in mind the international significance of the work.

f) There will be a joint meeting (*see* Appendix E 6, p. E 143) of the Comité Consultatif de Photométrie et Radiométrie (CCPR) and of the

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(1) Érard, L. and Petrossian, H. Intercomparaison de mesure de puissance de bruit radioélectrique entre la France et l'URSS, *Bulletin BNM,* **65**, 1989, pp. 27-29.

Working Group on Radiofrequency Quantities of the Comité Consultatif d'Électricité (CCE) on September 30, 1988 at the BIPM to discuss mutual interests of the two consultative committees in international comparisons of standards related to fibre optics. Mr. Érard summarized the position of GT-RF as follows :

(1) That this field of optical-fibre metrology should not be split between the CCPR and the GT-RF.

(2) Any comparison that has been proposed (or is in progress) should be completed by the party who proposed it (CCPR or GT-RF) but the other party should be kept fully informed of progress.

(3) Any new comparison should follow the same procedure as (2) above except there should be advance consultation between the two groups.

6. Date of the next meeting

The Working Group expects the next CCE meeting (after the September 1988 meeting) to be held in 1991. The exact date of the GT-RF meeting will be fixed when the date of that CCE meeting is known.

June 23, 1988

Rapporteur	Chairman
R. F. CLARK	L. ÉRARD

TABLE I

Comparisons completed since the last meeting of the Working Group (September 1986)

78-14 Power (1 mW) in 50 Ω coaxial line at 50 MHz.
(Pilot laboratory : NRC ; participants : CSIRO, ETL, FFV, IEN, LCIE, NBS, NPL, OMH, PTB, VSL).
The final report has been published in *IEEE Trans. Instrum. Meas.*, **IM-37**, 1988, pp. 160-162.

TABLE II

Comparisons nearly completed

72-1 Phase shift in waveguide R 100 at 9, 10 and 11.2 GHz.
(Pilot laboratory : NBS ; participants : CSIRO, ETL, NRC, RSRE).
As reported in 1978, all the laboratories have completed their measurements. Hope was expressed that the NBS would soon submit a final report.

78-11 Impedance in coaxial line at 100, 200 and 300 MHz using GR 900 connectors.
(Pilot laboratory : RSRE ; participants : CSIRO, NBS, PTB, VSL).
Though measurements by all laboratories were reported as completed in 1986, the pilot laboratory needs to carry out some final measurements. Completion of the final report is expected at the end of 1988.

83-3 Power at 94 GHz.
(Pilot laboratory : ETL ; participants : LCIE, NBS, RSRE).
All laboratories have completed their measurements. A draft of the final report and comments were presented to the meeting.

TABLE III

Comparisons in progress

a. Comparisons abandoned

After reviewing the state of progress and the degree of interest shown, the Working Group decided that the following comparisons should be terminated.

75-C 3 Pulse rise time in 50 Ω coaxial line.
(Pilot laboratory : NBS ; participants : ETL, NIM*, NPL).

78-7 CW laser power at 10.6 µm.
(Pilot laboratory : NBS ; participants : ETL, NPL, NRC, PTB).

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* to be confirmed.

78-9 Pulsed laser energy at 1.06 μm.
(Pilot laboratory : NBS ; participants : ETL, NPL, PTB, VSL).

86-7 Power in waveguide at 45 GHz.
(Pilot laboratory : NBS ; participants : ETL, RSRE).

b. Continuing comparisons*

75-A 4 Reflection coefficient in 50 Ω coaxial line at 500 MHz, 3 GHz and 7 GHz.
(Pilot laboratory : PTB ; participants : VSL, NRC, NBS, CSIRO, ETL, OMH, CSMU, NIM, RSRE, SNIIM).
The standards are now at the PTB for re-measurement, after which they will be shipped to the NIM.

75-A 6 Voltage (100 V) in 50 Ω coaxial line at 30 MHz.
(Pilot laboratory : PTB ; participants : NBS, NPLI).
Final measurements are under way at the NBS.

75-A 7 Voltage (1 mV) in 50 Ω coaxial line at 30 MHz.
(Pilot laboratory : PTB ; participants : ASMW, NBS, NIM, OMH, TTL, NPLI. Two laboratories, VSL and CSIRO, withdrew).
The PTB has the standards and will complete the final measurements and write the report.

75-A 11 Power in coaxial line at 12, 14 and 17 GHz : effective efficiency of bolometer mounts with APC-7 connectors.
(Pilot laboratory : PTB ; participants : NRC, NBS, IEN, CSIRO, LCIE, VSL, OMH).
The PTB now has the standards. They will shortly be sent to the LCIE.

75-A 14 Attenuation in 75 Ω coaxial line at 300 MHz with GR 900 connectors.
(Pilot laboratory : PTB ; participants : NPL, VSL, TTL, NRC).
The standards are now at the NPL awaiting shipment to the VSL for re-measurement. The other laboratories have completed their measurements.

75-B 3 Reflection coefficient in 75 Ω coaxial line at 1 GHz.
(Pilot laboratory : NRC ; participants : PTB, LCIE, NPL, VSL, TTL, OMH).
The comparison began in May, 1988. The travelling standards are now at the PTB.

78-1 Attenuation (60 and 100 dB) in 50 Ω coaxial line at 30 MHz.
(Pilot laboratory : PTB ; participants : VSL, LCIE, IEN, NPL, FFV, PKN, OMH, CSIRO, NBS, NIM, VNIIFTRI).
This comparison has been arranged under the aegis of both the BIPM and the EEC Bureau Communautaire de Référence (BCR). The BCR part of the comparison has been completed and a report on the result has been published in EEC literature. The standards are at the PTB and will be sent to the last laboratory, VNIIFTRI, shortly.

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

78-2 Power (10 mW) in 75 Ω coaxial line at 500 MHz (GR 900 connectors).
(Pilot laboratory : NRC ; participants : PTB, LCIE, NPL, VSL, OMH, TTL).
It is planned that the comparison will start in autumn 1988.

78-5 Horn gain and transverse polarization ratio between 8 and 12 GHz.
(Pilot laboratory : NBS ; participants : NPL, TUD, FTZ, IEN, CNET, NRC, CSIRO, ETL, VSL).
The standards are now at the CSIRO.

78-13 Noise power in waveguide R 100.
(Pilot laboratory : RSRE ; participants : NIM, CSIRO, NBS, PTB, LCIE. The ETL withdrew).
The transfer standards are at the RSRE and will be sent to the PTB after re-measurement.

83-4 Measurement of scattering coefficients (S parameters) by broad-band methods over the band 2-18 GHz. The comparison should begin soon.
(Pilot laboratory : RSRE ; participants : NBS, CSIRO, PTB, VSL).

86-1 Power flux density at 2.45 and 10 GHz.
Electric field strength between 300 and 1 000 MHz. The comparison is about to start.
(Pilot laboratory : NPL ; participants : IEN, LCIE, NBS, VSL, CSIRO, NRC*, PTB*, NIM*).

86-2 *Q*-factor at frequencies up to 30 MHz.
(Pilot laboratory : NBS ; participants : SESC, LCIE, NIM, CSIRO, PTB, VSL. The IEN withdrew).
Preliminary measurements have been made at the SESC.

86-3 Complex reflection coefficient in waveguide R320 at 27, 35 and 40 GHz.
(Pilot laboratory : RSRE ; participants : LCIE, NBS, NIM. The ETL and the NRC withdrew).
Standards have been prepared and it is expected that the comparison will start in October 1988.

86-4 Laser power at 0.85 μm, 1.3 μm and 1.55 μm.
(Pilot laboratory : NBS ; participants : NPL, PTB, CSIRO, NRC, VSL, IEN, INM, CSIC, SP, ETL, OMH, NPRL, NIM*).
Standards have been tested and sent in April 1988 to the NPL, the PTB and the CSIRO (the first part of the comparison). The CCPR is being kept informed of the details and progress of the comparison.

86-5 Attenuation (< 50 dB) in fibre-optic systems.
(Pilot laboratory : ETL ; participants : LCIE, CSELT, VSL, PTB).
The travelling standard is ready and the comparison should begin in September 1988.

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* to be confirmed.

86-6 Power in waveguide R 220 at 20 GHz ; effective efficiency of bolometer mounts.

(Pilot laboratory : LCIE ; participants : NRC, NBS, PTB, RSRE, VNIIFTRI).

The standards are now at the NRC for measurement.

86-8 Attenuation (< 25 dB) in waveguide R320 at 27, 35 and 40 GHz. (Pilot laboratory : RSRE ; participants : PTB, LCIE, NRC, NBS, NIM). The standards have been prepared. The comparison will begin in September 1988.

Table IV

Possible future topics for comparison

R 1 Horn gain at millimetre wavelengths.

The NBS and the NPL are still interested.

R 2 Dispersion in optical fibres (1.2 to 1.6 µm).

Cancelled because of lack of interest.

R 3 Noise power in coaxial line over the band 2-18 GHz, and in waveguide for frequencies above 12 GHz.

Interested laboratories : LCIE, NBS, NRC, PTB and RSRE. A possible pilot laboratory is the NBS.

R 4 Impedance in the band 0.1 to 1 000 MHz. This subject continues to interest several members of the Working Group but no concrete proposals were made.

R 5 Measurements at millimetre and sub-millimetre wavelengths (frequencies above 100 GHz).

The Working Group sets no definite upper limit to the range of frequencies with which it deals. It will consider all proposals and expects that comparisons of power and transmission parameters between 100 and 300 GHz may be organized.

R 6 Broad-band scattering coefficients (S-parameters) using type N connectors, over the band 2-18 GHz.

Cancelled because of lack of interest.

R 7 Reflection coefficient between 75 and 105 GHz (preferred frequencies : 94-95 GHz).

R 8 Power in waveguide R 320 at 35 GHz.

The IEN expressed interest in being the pilot laboratory for this international comparison and was encouraged by the Working Group to complete its preparation and to issue a formal proposal for this comparison at the next GT-RF meeting. Interested laboratories include : LCIE, NBS, NRC, PTB and VSL. Of course, the IEN should query all of the GT-RF's laboratories about their intention to participate.

APPENDIX E 1

Working documents submitted to the CCE at its 18th Meeting

(*see* the list of documents on page E 25)

APPENDIX E 2

Report from the Working Group on the Josephson Effect*

(Document CCE/88-34)

1. Introduction

1.1. Background

So that this report may also be of use to the community of electrical metrologists at large, we begin with a brief review.

The Comité Consultatif d'Électricité (CCE) of the Comité International des Poids et Mesures (CIPM) is one of eight Consultative Committees to the CIPM which together cover most of the areas of basic metrology. These committees, which may establish temporary or permanent « Working Groups » to study special subjects, coordinate the international work carried out in their respective fields, advise the CIPM about the work of the Bureau International des Poids et Mesures (BIPM) in these fields, and propose appropriate actions to the CIPM including recommendations concerning changes in the definitions and representations of units. The CIPM may endorse, modify, or reject these recommendations, submitting as appropriate those which will have a very broad impact to the Conférence Générale des Poids et Mesures (CGPM) for final approval.

As an organ of the Convention du Mètre, one of the responsibilities of the CCE is to ensure the propagation and improvement of the Système International d'Unités or SI. The SI serves as a basis for the promotion of long-term, world-wide uniformity of electrical measurements which is of considerable technical and economic importance to commerce and industry.

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* Members of this Working Group were: R. Kaarls, Van Swinden Laboratorium (Netherlands); B. P. Kibble, National Physical Laboratory (United Kingdom); B. N. Taylor, National Institute of Standards and Technology (USA); T. J. Witt [Coordinator], Bureau International des Poids et Mesures.

Consequently, at its 13th meeting held in 1972, the CCE suggested that the national standards laboratories adopt 483 594.0 GHz/V as the conventional value of the Josephson frequency-to-voltage quotient for use in realizing and maintaining accurate and stable national representations of the volt* by means of the Josephson effect [1]. While most national laboratories did in fact adopt this value, three did not. The USA, France and the USSR adopted values of the quotient which are, respectively $(1 - 1.20 \times 10^{-6})$, $(1 + 1.32 \times 10^{-6})$, and $(1 + 4.50 \times 10^{-6})$ times the value stated by the CCE in 1972 [2]. As a consequence, the national representations of the volt of these countries differ by $-1.20\,\mu V$, $1.32\,\mu V$, and $4.50\,\mu V$, respectively, from the national representations of those countries which use the 1972 value. Moreover, it has recently become evident that the 1972 value is about $(1 - 8 \times 10^{-6})$ times the SI value and thus the national representations of the volt of those countries that have adopted it are about $8\,\mu V$ smaller than the SI unit [3]. For the USA, France, and the USSR, the differences from SI are about $-9.2\,\mu V$, $-6.7\,\mu V$, and $-3.5\,\mu V$, respectively.

To address these two problems, non-uniformity among countries and inconsistency with the SI, the CCE at its 17th meeting held in September 1986 established through declaration 1986/1, concerning the Josephson effect for maintaining the representation of the volt, the CCE Working Group on the Josephson Effect [3]. The CCE charged the Working Group with making a proposal for a new value of the Josephson frequency-to-voltage quotient consistent with the SI value based upon all relevant data that become available by 15th June 1988.

Further, the CCE stated its intention to meet in September 1988 with a view to recommending a new value of this quotient to come into effect on 1st January 1990 for use by all those national standards laboratories (and others) that base their representation of the volt on the Josephson effect. This report by the Working Group on the Josephson Effect is in direct response to the charge by the CCE. It proposes a new value of the Josephson frequency-to-voltage quotient, gives the basis for this new value, and summarizes three approaches to how a representation of the volt based on the Josephson effect may be used in practice.

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* The volt is the SI unit of electromotive force (emf) or electric potential difference. Occasionally it may be referred to in the literature as the absolute volt. As-maintained volt, representation of the volt, laboratory representation of the volt, national « unit » of voltage, laboratory « unit » of voltage, practical realization of the volt, or other similar terms are commonly used to indicate a « practical unit » for expressing measurement results. However, to avoid possible confusion, it is preferable not to use the word *unit* in this context. (The only unit of emf in the SI is the volt.) This report uses the expression *representation of the volt* and variations thereof.

1.2. Permanence of the new representation of the volt

In its discussions leading to Declarations E1 and E2 (1986), the CCE agreed that while world-wide uniformity of electrical measurements can only be assured through the SI, in the particular areas of voltage and resistance, scientific, commercial and industrial requirements for long-term reproducibility now exceed the accuracy with which the SI units can be readily realized. To meet these very exacting demands, the CCE believes it is necessary that representations of the volt and the ohm be established that have a long-term reproducibility and constancy superior to those of the present direct realizations of the SI units themselves.

Although the Working Group believes that its recommended value for the Josephson frequency-to-voltage quotient upon which the new representation of the volt is to be based is consistent with the SI value within its assigned uncertainty, it recognizes that, most probably, future, more accurate measurements will show that the new recommended value differs from the SI value by some small amount. In keeping with the point of view of the CCE, the Working Group envisages that should such a situation occur, the CCE could simply note the difference between the volt and its new representation. This would be useful for those workers (mostly in the fields of realizing the electrical units and determining the fundamental physical constants) for whom the small difference may be significant. Since any such difference is expected to be sufficiently small that practical electrical measurements will be unaffected, the Working Group strongly believes that the new recommended value will not need to be significantly altered in the foreseeable future.

However, this last statement must not be interpreted to mean that improved realizations of the volt are now unnecessary. Because an accurate representation of the volt is important to science, commerce and industry, the Working Group considers it important for laboratories to continue their efforts to realize the volt with greater accuracy, either directly or indirectly through measurements of relevant fundamental constants. This could result in a significant reduction of the uncertainty assigned to the new representation.

1.3. Laboratories that do not use the Josephson effect

The purpose of the new volt representation is to improve world-wide uniformity of national representations of the volt and their consistency with the SI. The question thus arises as to the procedure to be followed by those laboratories which do not base their representation of the volt on the Josephson effect. In keeping with the viewpoint expressed by the CCE during its discussions in connection with Declaration E1 (1986), the Working Group proposes that on 1st January

1990, such laboratories adjust the value of their representation of the volt so that it is consistent with the new representation. Furthermore, this consistency should be maintained by having a transportable voltage standard periodically calibrated by a laboratory that does base its representation of the volt on the Josephson effect — for example, the BIPM.

2. Definitions, symbols, and nomenclature

2.1. Josephson frequency-to-voltage quotient

As is now well known, the Josephson effects (ac and dc) are characteristic of weakly coupled superconductors when cooled below their transition temperatures [4]. An example is two thin films of superconducting lead separated by an approximately 1 nm-thick thermally-grown oxide layer.

When, under the proper experimental conditions, such a « Josephson device » is irradiated with electromagnetic radiation of frequency ν, its current-voltage curve exhibits current steps at highly precise, quantized Josephson voltages U_J. The voltage of the nth step $U_J(n)$, n an integer, is related to the frequency of the radiation by

$$U_J(n) = n\nu / K_J, \tag{1}$$

where K_J is the Josephson frequency-to-voltage quotient which we term the Josephson constant. (Since no symbol has yet been adopted for this quotient, the Working Group proposes the use of K_J. It follows from Eq. (1) that the Josephson constant is equal to the frequency-to-voltage quotient of the $n = 1$ step.)

A significant amount of experimental evidence supports the view that the Josephson constant K_J is a universal quantity independent of experimental variables — for example, type of superconductor, temperature, and irradiation frequency and power — to very high precision [5-15]. Indeed, in one experiment it was shown that K_J was the same for two Josephson devices made of different superconducting materials to within a relative difference of 2×10^{-16} [11]. A Josephson device may thus be viewed as a nearly perfect frequency-to-voltage transducer.

The theory of the Josephson effects predicts, and the experimentally observed universality of the Josephson frequency-voltage relation [Eq. (1)] is consistent with the prediction, that K_J is equal to the invariant quotient of fundamental constants $2e/h$, where e is the elementary charge and h is the Planck constant [4, 16, 17, 18]. The Working Group thus assumes, for the purpose of including data from measurements of fundamental constants, that $2e/h = K_J$. (The same assumption was made by the CODATA Task Group on Fundamental Constants in obtaining their 1986 set of recommended values of the constants [19].)

2.2. The new representation of the volt and its practical use

In Appendix A of this report, we consider the currently available measurements of the Josephson constant K_J, deriving from them our recommended value in SI units and its assigned one-standard-deviation uncertainty* :

$$K_J = 483\,597.9 \text{ GHz/V} \tag{2a}$$

$$\text{Assigned standard deviation: } 0.2 \text{ GHz/V} \tag{2b}$$

$$\text{Corresponding relative standard deviation: } 4 \times 10^{-7}. \tag{2c}$$

For the purpose of basing a representation of the volt on the Josephson effect, the Working Group proposes to use Eq. (2*a*) to define the following conventional value for the Josephson constant :

$$K_{J\text{-}90} \overset{\text{def}}{=} 483\,597.9 \text{ GHz/V} \tag{3}$$

exactly, where the subscript 90 derives from the fact that the new representation of the volt is to come into effect starting on 1st January 1990.

The Working Group has identified three approaches to how a representation of the volt based on the Josephson effect and the defined physical quantity $K_{J\text{-}90}$ may be used in practice, each having both advantages and disadvantages. These approaches are summarized below. Two are both rigorous and correct, but in one we define a new unit, V_{90}, and in the other we define a new physical quantity, E_{90}. The Working Group believes that the best way to avoid confusion internationally is for the national standards laboratories to adopt a uniform approach. It is imperative that the laboratories avoid giving the impression that there is more than one representation of the volt in general use and that there may be significant differences between national realizations of the new representation of the volt.

2.2.1. Approach 1

A new unit of electromotive force (or electric potential difference) is defined via the equation

$$\mathrm{V}_{90} \overset{\text{def}}{=} (K_{J\text{-}90}/K_J)\ \mathrm{V} \tag{4}$$

exactly **. However, the experimental realization by a particular

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* Throughout this report, we treat uncertainties following the suggestions of the BIPM Working Group on the Statement of Uncertainties as embodied in Recommendation INC-1 (1980) and affirmed by the CIPM in Recommendation 1 (CI-1981) [20]. In particular, all uncertainties are given as one-standard-deviation estimates in keeping with CIPM Recommendation 1 (CI-1986) [21].

** Equation (4) is reminiscent of the familiar relation $V_{76\text{-BI}} = 483\,594 \text{ GHz}/K_J$, where the physical quantity $V_{76\text{-BI}}$ is the BIPM representation of the volt based on the Josephson effect which came into force starting on 1st January 1976.

laboratory of the defined unit V_{90} has an associated uncertainty. Based on the Josephson-effect apparatus in current use, this uncertainty will generally lie in the range 0.01 μV to 0.1 μV [2]. Since Eqs. (2), (3), and (4) imply that

$$1\ V_{90} = 1\ V \pm 0.4\ \mu V, \qquad (5)$$

the uncertainty with which a particular realization of V_{90} represents the volt will have two components : the 0.4 μV of Eq. (5) and the experimental uncertainty associated with the realization. If, to be specific, we assume that the latter is 0.07 μV, then the emf E' of a particular standard cell expressed in terms of V_{90} would be (again to be specific)

$$E' = (1.018\,603\,59 \pm 0.07 \times 10^{-6})\ V_{90}. \qquad (6)$$

(We also assume for simplicity a perfect standard cell and no uncertainty associated with the calibration process.) It follows from Eqs. (5) and (6) that the emf of the cell expressed in volts is

$$E' = (1.018\,603\,59 \pm 0.41 \times 10^{-6})\ V. \qquad (7)$$

If it is necessary to distinguish between different experimental realizations of V_{90}, the symbol $V_{90\text{-LAB}}$ may be used, where LAB stands for a convenient abbreviation of the name of the laboratory carrying out the realization. Such distinction should only be necessary for work involving two or more national standards laboratories ; it should not be required even in dealings with the most demanding users of calibration services.

Advantages of Approach 1

— It enables voltage measurements to be reported in a straightforward way in terms of a laboratory's realization of V_{90} (i.e., in terms of the laboratory's representation of the volt) with its relatively small uncertainty.

— It is consistent with current practice since most standards laboratories report the results of calibrations in terms of their representation of the volt. Consequently, it will be readily understood by users of calibration services.

— The incorrect practice of using the physical quantity V_{LAB} as a unit will be replaced by the correct practice of using the unit V_{90}.

Disadvantages of Approach 1

— It introduces a new unit which is likely to differ from the volt by some small amount and which is parallel to and thus in competition with the volt. Moreover, if Approach 1 is used in a similar way to define a new unit of resistance, Ω_{90}, based on the quantum Hall effect, then a complete parallel and thus competitive system of electrical units will have been introduced (i.e., one would have A_{90}, W_{90}, C_{90}, F_{90}, H_{90}, T_{90}, etc.). This could be detrimental to coherence in the expression of physical quantities. For example, consistency between electrical and mechanical power, assured by the SI, would no longer be guaranteed.

2.2.2. Approach 2

This is formally the same approach used by the Comité Consultatif de Thermométrie (CCT) to define the 1968 temperature scale and which it will likely use to define the new International Temperature Scale of 1990 (ITS-90) to come into effect on 1st January 1990.

Let E be the symbol for the physical quantity electromotive force whose unit is the volt. Let E_{90} be the symbol for a new physical quantity called « conventional electromotive force » exactly defined by

$$E_{90} \overset{\text{def}}{=} (K_J/K_{J\text{-}90})E \qquad (8)$$

whose unit is also the volt. (Clearly electric potential difference U may be treated in a similar way.) A calibration of the same standard cell (and under the same assumptions) discussed in Approach 1 in terms of a laboratory's experimental realization of E_{90} would be expressed as

$$E'_{90} = (1.018\,603\,59 \pm 0.07 \times 10^{-6})\text{V} \qquad (9)$$

[One way of demonstrating that Eq. (9) is correct is by combining Eqs. (4), (6), and (8).] It is important to recognize that E'_{90} is a new physical quantity; it is not the same as E' but is related to it through Eq. (8). However, the numerical value of E'_{90} expressed in volts [Eq. (9)] is the same as the numerical value of E' expressed in terms of the unit V_{90} [Eq. (6)], but E'_{90} has the units of volts. It follows from Eqs. (2), (3), (8), and (9) that E' in volts is

$$E' = (1.018\,603\,59 \pm 0.41 \times 10^{-6})\text{V}. \qquad (10)$$

As would be expected, Eq. (10) is identical with Eq. (7).

In a manner similar to that discussed under Approach 1, if it is necessary to distinguish between experimental realizations of E_{90} or measurement results such as E'_{90}, then the symbols $E_{90\text{-LAB}}$ or $E'_{90\text{-LAB}}$ may be used.

Advantages of Approach 2

It enables voltage measurements to be reported in a rigorous way in terms of a laboratory's representation of the volt with its relatively small uncertainty.

— It does not introduce a new unit to compete with the volt; measurements are reported in volts.

Disadvantages of Approach 2

— It is not consistent with current practice in electrical metrology and is likely to cause some confusion.

— It introduces a new physical quantity for emf which is likely to differ from emf by some small amount. Thus the same standard cell would have both a conventional emf and an emf. Moreover, if Approach 2 is used in a similar way to define a new physical quantity for resistance, R_{90}, based on the quantum Hall effect, then a complete parallel set of electrical quantities will have been introduced (i.e., one would have I_{90}, P_{90}, Q_{90}, C_{90}, L_{90}, B_{90}, etc.). However, although historically the confusion resulting from the use of concurrent systems of electrical units is well known, experience in the area of thermometry has shown that the introduction of a conventional temperature has not resulted in a comparable level of misunderstanding.

2.2.3. Approach 3

This approach is in reality Approach 1 but a unit such as V_{90} is not formally defined and used. The calibration of the above standard cell would be reported as

$$E' = (1.018\,603\,59 \pm 0.07 \times 10^{-6})\,\mathrm{V} \qquad (11)$$

but with accompanying text stating in effect that the value given is not really in volts but is actually based on the laboratory's representation of the volt which in turn is based on the Josephson effect and the internationally-adopted value of the Josephson constant as recommended by the CCE. Because the unit V is used in Eq. (11), equations such as (7) and (10) could not be readily given (assuming it was useful to do so). Instead, it would have to be stated in the text that the uncertainty of the emf of the cell in volts is ± 0.41 μV.

Advantages of Approach 3

— Because of its similarity with current practice in some laboratories, it should be readily understood.

— It avoids formally introducing a new unit of emf or a conventional emf.

Disadvantages of Approach 3.

— It lacks rigour ; Eq. (11) is incorrect since it gives the emf in volts but the uncertainty as if the emf were reported in terms of the laboratory's representation of the volt. If E' is reported in volts, its uncertainty should be given as 0.41 μV. In a rigorous variation of Approach 3, one avoids giving an incorrect equation such as Eq. (11) by deleting the unit V and adding further explanatory text. This increases further the amount of written material required to explain the reported value. Moreover, without such detailed information, this approach would be a continuing source of confusion.

— In contrast to Approaches 1 and 2, there is no clear indication that a new representation of the volt is in use.

2.2.4. Working Group Recommendation

Two members of the Working Group on the Josephson effect prefer Approach 2 because of its rigour and because it does not introduce a new unit in competition with the volt. One member prefers Approach 3 or its variant because it is in common use and will not be a real change. He believes that the lack of rigour of this approach is of little practical consequence. (Among the members of the Working Group on the Quantum Hall Effect, the preferences are : one member for Approach 1, four for Approach 2, and one for Approach 3.)

Because of its importance, the Working Group believes that the CCE in its entirety should consider this issue and recommend a solution.

3. Conclusion

- Based on direct measurements of the Josephson constant K_J, and indirect measurements involving fundamental physical constants, the Working Group adopts 483 597.9 GHz/V as its recommended value for K_J with an assigned one-standard-deviation uncertainty of 0.2 GHz/V, corresponding to a relative uncertainty of 4×10^{-7}.
- The uncertainty of the new representation of the volt, as based on the Josephson effect and the Working Group's recommended value for K_J, is 0.4 μV, one-standard-deviation estimate.
- The Working Group expects that its new recommended value for K_J will not need to be significantly altered in the foreseeable future.
- Because science, commerce and industry require an accurate and internationally uniform representation of the volt, the Working Group strongly supports the view of the CCE that the new value of the Josephson constant be adopted simultaneously on 1st January 1990 by all those laboratories that base their representation of the volt on the Josephson effect, and that beginning on this date all other laboratories adjust and maintain the value of their representation of the volt to be consistent with the new value.
- The Working Group's recommended value for the Josephson constant is approximately $(1 + 8.06 \times 10^{-6})$ times the value 483 594 GHz/V stated by the CCE in 1972. This implies that the new representation of the volt will exceed a representation of the volt based on the 1972 value by about 8.06 μV.

- The Working Group believes that, to avoid confusion internationally, the national standards laboratories should adopt a uniform approach to using the new representation of the volt. The laboratories must avoid giving the impression that there is more than one representation of the volt in use and that national realizations of the new representation differ significantly. This uniformity will be enhanced if laboratories refrain from using distinguishing symbols (except among themselves) to denote their representation of the volt.
- Given the importance of an accurate representation of the volt to science, commerce and industry, laboratories should continue their efforts to realize the volt with improved accuracy so that the uncertainty of the new representation may be reduced.

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Appendix A of the Report from the Working Group on the Josephson Effect

A.1. Derivation of the Working Group's recommended value of the Josephson constant K_J

A.1.1. Approach

Because the Working Group's recommended value of K_J is for use in realizing a practical representation of the volt by means of the Josephson effect, we adopt the following guiding principle for its derivation : the value should be so chosen that it is unlikely to require significant change in the foreseeable future. This means that the number of digits given for the recommended value should be the minimum possible and that the uncertainty should be conservatively assigned. This principle also implies that it is unnecessary to carry out a complete least-squares adjustment of the fundamental physical constants to derive the recommended value ; a straightforward treatment of the individual measurements of K_J currently available should suffice.

A.1.2. Summary of data

Table A1 summarizes the measurements of K_J to be considered while Fig. A1 compares them graphically, starting from the bottom of the figure. (To aid in the comparison, the most precise value and its uncertainty are indicated by dashed and full lines, respectively, as well as by the usual point and error bars.) Values are included only if they

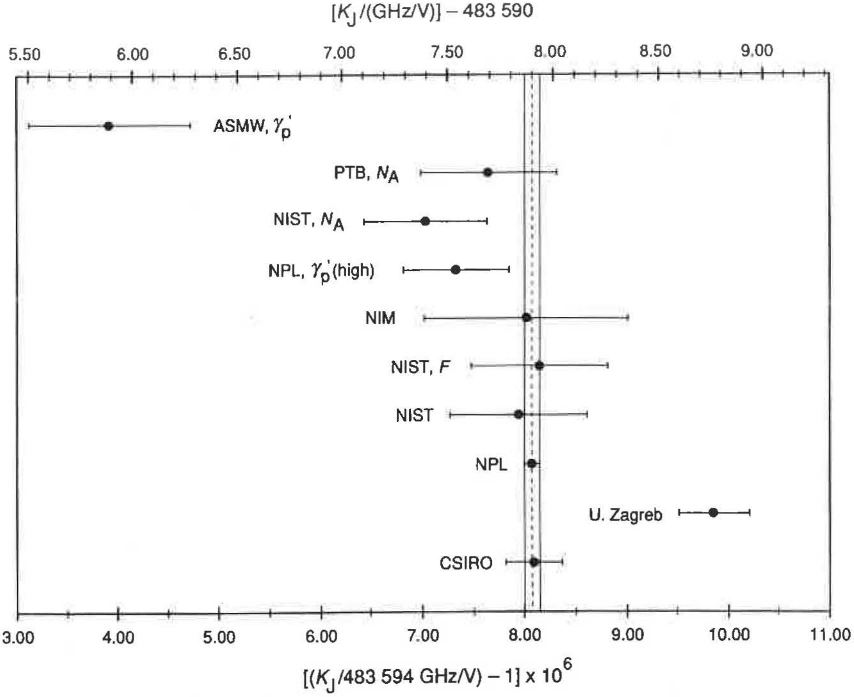

Fig. A1. — Comparison of the values of K_J and their standard deviation uncertainties as given in Table A1. The vertical dashed and solid lines indicate the value and standard deviation uncertainty of the most precise result.

were available by 15 June 1988 as stated by the CCE in its Declaration 1986/1 and for which some form of documentation was available to the Working Group. Although we shall assume $K_J = 2e/h$ as discussed in Sect. 2.1, only the last three entries of Table A1 (items 8, 9, 10) require this assumption. Such values are usually termed *indirect*, while those which do not require this assumption (items 1 through 7) are termed *direct*.

In general, we have excluded an earlier result from a particular experiment when it has been replaced by a more recent and presumably more reliable result from the same or a closely related experiment. Also excluded are measurements having a relative uncertainty larger than about 1 × 10^{-6} because they cannot contribute in a significant way to the derivation of our recommended value.

The values given in Table A1 require further explanation.

Item 1. The relative uncertainty of the result from the Commonwealth Scientific and Industrial Research Organization (CSIRO), National Measurement Laboratory (NML), Australia, obtained using an elevated mercury column or so-called mercury electrometer, has been reduced

TABLE A1

Summary of values of the Josephson constant K_J [a]

For ease of comparison, the values are given in two forms : in GHz/V (column 2) ; and in parts in 10^6 relative to the value for the Josephson constant stated by the CCE in 1972, namely, 483 594 GHz/V (column 3).

Item No.	K_J (GHz/V)	$[(K_J/483\,594\ \mathrm{GHz/V}) - 1] \times 10^6$	Remarks and references
1.	483 597.91 ± 0.13	8.09 ± 0.27	CSIRO/NML Hg electrometer [A1, A2]
2.	483 598.77 ± 0.17	9.86 ± 0.35	U. Zagreb capacitor volt balance, realization of farad via calculable capacitor and voltage calibrations in terms of K_J from other laboratories [A3]
3.	483 597.903 ± 0.037	8.070 ± 0.077	NPL realization of watt via moving-coil balance, realization of ohm via calculable capacitor [A4]
4.	483 597.84 ± 0.32	7.94 ± 0.67	NIST realization of watt via moving-coil balance, realization of ohm via calculable capacitor [A5-A7]
5.	483 597.94 ± 0.33	8.15 ± 0.67	NIST γ'_p(high) from F, γ'_p(low), realization of ohm via calculable capacitor [A8]
6.	483 597.88 ± 0.48	8.02 ± 0.99	NIM γ'_p(high), γ'_p(low), realization of ohm via calculable capacitor [A9-A12]
7.	483 597.54 ± 0.25	7.33 ± 0.52	NPL γ'_p(high), NIST γ'_p(low), NBS and NML realizations of ohm via calculable capacitor [A13]
8.	483 597.40 ± 0.29	7.03 ± 0.60	$2e/h$ from NIST N_A, $\alpha(a_e)$ [A14]
9.	483 597.70 ± 0.32	7.65 ± 0.66	$2e/h$ from PTB N_A using NIST silicon reference sample of known molar mass, $\alpha(a_e)$ [A15]
10.	483 595.90 ± 0.39	3.92 ± 0.80	$2e/h$ from ASMW γ'_p via γ'_p(low) and γ'_p(high), $\alpha(a_e)$ [A16]

[a] To minimize rounding errors, calculations were carried out with values generally having one or more digits in addition to those shown.

from 0.31×10^{-6} to 0.27×10^{-6} based on further measurements relating to the density of the reference mercury used in the NML experiment and to the stability of the density of mercury during long-term storage [A1, A2].

Item 2. The result from the Faculty of Electrical Engineering, University of Zagreb, Yugoslavia, given in the table is from their latest and most precise measurements [A3]. It was obtained using volt balance ETF-84 during late 1987 and the first half of 1988. However, it differs significantly from the results obtained from 1981 to 1985 using volt balances ETF-80 and ETF-82. Possible sources of systematic error in the present balance and associated equipment are being vigorously investigated. This experiment requires knowledge of the value of a reference capacitor in farads, but since it enters into the calculation of K_J to the one-half power, its contribution to the uncertainty is reduced by a factor of two.

Item 3. To obtain a value of K_J from a watt-realization experiment of the moving-coil type developed at the National Physical Laboratory (NPL), UK, a knowledge of a reference resistance in ohms is required. This resistance can either be an artifact-based resistance standard or the quantized Hall resistance. (The contribution of the uncertainty of this reference resistance to K_J is reduced by a factor of two since it enters to the one-half power.) The NPL value of K_J [A4] given in the table is based on an NPL realization of the ohm using a calculable capacitor. If it were based on the value of the von Klitzing constant recommended by the CCE Working Group on the quantum Hall effect (QHE), it would be 4.2 parts in 10^8 larger, a little over one half the standard deviation of the NPL value. Because this is a comparatively small shift and the relative uncertainty assigned by the QHE Working Group to the von Klitzing constant is 2×10^{-7}, we take the NPL result as given.

Item 4. The experiment to realize the watt by the moving-coil method at the National Institute of Standards and Technology (NIST), USA (formerly the National Bureau of Standards, NBS), is similar to that at NPL but it has not yet reached the same level of precision because a much weaker magnetic field is currently being used. The NIST result [A5-A7] is based on a realization of the ohm at NIST via a calculable capacitor. Using instead the value of the von Klitzing constant recommended by the QHE Working Group would increase the NIST result by less than one part in 10^8.

Item 5. A value of K_J can be obtained from so-called low- and high-field measurements of the gyromagnetic ratio of the proton, γ'_p(low) and γ'_p(high), and a realization of the ohm [A17] (the prime indicates a spherical, pure H_2O nuclear-magnetic-resonance or NMR sample at 25 °C). For this result, γ'_p(high) was derived from a NIST measurement of the Faraday constant F and the accepted values of well-known constants [A8]. The experiments to realize the ohm via the NIST calculable capacitor and to measure F and γ'_p(low) were carried out at NIST during the period 1973 to 1978.

Item 6. This result from the National Institute of Metrology (NIM), PRC, was obtained in the same way as item 5 except γ'_p(high) was measured directly using NMR and a force balance [A9-A12]. The experiments to realize the ohm and to measure γ'_p(low) and γ'_p(high) upon which it is based were carried out from October 1987 to May 1988 and supersede those of the 1970s.

Item 7. Like data items 5 and 6, data item 7 is based on a realization of the ohm and measurements of γ'_p(low) and γ'_p(high). It was obtained by the Working Group from the 1974 NPL measurement of γ'_p(high) [A13], the 1978 NIST measurement of γ'_p(low) [A18], a 1973 NIST calculable capacitor realization of the ohm [A19], NML calculable-capacitor realizations of the ohm carried out over the period 1964 to 1987 [A20, A21], and the results of the international comparisons of national representations of the ohm organized by BIPM over the same period. Because the same value of γ'_p(low) was used to obtain item 5, items 5 and 7 are not completely independent ; their correlation coefficient is 0.03. This correlation is taken into account in the calculations carried out in the next section as is appropriate. It is relatively small because the uncertainties of the two values of γ'_p(high) upon which items 5 and 7 are based are about six and five times larger, respectively, than the uncertainty of the NIST 1978 γ'_p(low) value.

Item 8. A value of $K_J = 2e/h$ can be obtained from a measurement of the Avogadro constant N_A via the relation

$$2e/h = [16R_\infty(m_p/m_e)N_A/(\mu_0 c^2 M_p \alpha)]^{1/2}, \qquad \text{(A1)}$$

where R_∞ is the Rydberg constant for infinite mass, m_p/m_e is the proton to electron mass ratio, $\mu_0 = 4\pi \times 10^{-7}\,\mathrm{N/A^2}$ exactly is the permeability of vacuum, $c = 299\,792\,458$ m/s exactly is the speed of light in vacuum, M_p is the molar mass of the proton, and α is the fine-structure constant. Item 8 was derived by the Working Group from this equation using (i) $N_A = 6.022\,129\,7(72) \times 10^{23}\,\mathrm{mol^{-1}}$ based on the most recent NIST silicon-lattice-spacing measurements [A14] and the NIST value for the molar volume of silicon used in the 1986 CODATA adjustment of the fundamental constants [A17] but updated to account for a new mass adjustment [A22] (the change is inconsequential) ; (ii) the CODATA value for m_p/m_e [A17] ; (iii) $R_\infty = 10\,973\,731.573(4)\,\mathrm{m^{-1}}$ [A23], a more recent and accurate value than that of CODATA ; (iv) $M_p = 1.007\,276\,468(7) \times 10^{-3}$ kg/mol based on the new value for the nuclidic mass of hydrogen from the new mass adjustment [A22] ; and (v), the most recent value of the fine-structure constant from the electron magnetic moment anomaly a_e [A24], $1/\alpha(a_e) = 137.035\,991\,4(11)$. While the NBS silicon-lattice-spacing result is not final, the value is unlikely to change by an amount of any significance in comparison with the 1.15×10^{-6} relative uncertainty of the silicon molar volume.

Item 9. This result for $K_J = 2e/h$ was derived by the Working Group from Eq. (A1) using the value $N_A = 6.022\,137\,3(79) \times 10^{23}\,\mathrm{mol^{-1}}$ as obtained from the Physikalisch-Technische Bundesanstalt, FRG, measurements of the lattice spacing and molar volume of silicon [A15]. Data items 8 and 9 are not entirely independent because they are based on the molar mass of the same silicon reference material. The 0.42×10^{-6} relative uncertainty of the molar mass of this material leads to a correlation coefficient between the two values of 0.11. This correlation is taken into account appropriately in the calculations carried out in the next section.

Item 10. This result for $K_J = 2e/h$ was derived by the Working Group from the Amt für Standardisierung, Messwesen und Warenprüfung (ASMW), DDR, low- and high-field measurements of the proton gyromagnetic ratio completed in 1985 [A16]. It is based on the relations

$$\gamma'_p = [\{\gamma'_p(\text{low})\}\{\gamma'_p(\text{high})\}]^{1/2}\ \text{s}^{-1}\text{T}^{-1} \qquad \text{(A2)}$$
$$2e/h = 4R_\infty\gamma'_p/[c\alpha^2(\mu'_p/\mu_B)], \qquad \text{(A3)}$$

where { } indicates numerical value only and it is assumed that $\gamma'_p(\text{low})$ and $\gamma'_p(\text{high})$ are measured in terms of the same laboratory representations of the volt and ohm ; μ'_p/μ_B is the magnetic moment of the proton in units of the Bohr magneton. Using the CODATA value of μ'_p/μ_B, $\gamma'_p = 2.675\,142\,7(21) \times 10^8\ \text{s}^{-1}\text{T}^{-1}$ from the ASMW measurements, and the values for the other constants indicated previously, yields the result in the table.

An alternative approach would have been to re-express the two ASMW measurements in terms of the BIPM representations of the volt and ohm and to use the NML calculable-capacitor realization of the ohm to obtain a value of K_J rather than of $2e/h$ in a manner similar to that used to obtain items 5, 6, and 7. However, the use of Eq. (A3) minimizes the considerable problems associated with the transfer to the BIPM representations without introducing any significant additional uncertainty since the constants entering Eq. (A3) are well known in comparison with the 0.80×10^{-6} relative uncertainty of the ASMW value of γ'_p.

A.1.3. Analysis of data

The simple mean and standard deviation of the mean of the ten measurements given in Table A1 are

$$K_J = (483\,597.68 \pm 0.23)\ \text{GHz/V} \qquad \text{(A4a)}$$
$$= K_{J\text{-}72}[1 + (7.61 \pm 0.47) \times 10^{-6}], \qquad \text{(A4b)}$$

where for convenience the value of the Josephson constant stated by the CCE in 1972 is denoted by the symbol $K_{J\text{-}72}$; that is, $K_{J\text{-}72} = 483\,594$ GHz/V exactly.

The simple mean and its standard deviation have little significance in the present case because of the large differences in precision among the measurements. The more appropriate weighted mean, taking as the weight of each measurement the reciprocal of the square of its assigned one-standard-deviation uncertainty, $w_i = 1/s_i^2$*, yields

$$K_J = (483\,597.907 \pm 0.086)\ \mathrm{GHz/V} \tag{A5a}$$
$$= K_{J\text{-}72}[1 + (8.08 \pm 0.18) \times 10^{-6}], \tag{A5b}$$

where the uncertainty has been calculated on the basis of external consistency. That is, the usual standard deviation of the weighted mean calculated on the basis of internal consistency, $s_I = \left[\sum_{i=1}^{N} w_i\right]^{-1/2}$, has been multiplied by the scale factor or Birge ratio $R_B = [\chi^2/\nu]^{1/2}$, where χ^2 is the statistic « chi square » and ν is the number of degrees of freedom ($\nu = N - 1 = 9$ in the present case). The reason is that the data are in disagreement ; $R_B = 2.55$ and $\chi^2 = 58.7$ rather than its expected value, equal to ν, of 9. The probability that such a large value of χ^2 has occurred by chance is essentially zero [i.e., $P(58.7|9) \simeq 0$].

The problem, of course, is that the University of Zagreb result, item 2, and the ASMW result, item 10, strongly disagree with each other as well as with most of the remaining data. This is readily apparent from an examination of Table A1 and Fig. A1. Indeed, item 2 accounts for about 44 % and item 10 for about 46 % of the above value of χ^2, respectively. If these two clearly discrepant items are deleted, one finds for the weighted mean

$$K_J = (483\,597.887 \pm 0.035)\ \mathrm{GHz/V} \tag{A6a}$$
$$= K_{J\text{-}72}[1 + (8.039 \pm 0.071) \times 10^{-6}], \tag{A6b}$$

where the uncertainty is now calculated on the basis of internal consistency (as will be the case for the remainder of this section). The eight values are in excellent agreement : $\chi^2 = 5.22$ for $\nu = 7$, $R_B = 0.86$, and $P(5.22|7) \simeq 0.63$. (We assume as usual that $P > 0.05$ indicates an acceptable level of agreement.)

It is clear that the NPL result, item 3, will dominate any weighted mean in which it is included because its assigned uncertainty is significantly smaller than that of any other value. If it is deleted along with the discrepant items 2 and 10, the weighted mean of the remaining seven items is

$$K_J = (483\,597.794 \pm 0.092)\ \mathrm{GHz/V} \tag{A7a}$$
$$= K_{J\text{-}72}[1 + (7.84 \pm 0.19) \times 10^{-6}], \tag{A7b}$$

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* This is the appropriate equation if all of the covariances or correlation coefficients between the measurements are zero. In fact, a generalized variance matrix was used because of the correlations between some of the data that were indicated in Sect. A.1.2.

with $\chi^2 = 4.03$ for $\nu = 6$, $R_B = 0.82$, and $P(4.03|6) = 0.67$. Again, these values are in excellent agreement among themselves. Moreover, their weighted mean is consistent with the highly precise NPL result, item 3. The relative difference is $(0.23 \pm 0.21) \times 10^{-6}$.

If the next most precise value, the CSIRO/NML result (item 1), is deleted along with the two discrepant items 2 and 10 and the NPL result (item 3), one finds

$$K_J = (483\,597.67 \pm 0.13)\ \mathrm{GHz/V} \qquad (A8a)$$
$$= K_{J\text{-}72}[1 + (7.60 \pm 0.27) \times 10^{-6}], \qquad (A8b)$$

with $\chi^2 = 2.38$ for $\nu = 5$, $R_B = 0.69$, and $P(2.38|5) = 0.79$. The relative difference between this value and the NPL value is $(0.47 \pm 0.28) \times 10^{-6}$, which is acceptable agreement.

Because item 10 is discrepant and the two remaining indirect values, items 8 and 9, are of low precision relative to the two most precise direct values, items 1 and 3, little can be learned from a detailed comparison of the means of the direct and indirect values. However, we do note that the relative difference between the weighted mean of the six consistent direct measurements, items 1, 3, 4, 5, 6, and 7, and that of items 8 and 9 is $(0.75 \pm 0.47) \times 10^{-6}$. The agreement is acceptable.

A.1.4. Selection of recommended value

It is clear from the above analysis that taking as the recommended value $K_J = 483\,597.9$ GHz/V is highly consistent with any reasonable treatment of the data and the Working Group's adopted guiding principle discussed in the first section of this Appendix. The question remains as to the one-standard-deviation uncertainty to be assigned to this value which will also be consistent with the principle.

Considering (i) that the peak-to-peak scatter among the individual measurements upon which the highly precise NPL result is based is about 0.35 GHz/V, which corresponds to a relative peak-to-peak scatter of 0.73×10^{-6}; (ii) that the difference between Eqs. (A6) and (A8) is 0.21 GHz/V, which corresponds to a relative difference of 0.44×10^{-6}; and (iii) the existence of the discrepant items 2 and 10, the Working Group believes that adopting 0.2 GHz/V as the one-standard-deviation uncertainty, which corresponds to a relative uncertainty of 4×10^{-7}, is consistent with both its guiding principle and the data. Thus the Working Group's recommended value and assigned uncertainty are

$$K_J = 483\,597.9\ \mathrm{GHz/V} \qquad (A9a)$$

Assigned standard deviation: 0.2 GHz/V (A9b)

Corresponding relative standard deviation: 4×10^{-7}. (A9c)

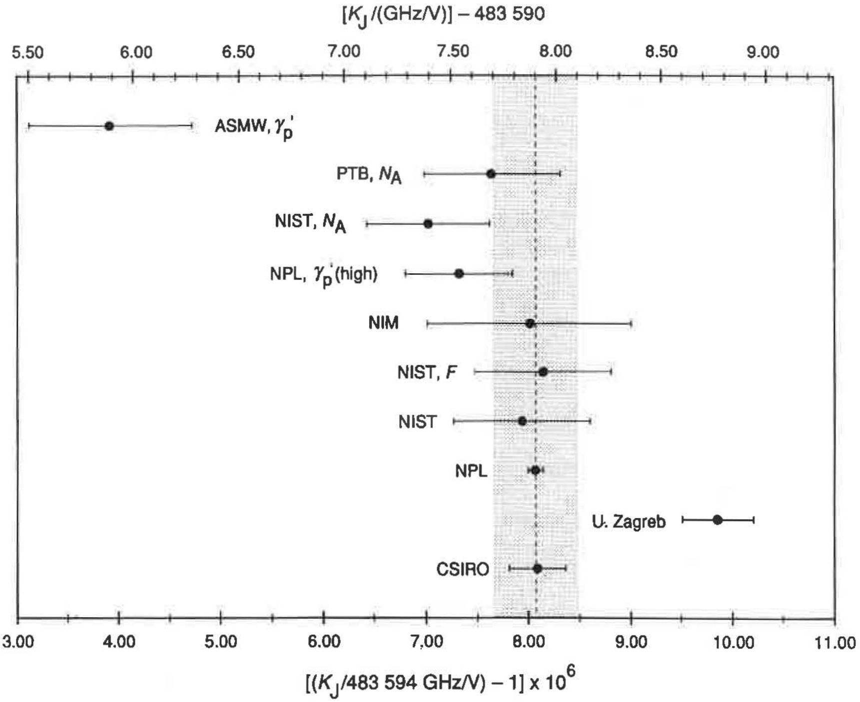

Fig. A2. — Comparison of the recommended value of K_J (vertical dashed line) and its assigned standard deviation uncertainty (delimited by the shading) with the values of K_J and their standard deviation uncertainties given in Table A1.

Figure A2 graphically compares this value with the data of Table A1. (The dashed line is the recommended value and the shading delimits its uncertainty.) Equation (A9) is consistent with the 1986 CODATA value $K_J = (483\ 597.67 \pm 0.14)$ GHz/V [A17].

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Note added in proof. The University of Zagreb group under Professor V. Bego has identified several unsuspected systematic errors in their volt balance and associated equipment (see *Item* 2, Sect. A.1.2 and Table A1). When these are taken into account, the U. Zagreb value of K_J agrees with the recommended value. However, a final result from the experiment will not be available until additional data are obtained and the analysis of all known possible sources of error is completed (V. Bego, private communication, January 1989).

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APPENDIX E 3

Report from the Working Group on the Quantum Hall Effect*

(Document CCE/88-35)

1. Introduction

1.1. Background

So that this report may also be of use to the community of electrical metrologists at large, we begin with a brief review.

The Comité Consultatif d'Électricité (CCE) of the Comité International des Poids et Mesures (CIPM) is one of eight Consultative Committees to the CIPM which together cover most of the fields of basic metrology. These committees, which may establish temporary or permanent « Working Groups » to study special subjects, coordinate the international work carried out in their respective fields, advise the CIPM about the work of the Bureau International des Poids et Mesures (BIPM) in these fields, and propose appropriate actions to the CIPM including recommendations concerning changes in the definitions and representations of units. The CIPM may endorse, modify, or reject these recommendations, submitting as appropriate those which will have a very broad impact to the Conférence Générale des Poids et Mesures (CGPM) for further approval.

As an organ of the Convention du Mètre, one of the responsibilities of the CCE is to ensure the propagation and improvement of the Système International d'Unités or SI. The SI serves as a basis for the promotion of long-term, world-wide uniformity of electrical measurements which is of considerable technical and economic importance to commerce and industry.

As a consequence, the CCE has become increasingly concerned that, because most national standards laboratories base their representation

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* Members of this Working Group were : F. Delahaye, Bureau International des Poids et Mesures ; T. Endo, Electrotechnical Laboratory (Japan) ; O. C. Jones, National Physical Laboratory (United Kingdom) ; V. Kose, Physikalisch-Technische Bundesanstalt (Fed. Rep. of Germany) ; B. N. Taylor [Coordinator], National Institute of Standards and Technology (USA) ; B. M. Wood, National Research Council (Canada).

of the ohm* on the mean resistance of a particular group of precision wire-wound standard resistors, and because these artifact standards age, the various national representations of the ohm differ significantly from each other and the ohm, and some are drifting excessively. Indeed, current evidence indicates that most national representations of the ohm are from a few tenths μΩ larger to a few μΩ smaller than the ohm and that their drift rates lie in the range − 0.07 to + 0.07 μΩ/year [1].

Although in principle a so-called Thompson-Lampard calculable capacitor can be used to realize the ohm with an uncertainty of less than 0.1 μΩ, this is in practice a difficult experiment to carry out routinely ; only one laboratory in the world has had such an apparatus in continuous operation since the method was first developed in the early 1960s [2]. Consequently, electrical metrologists enthusiastically welcomed von Klitzing's 1980 discovery of the quantum Hall effect (QHE) [3] since it promised to provide a method for basing a representation of the ohm on fundamental constants in much the same manner as the Josephson effect has provided a method for basing a representation of the volt on fundamental constants. The QHE clearly had the potential of virtually eliminating in a relatively simple way the problems of non-uniformity of national representations of the ohm and their variation with time. When combined with results of realizations of the ohm, the QHE could also serve to remove their inconsistency with the SI.

Recognizing the rapid advances that have been made in understanding the QHE since its comparatively recent discovery, the CCE at its 17th meeting held in September 1986 established through Declaration 1986/2, « Concerning the quantum Hall effect for maintaining a representation of the ohm », the Working Group on the Quantum Hall Effect [4]. The CCE charged the Working Group to (i) propose to the CCE, based upon all relevant data that become available by 15th June 1988, a conventional value of the quantized Hall resistance (QHR), that is a good approximation of the true SI value, for use in realizing and maintaining accurate and stable national representations of the ohm by means of the QHE ; and (ii) develop detailed guidelines for the proper use of the QHE to realize such representations reliably.

Further, the CCE stated its intention to meet in September 1988 with a view to recommending this value of the QHR to come into effect on 1st January 1990 for use by all those national standards

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* The ohm is the SI unit of resistance. Occasionally it may be referred to in the literature as the absolute ohm. As-maintained ohm, representation of the ohm, laboratory representation of the ohm, national « unit » of resistance, laboratory « unit » of resistance, practical realization of the ohm, or other similar terms are commonly used to indicate a « practical unit » for expressing measurement results. However, to avoid possible confusion, it is preferable not to use the word *unit* in this context. (The only unit of resistance in the SI is the ohm.) This report uses the expression *representation of the ohm* and variations thereof.

laboratories (and others) that choose to base their representation of the ohm on the QHE.

This report by the Working Group on the Quantum Hall Effect is in direct response to the charge by the CCE. It proposes the value of the QHR to be adopted, gives the basis for this value, and summarizes three approaches to how a representation of the ohm based on the QHE may be used in practice. Additionally, technical guidelines for the reliable measurement of the QHR are provided in a companion report (Appendix E 4). Since such measurements are required for the practical realization of an accurate and reproducible representation of the ohm based on the QHE, these guidelines are of exceptional importance.

1.2. Permanence of the new representation of the ohm

In its discussions leading to Declarations 1986/1 and 1986/2, the CCE agreed that while world-wide uniformity of electrical measurements can only be assured through the SI, in the particular areas of voltage and resistance, scientific, commercial and industrial requirements for long-term reproducibility now exceed the accuracy with which the SI units can be readily realized. To meet these very exacting demands, the CCE believes it is necessary that representations of the volt and ohm be established that have a long-term reproducibility and constancy superior to those of the present direct realizations of the SI units themselves.

Although the Working Group believes that its recommended value for the QHR upon which the new representation of the ohm is to be based is consistent with the SI value within its assigned uncertainty, it recognizes that, most probably, future, more accurate measurements will no doubt show that the recommended value differs from the SI value by some small amount. In keeping with the point of view of the CCE, the Working Group envisages that should such a situation occur, the CCE could simply note the difference between the ohm and its new representation. This would be useful for those workers (mostly in the fields of realizing the SI electrical units and determining the fundamental physical constants) for whom the small difference may be significant. Since any such difference is expected to be sufficiently small that practical electrical measurements will be unaffected, the Working Group strongly believes that the recommended value will not need to be significantly altered in the foreseeable future.

However, this last statement must not be interpreted to mean that improved realizations of the ohm are now unnecessary. Because an accurate representation of the ohm is important to science, commerce and industry, the Working Group considers it important for laboratories to continue their efforts to realize the ohm with greater accuracy, either directly or indirectly through measurements of relevant fundamental constants. This could result in a significant reduction of the uncertainty assigned to the new representation.

1.3. Laboratories that do not use the quantum Hall effect

The purpose of the new ohm representation is to improve worldwide uniformity of national representations of the ohm and their consistency with the SI. The question thus arises as to the procedure to be followed by those laboratories which will not base their representation of the ohm on the QHE. In keeping with the viewpoint expressed by the CCE during its discussions in connection with Declaration 1986/2, the Working Group proposes that on lst January 1990, such laboratories adjust the value of their representation of the ohm so that it is consistent with the new representation. Furthermore, this consistency should be maintained by having a transportable resistance standard periodically calibrated by a laboratory that does base its representation of the ohm on the QHE — for example the BIPM.

2. Definitions, symbols, and nomenclature

2.1. Hall voltage-to-current quotient or quantized Hall resistance

As is now well known, the quantum Hall effects (integral and fractional) are characteristic of a two-dimensional electron gas (2 DEG). A 2 DEG may be realized in a high-mobility semiconductor device such as a silicon MOSFET (metal-oxide-semiconductor field-effect transistor) or GaAs-$Al_xGa_{1-x}As$ heterostructure, of standard Hall-bar geometry, when the applied magnetic flux density is of the order of 10 T and the device is cooled to a temperature of a few kelvins [5]. Under these conditions, the 2 DEG is completely quantized and for a fixed current I through the device there are regions in the curve of Hall voltage vs. gate voltage, or of Hall voltage vs. magnetic flux density, where the Hall voltage U_H remains constant as the gate voltage or magnetic flux density is varied. These regions of constant Hall voltage are termed Hall plateaux.

In the limit of zero dissipation in the direction of current flow, the Hall resistance of the ith plateau $R_H(i)$, defined as the quotient of the Hall voltage of the ith plateau to the current I, is quantized :

$$R_H(i) = U_H(i)/I = R_K/i, \qquad (1)$$

where i is an integer* and R_K is the von Klitzing constant. (It follows

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* We restrict ourselves to the integral QHE for which i is an integer. The fractional QHE, for which i is the ratio of two integers, has not yet been studied sufficiently to warrant its use as a basis for a representation of the ohm.

from Eq. (1) that R_K is equal to the resistance of the $i = 1$ plateau, $R_H(1)$. Since the term QHR is often used to mean $R_H(i)$, to avoid confusion the Working Group proposes the use of R_K as the symbol for the Hall voltage-to-current quotient or resistance of the $i = 1$ plateau, and to refer to it as the von Klitzing constant after the discoverer of the QHE.

A significant amount of experimental evidence supports the view that the von Klitzing constant R_K is a universal quantity, provided that the particular QHE device used meets certain criteria. While the universality of R_K has not yet been demonstrated to a level of precision approaching that of the Josephson frequency-to-voltage quotient or Josephson constant K_J, studies of the influence of experimental variables such as current, temperature, device type, device material and plateau number have shown that if certain precautions are taken and tests performed, then R_K may be reproduced with a relative precision approaching one part in 10^8 or possibly even several parts in 10^9 [6-12]. Carrying out QHR measurements according to the companion report prepared by the Working Group entitled « Technical Guidelines for Reliable Measurements of the Quantized Hall Resistance » should allow this level of precision to be reached. Throughout the remainder of this report we assume that these guidelines are implemented.

The current theory of the QHE predicts, and the experimentally observed universality of the fundamental QHR relation [Eq. (1)] is consistent with the prediction, that R_K is equal to the invariant quotient of fundamental constants h/e^2, where h is the Planck constant and e is the elementary charge [5, 13, 14, 15]. Although the accuracy of this equality and Eq. (1) are still under active theoretical and experimental investigation, the Working Group assumes, for the purpose of including data from measurements of fundamental constants, that $h/e^2 = R_K$. (The same assumption was made by the CODATA Task Group on Fundamental Constants in obtaining their 1986 recommended values of the constants [16].)

In particular, the fine-structure constant $\alpha \simeq 1/137$ and h/e^2 are related by defined quantities : $h/e^2 = \mu_0 c/2\alpha$, where $\mu_0 = 4\pi \times 10^{-7}$ N/A^2 exactly is the permeability of vacuum and $c = 299\,792\,458$ m/s exactly is the speed of light in vacuum. As a consequence of the above assumption, a measurement of α having a particular relative uncertainty will yield a value of R_K in ohms with the same relative uncertainty.

2.2. The new representation of the ohm and its practical use

In Appendix A of this report, we consider the currently available measurements of the von Klitzing constant R_K, deriving from them our recommended value in SI units and its assigned one-standard-deviation uncertainty* :

$$R_K = 25\,812.807\ \Omega \tag{2a}$$

$$\text{Assigned standard deviation: } 0.005\ \Omega \tag{2b}$$

$$\text{Corresponding relative standard deviation: } 2 \times 10^{-7}. \tag{2c}$$

For the purpose of basing a representation of the ohm on the QHE, the Working Group proposes to use Eq. (2a) to define the following conventional value for the von Klitzing constant :

$$R_{K\text{-}90} \overset{\text{def}}{=} 25\,812.807\ \Omega \tag{3}$$

exactly, where the subscript derives from the fact that the new representation of the ohm is to come into effect starting on 1st January 1990.

The Working Group has identified three approaches to how a representation of the ohm based on the QHE and the defined physical quantity $R_{K\text{-}90}$ may be used in practice, each having both advantages and disadvantages. These approaches are summarized below. Two are both rigorous and correct, but in one we define a new unit, Ω_{90}, and in the other we define a new physical quantity, R_{90}. The Working Group believes that the best way to avoid confusion internationally is for the national standards laboratories to adopt a uniform approach. It is imperative that the laboratories avoid giving the impression that there is more than one representation of the ohm in general use and that there may be significant differences between national realizations of the new representation of the ohm.

2.2.1. Approach 1

A new unit of resistance is defined via the equation

$$\Omega_{90} \overset{\text{def}}{=} (R_K/R_{K\text{-}90})\,\Omega \tag{4}$$

exactly. However, the experimental realization by a particular laboratory of the defined unit Ω_{90} has an associated uncertainty. Based on the QHR apparatus in current use, this uncertainty will generally lie in the range 0.01 μΩ to 0.1 μΩ [1]. Since Eqs. (2), (3), and (4) imply that

$$1\ \Omega_{90} = 1\ \Omega \pm 0.2\ \mu\Omega, \tag{5}$$

the uncertainty with which a particular realization of Ω_{90} represents the

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* Throughout this report, we treat uncertainties following the suggestions of the BIPM Working Group on the Statement of Uncertainties as embodied in Recommendation INC-1 (1980) and affirmed by the CIPM in Recommendation 1 (CI-1981) [17]. In particular, all uncertainties are one-standard-deviation estimates in keeping with CIPM Recommendation 1 (CI-1986) [18].

ohm will have two components: the $0.2\ \mu\Omega$ of Eq. (5) and the experimental uncertainty associated with the realization. If, to be specific, we assume that the latter is $0.05\ \mu\Omega$, then the resistance R' of a particular standard resistor expressed in terms of Ω_{90} would be (again to be specific)

$$R' = (1.000\,003\,59 \pm 0.05 \times 10^{-6})\ \Omega_{90}. \tag{6}$$

(We also assume for simplicity a perfect resistor and no uncertainty associated with the calibration process.) It follows from Eqs. (5) and (6) that the resistance of the resistor expressed in ohms is

$$R' = (1.000\,003\,59 \pm 0.21 \times 10^{-6})\ \Omega. \tag{7}$$

If it is necessary to distinguish between different experimental realizations of Ω_{90}, the symbol $\Omega_{90\text{-LAB}}$ may be used, where LAB stands for a convenient abbreviation of the name of the laboratory carrying out the realization. Such distinction should only be necessary for work involving two or more national standards laboratories; it should not be required even in dealings with the most demanding users of calibration services.

Advantages of Approach 1

— It enables resistance measurements to be reported in a straightforward way in terms of a laboratory's realization of Ω_{90} (*i.e.*, in terms of the laboratory's representation of the ohm) with its relatively small uncertainty.

— It is consistent with current practice since most standards laboratories report the results of calibrations in terms of their representation of the ohm. Consequently, it will be readily understood by users of calibration services.

— The incorrect practice of using the physical quantity Ω_{LAB} as a unit will be replaced by the correct practice of using the unit Ω_{90}.

Disadvantages of Approach 1

— It introduces a new unit which is likely to differ from the ohm by some small amount and which is parallel to and thus in competition with the ohm. Moreover, if Approach 1 is used to define a new unit of emf, V_{90}, based on the Josephson effect, then a complete parallel and thus competitive system of electrical units will have been introduced (i.e., one would have A_{90}, W_{90}, C_{90}, F_{90}, H_{90}, T_{90}, etc.). This could be detrimental to coherence in the expression of physical quantities. For example, consistency between electrical and mechanical power, assured by the SI, would no longer be guaranteed.

2.2.2. Approach 2

This is formally the same approach used by the Comité Consultatif de Thermométrie (CCT) to define the 1968 temperature scale and which it will likely use to define the new International Temperature Scale of 1990 (ITS-90) to come into effect on lst January 1990.

Let R be the symbol for the physical quantity resistance whose unit is the ohm. Let R_{90} be the symbol for a new physical quantity called « conventional resistance » exactly defined by

$$R_{90} \overset{\text{def}}{=} (R_{\text{K-90}}/R_{\text{K}})R \qquad (8)$$

whose unit is also the ohm. A calibration of the same standard resistor (and under the same assumptions) discussed in Approach 1 in terms of a laboratory's experimental realization of R_{90} would be expressed as

$$R'_{90} = (1.000\,003\,59 \pm 0.05 \times 10^{-6})\,\Omega. \qquad (9)$$

[One way of demonstrating that Eq. (9) is correct is by combining Eqs. (4), (6), and (8).] It is important to recognize that R'_{90} is a new physical quantity ; it is not the same as R' but is related to it through Eq. (8). However, the numerical value of R'_{90} expressed in ohms [Eq. (9)] is the same as the numerical value of R'_{90} expressed in terms of the unit Ω_{90} [Eq. (6)], but R'_{90} has the units of ohms. It follows from Eqs. (2), (3), (8), and (9) that R' in ohms is

$$R' = (1.000\,003\,59 \pm 0.21 \times 10^{-6})\,\Omega. \qquad (10)$$

As would be expected, Eq. (10) is identical with Eq. (7).

In a manner similar to that discussed under Approach 1, if it is necessary to distinguish between experimental realizations of R_{90} or measurement results such as R'_{90}, then the symbols $R_{\text{90-LAB}}$ or $R'_{\text{90-LAB}}$ may be used.

Advantages of Approach 2

It enables resistance measurements to be reported in a rigorous way in terms of a laboratory's representation of the ohm with its relatively small uncertainty.

— It does not introduce a new unit to compete with the ohm ; measurements are reported in ohms.

Disadvantages of Approach 2

— It is not consistent with current practice in electrical metrology and is likely to cause some confusion.

— It introduces a new physical quantity for resistance which is likely to differ from resistance by some small amount. Thus the same resistor would have both a conventional resistance and a resistance.

Moreover, if Approach 2 is used in a similar way to define a new physical quantity for emf, E_{90}, based on the Josephson effect, then a complete parallel set of electrical quantities will have been introduced (i.e., one would have I_{90}, P_{90}, Q_{90}, C_{90}, L_{90}, B_{90}, etc.). However, although historically the confusion resulting from the use of concurrent systems of electrical units is well known, experience in the area of thermometry has shown that the introduction of a conventional temperature has not resulted in a comparable level of misunderstanding.

2.2.3. Approach 3

This approach is in reality Approach 1 but a unit such as Ω_{90} is not formally defined and used. The calibration of the above standard resistor would be reported as

$$R' = (1.000\,003\,59 \pm 0.05 \times 10^{-6})\,\Omega \qquad (11)$$

but with accompanying text stating in effect that the value given is not really in ohms but is actually based on the laboratory's representation of the ohm which in turn is based on the QHE and the internationally adopted value of the von Klitzing constant as recommended by the CCE. Because the unit Ω is used in Eq. (11), equations such as (7) and (10) could not be readily given (assuming it was useful to do so). Instead, it would have to be stated in the text that the uncertainty of the resistance of the resistor in ohms is ± 0.21 μΩ.

Advantages of Approach 3

— Because of its similarity with current practice in some laboratories, it should be readily understood.

— It avoids formally introducing a new unit of resistance or a conventional resistance.

Disadvantages of Approach 3

— It lacks rigour ; Eq. (11) is incorrect since it gives the resistance in ohms but the uncertainty as if the resistance were reported in terms of the laboratory's representation of the ohm. If R' is reported in ohms, its uncertainty should be given as 0.21 μΩ. In a rigorous variation of Approach 3, one avoids giving an incorrect equation such as Eq. (11) by deleting the unit Ω and adding further explanatory text. This increases further the amount of written material required to explain the reported value. Moreover, without such detailed information, this approach would be a continuing source of confusion.

— In contrast to Approaches 1 and 2, there is no clear indication that a new representation of the ohm is in use.

2.2.4. Working Group Recommendation

One member of the Working Group on the Quantum Hall Effect prefers Approach 1 because it is readily understood and consistent with current practice. Four members prefer Approach 2 because of its rigour and because it does not introduce a new unit in competition with the ohm. One member prefers Approach 3 or its variant because it is in common use and will not be a real change. He believes that the lack of rigour of this approach is of little practical consequence. (Among the members of the Working Group on the Josephson Effect, the preferences are : two members for Approach 2 and one for Approach 3.)

Because of its importance, the Working Group believes that the CCE in its entirety should consider this issue and recommend a solution.

3. Conclusion

- Based on direct measurements of the von Klitzing constant R_K, and indirect measurements involving fundamental physical constants, the Working Group adopts 25 812.807 Ω as its recommended value for R_K with an assigned one-standard-deviation uncertainty of 0.005 Ω, corresponding to a relative uncertainty of 2×10^{-7}.
- The uncertainty of the new representation of the ohm, as based on the QHE and the Working Group's recommended value for R_K, is 0.2 μΩ, one-standard-deviation estimate.
- The Working Group expects that its recommended value for R_K will not need to be significantly altered in the foreseeable future.
- Because science, commerce and industry require an accurate and internationally uniform representation of the ohm, the Working Group strongly supports the view of the CCE that the recommended value of the von Klitzing constant be adopted simultaneously on lst January 1990 by all those laboratories that choose to base their representation of the ohm on the QHE and that beginning on this date all other laboratories adjust and maintain the value of their representation of the ohm to be consistent with the recommended value.
- The Working Group believes that to avoid confusion internationally, the national standards laboratories should adopt a uniform approach to using the new representation of the ohm. The laboratories must avoid giving the impression that there is more than one representation of the ohm in use and that national realizations of the new representation differ significantly. This uniformity will be enhanced if laboratories refrain from using distinguishing symbols (except among themselves) to denote their representation of the ohm.
- Given the importance of an accurate representation of the ohm to science, commerce and industry, laboratories should continue their efforts to realize the ohm with improved accuracy so that the uncertainty of the new representation may be reduced.

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Appendix A of the Report from the Working Group on the Quantum Hall Effect

A.1. Derivation of the Working Group's recommended value of the von Klitzing constant R_K

A.1.1. Approach

Because the Working Group's recommended value of R_K is for use in realizing a practical representation of the ohm by means of the QHE, we adopt the following guiding principle for its derivation : the value should be so chosen that it is unlikely to require significant change in the foreseeable future. This means that the number of digits given for the recommended value should be the minimum possible and that the uncertainty assigned to the value should be conservative. This principle also implies that it is unnecessary to carry out a complete least-squares adjustment of the fundamental physical constants to derive the recommended value ; a straightforward treatment of the individual measurements of R_K currently available should suffice.

A.1.2 Summary of data

Table A1 summarizes the measurements of R_K to be considered while Fig. A1 compares them graphically, starting from the bottom of the figure but with items 1(a) and 1(b) at the top. (To aid in the comparison, the most precise value and its uncertainty are indicated by dashed and full lines, respectively, as well as by the usual point and error bars.) Values are included only if they were available by 15 June 1988 as stated by the CCE in its Declaration 1986/2 and for which some form of documentation was available to the Working Group. Although we shall assume $R_K = h/e^2 = \mu_0 c \alpha^{-1}/2$ as discussed in Section 2.1, only the last four entries of Table A1 (items 8 through 11) require this assumption. These values are termed indirect, while those which do not require this assumption (items 1 through 7) are termed direct. In general, we have excluded an earlier result from a particular experiment when it has been replaced by a more recent and presumably more reliable result from the same or a closely related experiment.

TABLE A1

Summary of values of the von Klitzing constant R_K [a]

For ease of comparison, the values are given in two forms : in Ω (column 2) ; and in parts in 10^6 relative to the convenient reference resistance 25 812.8 Ω (column 3).

Item No.	$\frac{R_K}{(\Omega)}$	$[(R_K/25\ 812.8\ \Omega)-1]\times 10^6$	Remarks and references
1.	25 812.809 4 ± 0.001 7	0.363 ± 0.066	CSIRO/NML quantized Hall resistance (QHR) measurements and realization of ohm via calculable capacitor [A1, A2]
(a)	25 812.808 6 ± 0.001 7	0.333 ± 0.065	BIPM QHR, CSIRO/NML realization of ohm via calculable capacitor [A3, A4]
(b)	25 812.813 4 ± 0.002 1	0.520 ± 0.080	Gakushuin University (G.U.) QHR, CSIRO/NML realization of ohm via calculable capacitor [A5]
2.	25 812.809 2 ± 0.001 4	0.356 ± 0.054	NPL QHR and realization of ohm via calculable capacitor [A6]
3.	25 812.801 8 ± 0.005 7	0.070 ± 0.220	LCIE QHR and realization of ohm via calculable capacitor [A7]
4.	25 812.806 4 ± 0.006 7	0.247 ± 0.260	ETL QHR and realization of ohm via calculable capacitor [A8]
5.	25 812.807 23 ± 0.000 61	0.280 ± 0.024	NIST QHR and realization of ohm via calculable capacitor [A9-A11]
6.	25 812.806 5 ± 0.008 3	0.250 ± 0.320	Institute of Metrological Service (IMS) QHR, IMM realization of ohm via calculable capacitor [A12, A13]
7.	25 812.805 5 ± 0.015 6	0.214 ± 0.606	NIM QHR and realization of ohm via calculable capacitor [A14, A15]
8.	25 812.805 99 ± 0.000 21	0.232 1 ± 0.008 0	α^{-1} from electron magnetic moment anomaly a_e [A16, A17]
9.	25 812.806 2 ± 0.004 2	0.241 ± 0.163	α^{-1} from muonium ground-state hyperfine splitting ν (Muhfs) [A18]
10.	25 812.804 60 ± 0.000 95	0.178 ± 0.037	α^{-1} from NIST γ'_p (low), QHR, and Josephson $2e/h$ [A19, A9, A20, A11]
11.	25 812.803 3 ± 0.001 5	0.127 ± 0.056	α^{-1} from NIST γ'_p (low), realization of ohm via calculable capacitor and Josephson $2e/h$ [A19, A10, A20, A11]

[a] To minimize rounding errors, calculations were carried out with values generally having one or more digits in addition to those shown.

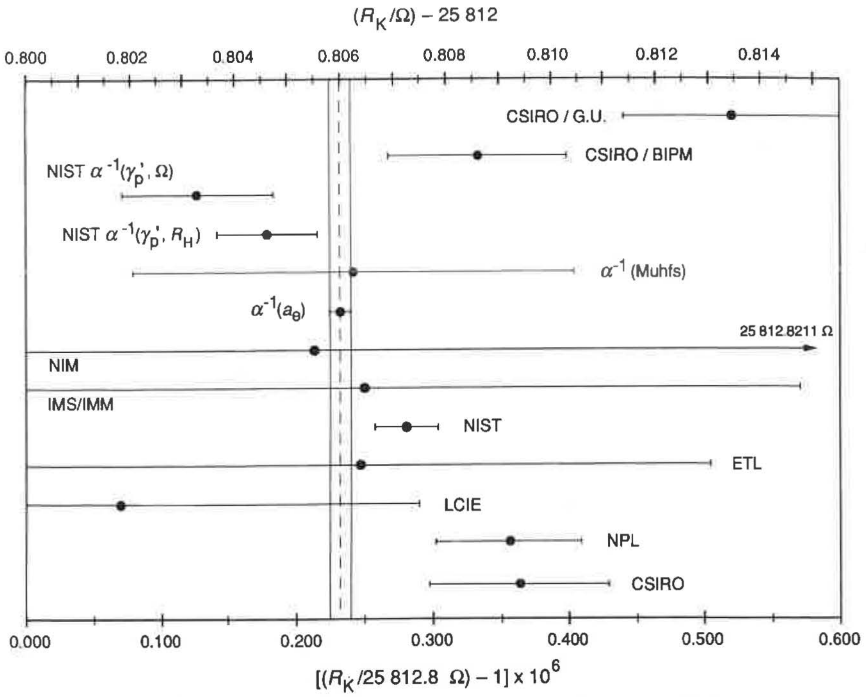

Fig. A1. — Comparison of the values of R_K and their standard deviation uncertainties as given in Table A1. The vertical dashed and solid lines indicate the value and standard deviation uncertainty of the most precise result.

The values given in Table A1 require further explanation.

Item 1. This result was obtained by the Commonwealth Scientific and Industrial Research Organization (CSIRO), National Measurement Laboratory (NML), Australia, from its own quantized-Hall-resistance (QHR) measurements (i.e., determinations of $R_H(i)$ in terms of laboratory reference resistors) and realizations of the ohm via the CSIRO/NML calculable capacitor [A1, A2]. The values labeled (a) and (b) were obtained from QHR measurements carried out at the BIPM [A3, A4] and Gakushuin University (G.U.), Tokyo, Japan [A5], respectively, and CSIRO/NML ohm realizations transferred directly to these laboratories by means of one-ohm artifact resistance standards. Clearly, item 1 agrees well with 1(a) but not with 1(b)*. The G.U. result is based on measurements using a silicon MOSFET sample. A more recent but still preliminary G.U. result using a GaAs heterostructure is about 9 parts

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* The agreement of items 1 and 1(a) implies agreement of the CSIRO/NML QHR measurements with those of BIPM. The QHR measurements of a number of other laboratories also agree well with those of BIPM and hence with those of CSIRO/NML; *see* Ref. [A3], and also Ref. [A21].

in 10^8 smaller [A5], thereby bringing into question item 1(b). (Item 6 was also obtained from silicon-MOSFET measurements. All other values were obtained using heterostructures.) Further, item 1 is based on QHR and ohm-realization measurements both of which were carried out in CSIRO/NML. In the opinion of some members of the Working Group, it is preferable to use values of R_K based solely on data obtained in the same laboratory because of the difficulties associated with accurately transferring representations of the ohm between laboratories. For these reasons, only item 1 is included in our calculations. Item 1(b) does give some indication of the problems which can arise in connection with QHR measurements.

Items 2 *to* 7. The values of R_K from the National Physical Laboratory (NPL), UK (item 2) [A6] ; the Laboratoire Central des Industries Électriques (LCIE), France (item 3) [A7] ; the Electrotechnical Laboratory (ETL), Japan (item 4) [A8] ; the National Institute of Standards and Technology (NIST), USA, formerly the National Bureau of Standards (NBS) (item 5) [A9-A11] ; and the National Institute of Metrology (NIM), PRC (item 7) [A14, A15], are all based on QHR and ohm-realization measurements carried out in the same laboratory. For item 6, the QHR measurements were carried out in the Institute of Metrological Service (IMS), Moscow, USSR, and the ohm-realization measurements in the Mendeleev Institute of Metrology (IMM), Leningrad, USSR [A12, A13]. An artifact resistance standard was used to transfer the measurements between IMS and IMM. The variation in the uncertainty assigned to the seven direct values, items 1 through 7, is mainly due to the design and construction details of the calculable capacitor and associated impedance bridges used in the ohm-realization experiments.

Item 8. This indirect result is based on the value of the inverse fine-structure constant α^{-1} obtained from the experimental measurement of the electron magnetic moment anomaly a_e at the University of Washington (relative uncertainty of 4×10^{-9}) [A16] ; and the theoretical expression for a_e given by T. Kinoshita, Cornell University (relative uncertainty of 7×10^{-9} arising from numerical integrations) [A17]. Although Kinoshita's calculations are not final, he has assigned the uncertainty conservatively and the value of R_K is not expected to change significantly. This is the most precise result currently available, assuming the correctness of the relation $R_K = \mu_0 c \alpha^{-1}/2$.

Item 9. This result is based on the value of α^{-1} obtained by the Working Group from the ground-state hyperfine splitting interval of muonium (μ^+e^- atom) following the CODATA 1986 least-squares adjustment of the fundamental constants [A18]. However, the more recent and accurate value $R_\infty = (10\,973\,731.573 \pm 0.004)\ \mathrm{m}^{-1}$ has been used for the Rydberg constant for infinite mass [A22] ; and the theoretical expression for the interval used by CODATA as taken from the work of Sapirstein *et al.* has been updated to include the additional terms calculated by Eides *et al.* [A23] and Starshenko and Faustov [A24], and the exact analytic expressions obtained by Karshenboim *et al.* [A25] and by Eides *et al.* [A26] for the corresponding numerically evaluated terms given by Sapirstein *et al.*

Item 10. The relationship [A18]

$$\alpha^{-1} = [(\mu_p'/\mu_B)\,(2e/h)R_K/(2\mu_0 R_\infty \gamma_p')]^{1/3}, \tag{A1}$$

where μ_p'/μ_B is the magnetic moment of the proton in units of the Bohr magneton and γ_p' is the gyromagnetic ratio of the proton (the prime indicates a spherical, pure H_2O nuclear-magnetic-resonance or NMR sample at 25 °C), has the unique property that it remains valid if $2e/h$ is measured by the Josephson effect and is expressed in terms of V_{LAB}; R_K is expressed in terms of Ω_{LAB}; and γ_p' is measured by the so-called low-field method and is expressed in terms of $T_{LAB} \propto A_{LAB} = V_{LAB}/\Omega_{LAB}$, where T_{LAB}, V_{LAB}, and Ω_{LAB} are the laboratory representations of the tesla, volt, and ohm, respectively. Item 10 was obtained by NIST from this equation and a new NIST determination of γ_p' (low) [A19], maintenance of V_{NBS} using Josephson arrays [A20], measurements of R_K in terms of Ω_{NBS} [A9], the 1986 CODATA value of μ_p'/μ_B, and the value of R_∞ given under item 9. Because items 5 and 10 are based on the same QHR measurements, they are not totally independent; their correlation coefficient is 0.04.

Item 11. If the equation $R_K = \mu_0 c \alpha^{-1}/2$ is used to eliminate R_K from Eq. (A1), the resulting expression is

$$\alpha^{-1} = [c(\mu_p'/\mu_B)\,(2e/h)/(4R_\infty \gamma_p')]^{1/2}. \tag{A2}$$

If as before $2e/h$ is measured by the Josephson effect and is expressed in V_{LAB}, and γ_p' is measured by the low-field method and is expressed in $T_{LAB} \propto A_{LAB} = V_{LAB}/\Omega_{LAB}$, the quantity Ω_{LAB} is introduced in the denominator. That is, γ_p' is replaced with $\Omega_{LAB}\gamma_p'$ (low), where Ω_{LAB} is to be expressed in ohms. Item 11 was obtained by NIST from this equation using the result of its recent experiment to realize the ohm via the NIST calculable capacitor [A10]. Because the same ohm-realization result was used by NIST to obtain item 5, the two are not independent; their correlation coefficient is − 0.17. Similarly, the correlation coefficient of items 10 and 11 is 0.98, mainly because both are based on the same value of γ_p' (low). NBS items 5, 10, and 11 are related in such a way that, assuming their correlations are properly considered, the weighted mean of any two of them (and all three of them) gives the same result. This is taken into account appropriately in the calculations carried out in the following section.

A.1.3. Analysis of data

The simple mean and standard deviation of the mean of the ten measurements 1 through 9 plus 11 are

$$R_K = (25\,812.806\,26 \pm 0.000\,80)\,\Omega \qquad \text{(A3a)}$$
$$= R_0[1 + (0.242 \pm 0.031) \times 10^{-6}], \qquad \text{(A3b)}$$

where the convenient reference resistance 25 812.8 Ω is denoted by the symbol R_0. (Including item 10 instead of item 11 yields a similar result.)

However, the simple mean and its standard deviation have little significance in the present case because of the large differences in precision of the measurements. The more appropriate weighted mean, taking as the weight of each measurement the reciprocal of the square of its assigned one-standard-deviation uncertainty, $w_i = 1/s_i^2$, * yields

$$R_K = (25\,812.806\,15 \pm 0.000\,25)\,\Omega \qquad \text{(A4a)}$$
$$= R_0[1 + (0.238\,4 \pm 0.009\,6)], \qquad \text{(A4b)}$$

where the uncertainty has been calculated on the basis of external consistency. That is, the usual standard deviation of the weighted mean calculated on the basis of internal consistency, $s_I = \left[\sum_{i=1}^{N} w_i\right]^{-1/2}$, has been multiplied by the scale factor or Birge ratio $R_B = [\chi^2/\nu]^{1/2}$, where χ^2 is the statistic « chi square » and ν is the number of degrees of freedom ($\nu = 9$ in the present case). The reason is that the data are only marginally in agreement ; $R_B = 1.31$ and $\chi^2 = 15.6$ and not 9, the expected value for $\nu = 9$. The probability that this value of χ^2 has occurred by chance is about 8 %, i.e., $P(15.6|9) \simeq 0.08$. (We assume as usual that $P > 0.05$ indicates an acceptable level of agreement.)

It is clear that the value of R_K from $\alpha^{-1}(a_e)$, item 8, will dominate any weighted mean in which it is included because its assigned uncertainty is significantly smaller than that of any other value. If it is deleted, one obtains

$$R_K = (25\,812.806\,97 \pm 0.000\,56)\,\Omega \qquad \text{(A5a)}$$
$$= R_0[1 + (0.270 \pm 0.022) \times 10^{-6}], \qquad \text{(A5b)}$$

where the uncertainty is calculated on the basis of external consistency. $\chi^2 = 11.8$ for $\nu = 8$, $R_B = 1.22$, and $P(11.8|8) \simeq 0.16$. The agreement is reasonable.

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* This is the appropriate equation if all of the covariances or correlation coefficients between the measurements are zero. In fact, a generalized variance matrix was used because of the correlations between some of the data that were indicated in Section A1.2.

It is of interest to calculate a value of R_K based solely on the seven direct measurements, items 1 through 7. The result is

$$R_K = (25\,812.807\,65 \pm 0.000\,52)\,\Omega \qquad \text{(A6a)}$$
$$= R_0[1 + (0.296 \pm 0.020) \times 10^{-6}], \qquad \text{(A6b)}$$

where the uncertainty has been calculated on the basis of internal consistency; $\chi^2 = 3.85$ for $\nu = 6$, $R_B = 0.80$, and $P(3.85|6) \simeq 0.70$. The agreement is excellent.

Because items 1, 2, and 5 are significantly more precise than items 3, 4, 6, and 7, they essentially determine the weighted mean of the seven direct measurements. Indeed, the weighted mean of just these three more precise values is

$$R_K = (25\,812.807\,72 \pm 0.000\,61)\,\Omega \qquad \text{(A7a)}$$
$$= R_0[1 + (0.299 \pm 0.024) \times 10^{-6}], \qquad \text{(A7b)}$$

where the uncertainty has been calculated on the basis of external consistency; $\chi^2 = 2.70$ for $\nu = 2$, $R_B = 1.16$, and $P(2.70|2) = 0.26$. The agreement is quite reasonable.

An indirect value based on the weighted mean of items 8, 9, and 11 may be obtained for comparison:

$$R_K = (25\,812.805\,94 \pm 0.000\,27)\,\Omega \qquad \text{(A8a)}$$
$$= R_0[1 + (0.230 \pm 0.010) \times 10^{-6}], \qquad \text{(A8b)}$$

where the uncertainty has been calculated on the basis of external consistency; $\chi^2 = 3.40$ for $\nu = 2$, $R_B = 1.30$, and $P(3.40|2) \simeq 0.18$. The agreement is reasonable. The difference between Eqs. (A7) and (A8) is $(0.001\,78 \pm 0.000\,67)\,\Omega$, which corresponds to a relative difference of $(0.069 \pm 0.026) \times 10^{-6}$. Compared in this way, the direct and indirect values are not in particularly good agreement. (Using item 10 in place of item 11 yields a similar result.) Indeed, the uncertainty of item 8 is sufficiently small compared with the uncertainties of the other indirect values that it essentially determines the indirect value. The difference between Eq. (A7) and item 8 is $(0.001\,73 \pm 0.000\,65)\,\Omega$, which corresponds to a relative difference of $(0.067 \pm 0.025) \times 10^{-6}$.

Finally, the result of the above comparison of Eqs. (A7) and (A8) leads us to calculate the weighted mean of just items 1, 2, 5, 8, and 10. These five more precise values of R_K have relative uncertainties of less than 7×10^{-8} which is less than one half that of the next most precise value. They yield

$$R_K = (25\,812.806\,16 \pm 0.000\,37)\,\Omega \qquad \text{(A9a)}$$
$$= R_0[1 + (0.239 \pm 0.014) \times 10^{-6}], \qquad \text{(A9b)}$$

where the uncertainty has been calculated on the basis of external consistency; $\chi^2 = 15.0$ for $\nu = 4$, $R_B = 1.93$, and $P(15.0|4) \simeq 0.005$. As could be anticipated from the above comparison, the agreement is poor. (Including item 11 in place of item 10 yields the identical result because of the relationship between items 5, 10, and 11 discussed previously.)

A.1.4. Selection of recommended value

Based on the weighted mean of all the data as given in Eq. (A4), and the Working Group's adopted guiding principle discussed in the first section of this Appendix, an obvious choice for the recommended value is 25 812.806 Ω. That this is identical with the value of R_K obtained from $\alpha^{-1}(a_e)$, item 8, is in large part due to the latter's small uncertainty in comparison with the uncertainties of the other values. On the other hand, based on the weighted mean of the direct measurements only rather than all the measurements, an obvious choice is 25 812.808 Ω as given in either Eqs. (A6) or (A7).

The Working Group believes that its recommended value of R_K should not be dominated by a single indirect value which has not been verified by independent experiments and calculations, and that it should

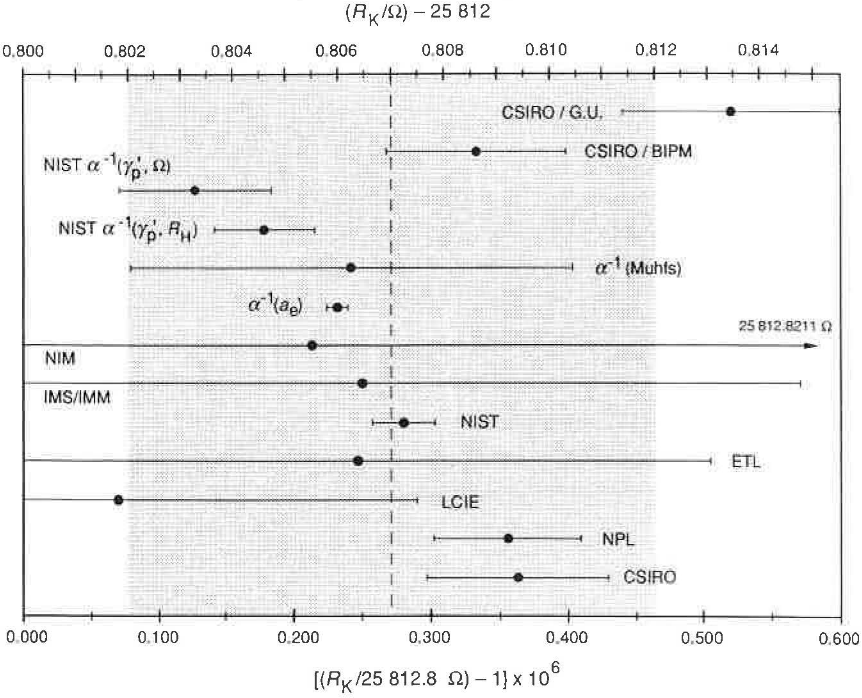

Fig. A2. — Comparison of the recommended value of R_K (vertical dashed line) and its assigned standard deviation uncertainty (delimited by the shading) with the values of R_K and their standard deviation uncertainties given in Table A1.

reflect the results of the direct measurements. On this basis, the recommended value is taken as the simple mean of the above two values, namely, 25 812.807 Ω.

The question remains as to the one-standard-deviation uncertainty to be assigned to this value which will also be consistent with the Working Group's guiding principle. Considering that the peak-to-peak scatter among the values of R_K given in Table Al (including item 1b) is about 0.01 Ω, and that the relation $R_K = \mu_0 c \alpha^{-1}/2$ as well as Eq. (1) are under active theoretical and experimental investigation, the Working Group believes that adopting 0.005 Ω as the one-standard-deviation uncertainty, which corresponds to a relative uncertainty of 2×10^{-7}, is consistent with both its guiding principle and the current situation. Thus the Working Group's recommended value and assigned uncertainty are

$$R_K = 25\,812.807\ \Omega \qquad \text{(A10a)}$$

$$\text{Assigned standard deviation: } 0.005\ \Omega \qquad \text{(A10b)}$$

$$\text{Corresponding relative standard deviation: } 2 \times 10^{-7}. \qquad \text{(A10c)}$$

Figure A2 graphically compares this value with the data of Table A1. (The dashed line is the recommended value and the shading delimits its uncertainty.) Equation (A10) is consistent with the 1986 CODATA value $R_K = (25\,812.805\,6 \pm 0.001\,2)\ \Omega$ [A18].

August 1988

Revised September 1988

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APPENDIX E 4

Technical guidelines for reliable measurements of the quantized Hall resistance

by F. Delahaye, T. Endo, O. C. Jones, V. Kose, B. N. Taylor and B. M. Wood*

(Revision of Document CCE/88-40)

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1. Introduction

This document integrates the main information and suggestions communicated to the CCE Working Group on the Quantum Hall Effect on the subject of reliable measurements of the quantized Hall resistance R_H for realizing laboratory representations of the ohm. (Throughout, the symbol R_K is used for the $i = 1$ plateau $\cong 25\,812.8\ \Omega$ as suggested by the Working Group in its report to the CCE. The symbol R_H is used for the quantized Hall resistance in general, i.e., for any plateau.)

Its aim is not to recommend strict rules but rather to propose guidelines to serve as a reminder of the main tests and precautions necessary to assure reliable measurements of R_H at a relative uncertainty of a few parts in 10^8.

Laboratories are strongly encouraged, when reporting their results, to describe their own tests and procedures related to the possible error sources addressed here. Also, workers engaged in measurements of R_H and wishing to suggest modifications or additions to be included in future editions of these guidelines are encouraged to do so by writing to the BIPM.

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2. Sample choice

Metal-oxide-semiconductor field-effect transistors (MOSFETs) or GaAs/GaAlAs devices (and possibly alternative heterostructures) can be used for accurate measurement of the quantized Hall resistance R_H.

GaAs/GaAlAs devices have an important advantage over MOSFETs: at a temperature of 1.5 K or lower and for magnetic flux density B in the range, say, 6 to 12 T, they can often tolerate, without measurable dissipation in the longitudinal direction, a « source-drain » current I_{SD} of 20 to 50 µA, which is significantly higher than that of MOSFETs (10 µA maximum). This allows the reduction of the random or Type A uncertainty in the measurement of R_H to 1 part in 10^8 for a reasonable measuring time.

On the other hand, MOSFETs may have decreased leakage current between contacts [1] and long lifetime [2].

Further accurate comparisons, when possible, between MOSFETs and GaAs devices should be encouraged as a test of the independence of R_H on the type of sample used [3].

In the case of GaAs/GaAlAs devices, a mobility μ of order 10 to 20 T^{-1} and a carrier concentration n in the range 3 to 6 × 10^{15} m^{-2} are suitable in order to obtain wide and well-quantized $i = 2$ plateaux for the values of temperature mentioned above and B in the range 6 to 12 T [4]. Devices with higher n (from 6 to 8 × 10^{15} m^{-2}) can also yield good quantization conditions for their $i = 4$ plateaux in the range 6 to 8 T.

In the case of silicon MOSFETs a mobility of 1.5 to 4.5 T^{-1} is suitable in order to obtain wide and well-quantized $i = 2$, 4 or 8 plateaux at a temperature of 0.5 K or lower and for B in the range 8 to 12 T [2].

The samples should be fitted with source S and drain D contacts (gate and substrate for MOSFETs), and with at least two, preferably three, pairs of Hall-voltage contacts (Fig. 1).

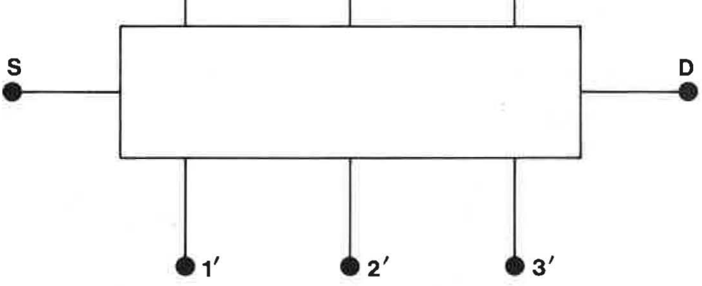

Fig. 1. — Sample with three pairs of Hall-voltage contacts.

3. Sample cool-down and handling

Samples should be cooled slowly, in the dark, and in an environment which is shielded from rf radiation.

MOSFETs should be cooled with a gate voltage applied from the very beginning of cooling or, alternatively, with the gate short-circuited to the source or drain contact.

Output wires attached to the sample should be handled cautiously, as connecting them to accidental environmental noise sources may induce longitudinal dissipation (the longitudinal resistivity, ρ_{xx}, assumes a finite value) in a sample previously in a dissipationless state ($\rho_{xx} \cong 0$). This is particularly true for MOSFETs but has also been observed on some occasions for GaAs devices. Restoration to a dissipationless state is often possible, however, by sweeping B through zero or by cycling the device to room temperature for a short time, in the case of GaAs devices, or for several weeks, in the case of MOSFETs.

4. Contact resistance

Poor contact resistances are often the major sample-related limitation encountered by metrologists. The perturbing effects of poor contacts may include the following three characteristics :

— Poor source-drain contacts induce noise in I_{SD} despite the use of a current source with a relatively high (with respect to R_H) internal impedance. This noise often makes precise measurements impossible.

— Potential contacts may themselves generate excessive voltage noise when connected to a nanovoltmeter.

— Even in the case of an acceptable level of voltage noise, imperfect potential contacts can generate dc offset voltages (possibly by a process of rectification of noise) which depend on the polarity of I_{SD} and which can introduce systematic errors in measurements of R_H.

It has been observed that the contact behaviour can deteriorate with time over, say, several months. In addition, if, during an experiment, the device remains at low temperature for several days, or I_{SD} is increased to a value at which the current flow is no longer dissipationless [4], deterioration may also occur. In the latter two cases, restoration is often possible by cycling the device to room temperature for a period of time which may depend on the sample used.

The following tests can be used to detect imperfect contacts. It is assumed that B (or the gate voltage) is first adjusted to a value corresponding to the centre of a Hall plateau of resistance R_K/i.

— The resistance between any two contacts of the sample is determined by two-terminal measurements. The measured values depend on the material of the sample and on the material and the thickness of the contacts and the way they are made [5]. For example, for diffused tin contacts on GaAs/GaAlAs samples, the values should be ideally within 1×10^{-4} of $R_K/i + R_L$, where R_L is the resistance of the leads, and independent of current polarity [6]. However, for AuGeNi contacts on GaAs/GaAlAs samples, contact resistances exceeding those calculated with the latter equation by up to about 1 kΩ have been observed to have no measurable effect upon $R_K/2$ [7]. If higher values are measured, extra precautions should be taken to verify the absence of dc offset voltages generated in the contacts [8]. For a sample with all contacts similarly made, the resistance of all sets of contacts, deduced from two-terminal measurements, should not differ by more than about a factor of ten.

The problem of possible noise contamination, mentioned above, should be kept in mind while making this test. In particular, it is not recommended to connect a MOSFET sample to a mains-operated digital ohmmeter. In all cases, the value of the measuring current supplied by the ohmmeter should be low enough to avoid degrading the sample.

— The voltage noise across contact pairs (with $I_{SD} = 0$) is evaluated using a nanovoltmeter with a sufficiently high input resistance ($\geqslant$ 10 kΩ), sufficiently low offset current ($\leqslant$ 1 pA), and sufficiently low voltage noise for source impedances of the order of 10 kΩ in the frequency band 0 to 1 Hz.

The noise measured across pairs should be less than or equal to that observed with the meter's leads connected to the terminals of a good-quality, wire-wound resistor of resistance R_K/i at room temperature. A higher level of noise may be due to poor contacts, and also possibly to microphonic noise in the leads connected to the sample.

— In the quantized regime and with the usual operating value of I_{SD}, the longitudinal voltage, V_x, between contacts on the same side of the sample is determined for both directions ($I_{SD} = \pm I$) of the current.

Ideally, both measured values should be negligible within the resolution of the measuring instrument, i.e.:

$$|V_x(I_{SD} = +I) - V_x(I_{SD} = 0)| = |V_x(I_{SD} = -I) - V_x(I_{SD} = 0)| \cong 0.$$

This tests for the possible presence of offset voltages which depend on current polarity and which could be caused by poor contact behaviour or possibly other factors such as leakage currents.

5. Conditions of quantization

The quantity to be measured, the quantized Hall resistance R_K/i, is believed to be the value of the Hall resistivity ρ_{xy} on a plateau of a two-dimensional electron gas in a dissipationless state, i.e., with $\rho_{xx} = 0$. The following tests are useful for detecting a possible imperfect quantization :

5.1. Evaluation of the residual longitudinal resistivity

The condition for the absence of dissipation can be tested by measuring the longitudinal voltage, V_x, between two contacts on the same side of the sample while sweeping the magnetic flux density (in the case of heterostructures) or the gate voltage (in the case of MOSFETs) through the range corresponding to the plateau of Hall resistance.

Ideally, this voltage drop should be « non-measurable », within the limit of resolution of the measuring instrument (usually of the order of 10 nV), for a central region of the sweeping range. Under practical conditions of temperature and magnetic field this is not always the case : V_x may present only a finite minimum value, $V_x^{\min}$, when the range is swept. The value of the minimum longitudinal resistivity $\rho_{xx}^{\min}$, corresponding to $V_x^{\min}$ is given by : $\rho_{xx}^{\min} = \frac{V_x^{\min}}{I_{SD}} \times \frac{W}{l}$ where W is the width of the sample and l the distance between the V_x contacts. (Note that this equation will always yield an approximate value for $\rho_{xx}^{\min}$ because of possible sample inhomogeneities and because W and l are never precisely defined.) In the more favourable case where V_x becomes « non-measurable », the above formula can also be used to calculate an upper limit to the possible residual longitudinal resistivity with $V_x^{\min}$ taken as the limit of resolution of the measurement (for instance 10 nV). This upper limit may be as low as $\simeq 0.25$ mΩ (in the case of MOSFETs with $\frac{W}{l} \simeq \frac{1}{4}$ and with $I_{SD} \simeq 10$ μA) or even $\simeq 0.05$ mΩ (in the case of GaAs/AlGaAs heterostructures with $\frac{W}{l} \simeq \frac{1}{4}$ and with $I_{SD} \simeq 50$ μA).

5.2. Possible temperature dependence

Varying the temperature with I_{SD} held constant is an important test for the characterization of a sample. It is recommended that it be carried out at least once for a given sample.

Ideally, the plateau value of ρ_{xy} should be invariant, within the limit of resolution of the measurements, over an appreciable range of temperature starting from the lowest temperature attainable with the cryogenic equipment used, T_1.

This is not always the case and, indeed, a sufficiently large increase in temperature produces measurable and increasing values of ρ_{xx}^{min} and measurable variations of ρ_{xy}. The variation of ρ_{xy} as a function of ρ_{xx}^{min} can be quite different in magnitude, sign and character depending on the set of Hall contacts used, the magnetic field direction and the value of I_{SD}. It has often been observed [9, 10, 11] that ρ_{xy} varies linearly with ρ_{xx}^{min}, at least for a limited range of temperature, and obeys the equation

$$\Delta\rho_{xy} = \rho_{xy}(\rho_{xx}^{min}) - \rho_{xy}(0) = s\rho_{xx}^{min}$$

where s is a constant and $\rho_{xy}(0)$ is the extrapolated value of ρ_{xy} at $\rho_{xx}^{min} = 0$, which is believed to be equal to R_K/i.

The measured values of ρ_{xx}^{min} may vary for different pairs of V_x contacts. Consequently, s is a function of the chosen set of Hall voltage and V_x contacts.

The measured values of s are usually less than 1, possibly as low as 0.1. It should be remembered that s depends on the direction of B (its sign may change when the direction is reversed) and on the value of I_{SD}, as is pointed out in the following section on current dependence. Furthermore, the determination of s is very time-consuming and is not necessarily reproducible with thermal cycling.

As a consequence of this, a sample showing a measurable temperature dependence of ρ_{xy} near T_1 can possibly be used for accurate measurements of R_H but only when it has been verified beforehand that s is reasonably reproducible. Furthermore, the relative value of the correction applied to ρ_{xy}, i.e., $-s\frac{\rho_{xx}^{min}}{\rho_{xy}}$, should not exceed a few parts in 10^8.

It is, of course, much better to use a sample for which ρ_{xy} is invariant with respect to a significant increase of the temperature above T_1. This is usually associated with a « non-measurable » value of ρ_{xx} at T_1. A knowledge of s is not necessary for such a sample when the ρ_{xy} measurements are made at T_1.

5.3. Possible current dependence

The check of the invariance of ρ_{xy} with respect to significant changes in I_{SD} is important as it may reveal imperfect quantization. It also offers a means of detecting leakage currents, when present.

It should be noted that, when observed, the *current-induced* variations of ρ_{xx}^{min} result in variations $\Delta\rho_{xy}$ of the Hall resistance that may differ from those associated with *temperature-induced* variations of ρ_{xx}^{min}. This has been observed for GaAs devices [12, 13] but not, however, in the experiments on MOSFETs described in reference [9].

For this reason, I_{SD} should be held constant when ρ_{xy} and ρ_{xx}^{min} are measured at different temperatures to evaluate the slope s. This slope may depend on the value of I_{SD} used. For instance, it has been found [13] that, for a particular GaAs/GaA1As sample, the value of s measured with $I_{SD} = 40\ \mu A$ was approximately twice the value measured with $I_{SD} = 10\ \mu A$.

5.4. Possible magnetic-field (or gate-voltage) dependence

The flatness of the Hall plateau should be verified, at least once for a given sample, by making measurements of ρ_{xy} not only at the centre of the plateau but at a few points on either side of the centre. Flatness is necessary for useful measurements but does not imply that the correction due to finite ρ_{xx}^{min} is negligible. Also, ρ_{xx}^{min} should occur at the same value of B when it is measured on both sides of the sample. If ρ_{xx}^{min} does not occur at the center of the plateau, ρ_{xy} should be determined at the value of B corresponding to ρ_{xx}^{min}, but extra precautions should be taken to demonstrate the flatness of the plateau.

Another test for imperfect quantization that should be made at least once is that of the invariance of ρ_{xy} with respect to the direction of B.

5.5. Possible geometric dependence

To ensure that the finite aspect ratio of the quantum-Hall-effect device does not cause a significant error in the determination of R_H [14], measurements of this quantity at all three Hall-contact pairs along the length of the device (or at least the pair at the centre and one pair on the end) should yield the same value.

6. Measurement of R_H

All the tests mentioned above are very time-consuming and cannot be repeated each time a measurement of R_H is made. This section suggests the minimum number of measurements that might be made, in one day, during a particular determination of R_H. It is assumed that the sample has already been thoroughly characterized and has been found to be free from significant corrections due to a finite value of ρ_{xx}^{min} at the operating values of temperature (usually T_1) and I_{SD}.

6.1. Fast check of the contacts

Two-terminal measurements between contact pairs, which are not time-consuming, can easily be made before each R_H measurement. To avoid any possible problem due to noise contamination, a battery-operated ohmmeter or tester, even of modest resolution, may be used.

6.2. Measurement of ρ_{xx}^{min}

ρ_{xx}^{min} should be evaluated on both sides of the channel, using two opposite pairs of V_x contacts, for instance 1-3 and 1′-3′ (Fig. 1) [15]. This checks that the characteristics of ρ_{xx}^{min} in the area of the channel delimited by these pairs are reasonably homogeneous. Ideally, the measured values should be limited by the measurement resolution (from $\simeq 0.05$ mΩ to $\simeq 0.25$ mΩ). If not, they should at least be similar to those obtained previously with this sample.

It is a good precaution to repeat the evaluation of ρ_{xx}^{min} on both sides of the sample immediately *after* the precise measurements of ρ_{xy} to check that no accidental change occurred during the experiment.

6.3. Measurement of ρ_{xy}

Whenever possible the ρ_{xy} measurements should be made on two different pairs of Hall contacts. These two pairs should be either those delimiting the area mentioned in 6.2 and sharing their contacts with the V_x pairs, i.e., 1-1′ and 3-3′, or, where applicable, a delimiting pair (1-1′ or 3-3′) and a central one (2-2′). However, it may be argued that to unequivocally ensure contact reliability, the two pairs of V_x contacts should involve the same pads as the two V_H pairs. Additionally, the voltages of the two V_x pairs and those of the two V_H pairs should, to within the random uncertainties, sum to zero around the loop.

Good agreement between the values of ρ_{xy} obtained with two different pairs is a confirmation that there is no significant problem due to the contacts.

7. Consistency of R_H measurements for different samples and different quantum numbers

A last but essential criterion for judging a particular measurement of R_H is its agreement with measurements made on other samples, preferably from different wafers, and with different quantum numbers.

Such comparisons test for shunting resistances (parallel conduction) across the sample, especially those between source and drain which are not revealed by $\rho_{xx}^{\min}$ measurements. In the case of different quantum numbers, this is also an excellent test for leakage resistances in the measuring equipment. (For example, compare R_K values as obtained from the $i = 2$ and $i = 4$ plateaux on the same sample and during the same run.)

8. Comments on the measuring equipment

— All electronic apparatus used in the experiment should introduce a minimum amount of extraneous electrical noise to prevent possible noise rectification and damage to the sample.

— All the components of the equipment used to measure R_H, including the sample holder*, should have leakage resistances as high as possible.

For the accuracies which concern us here, minimum leakage resistances of $10^{12}\,\Omega$ would normally be required. However, gated samples in which the gate voltage is much greater than the Hall voltage require a minimum leakage resistance of $10^{14}\,\Omega$ in the leads connected to the gate [12]. Other voltage sources (usually batteries) incorporated in the equipment and which may drive excessive leakage current should also have leakage resistances of the order of $10^{14}\,\Omega$. In all cases, it is a necessary precaution to check the leakage resistances or currents before each precise measurement of R_H, as they may deteriorate with time.

Guarding techniques limiting the effect of the leakage currents can be used but, if care is not taken, the guard circuits themselves can inject currents into the measurement system that are difficult to detect.

— Many laboratories use, for the first step of the scaling process from R_H to $1\,\Omega$ standards, a potentiometric method whereby R_H is placed in series with a standard resistor of resistance R nominally equal to R_H or to $10\,\mathrm{k}\Omega$. Significant « interchange errors » have been reported [12] for such potentiometers, which means that the measured ratio R_H/R depends on the relative position of these two resistors in the series circuit. Whenever possible, this test should be carried out and the results reported.

— If the two resistors in the series circuit, R_H and R, do not have the same nominal value (for instance, if $R = 10\,\mathrm{k}\Omega$), the voltage drops accross them are significantly different. Consequently, the linearity errors of the potentiometers used to measure them must be carefully checked.

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* Many laboratories now mount samples in non-magnetic headers of the TO-8 type (diameter $\simeq$ 15 mm) and use the mating sockets for easy connection to the sample holder. The use of this type of socket and header is encouraged in order to facilitate the exchange of samples between laboratories.

In particular, commercially available potentiometers that use a fixed internal resistor to generate the output voltage may introduce significant errors due to the power coefficient of this resistor.

Generally speaking, the effect of the power coefficient of any standard resistor used at different power levels in the course of measurements of R_H or in the scaling-down process should be checked.

Even if R_H and R differ by only a few parts in 10^6, it is necessary to calibrate the linearity of the null detector used in the measurements. Since the calibration curve for the detector is likely to depend upon time, ambient temperature and the particular characteristics of the digital voltmeter used to read the output of the detector, its determination requires careful attention.

9. Reporting results

In order to compare values of R_H obtained in different laboratories, the assigned uncertainties must be estimated in a uniform manner. This should be done following Recommendation INC-1 (1980) of the CIPM Working Group on the Statement of Uncertainties [16] and Recommendation 1 (CI-1986) of the CIPM [17] advocating that the uncertainties be expressed as one-standard-deviation estimates. In particular, a detailed and complete listing of the Type A and Type B uncertainties should be given, along with measurement dates, the number of measurements made, a clear statement as to the units in which the result is being reported, and other useful information. As noted above, special attention should be given to describing the characteristics of the devices used and the tests and procedures employed to address the possible sources of error discussed in these guidelines.

Acknowledgements. The authors thank all of the experts who participated in the preparation of these guidelines.

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APPENDIX E 5

Report on the 1987 international comparison of one-ohm resistance standards at the BIPM and the resulting agreement among determinations of R_H

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(Document CCE/88-36)

Abstract. — In order to evaluate the agreement among determinations of the quantized Hall resistance, R_H, at the request of the CCE the BIPM organized and conducted an international comparison of one-ohm resistance standards among twelve laboratories. The weighted mean and standard deviation are $R_H = 25\,812.8\,[1 + (2.059 \pm 0.021) \times 10^{-6}]\ \Omega_{69\text{-BI}}$ on October 20, 1987. Values and uncertainties for R_H in Ω_{LAB} and for $\Omega_{LAB} - \Omega_{69\text{-BI}}$ are given.

I. Introduction

In September 1986, at its 17th meeting, the Comité Consultatif d'Électricité (CCE) expressed its intention to meet in September 1988 to recommend an internationally accepted value for the quantized Hall resistance, R_H, to be used from January 1, 1990 by national standards laboratories to maintain representations of the ohm by means of the quantum Hall effect. To aid it in setting a conventional value of R_H which is very close to the best estimates of its SI value and to evaluate the international uniformity to be gained by its implementation, the CCE requested the Bureau International des Poids et Mesures (BIPM) to carry out an international comparison of one-ohm resistance standards limited to those laboratories measuring R_H or making absolute determinations of the ohm. The measurements at the BIPM were carried out using new equipment and procedures outlined in Section II. In Section III we present the results of each determination of R_H in terms of the local laboratory representation of the ohm (Ω_{LAB}), the difference $\Omega_{LAB} - \Omega_{69\text{-BI}}$ and the resulting values of R_H in $\Omega_{69\text{-BI}}$. The corresponding uncertainty estimates as well as some estimates of the *a posteriori* uncertainty in travelling standards are also given in Section III. In Section IV we discuss some general conclusions of this comparison.

II. Experimental procedures and equipment

A. *Requested procedural rules*

Among the laboratories solicited, eleven responded affirmatively, indicating that they would provide a link between their travelling standards and their own determination of R_H, the absolute ohm, or both. The eleven participating national laboratories were the following : CSIRO, ETL, IMM, LCIE, NIST (ex NBS), NIM, NPL, NRC, OFM, PTB and VSL.

Thus, including the BIPM, twelve laboratories took part in the comparison.

Each participant was requested to send three one-ohm travelling standards along with values of their temperature and pressure coefficients at 20 °C and 101 325 Pa (the reference values), precise but « preliminary » values of the travelling standards and estimates of their drift rates. It was hoped that the latter two data could help uncover possible unusual behavior of the travelling standards in case of mishaps in transport. This proved to be useful in two cases and we recommend that in future comparisons laboratories endeavour to have ready several back-up travelling standards which have been measured at the same time as those sent to the BIPM and which can replace the travelling standards in case of need. The laboratories were informed that the BIPM's measurements would be made at a current of 50 mA. All final results are meant to be referred to this value of current. Laboratories measuring at different currents were requested to correct their results to this value.

B. *Equipment at the BIPM*

The equipment and procedures used at the BIPM differed greatly from the previous comparison [1]. The six one-ohm standards, the mean of which defines our representation of the ohm, designated $\Omega_{69\text{-BI}}$, were treated almost in the same way as the travelling standards. All resistors, including those of the BIPM were compared to two transfer resistors, 905 and 907, designed and built by the CSIRO [2] to have small temperature and pressure coefficients and, for these reasons, introducing lower uncertainty than $\Omega_{69\text{-BI}}$ itself. The most important new equipment is the resistance bridge based on a cryogenic current comparator (CCC) [3], [4]. The CCC bridge permits the establishment of an accurately known, adjustable ratio of current passing through one-ohm resistors in separate circuits. This current ratio, which is maintained rigorously constant by feedback from a SQUID, and the measured difference in voltage drops across the resistors give the ratio of their resistances. A desk-top microcomputer acquires and treats voltmeter readings, switches current polarities, calculates resistance ratios and stores data.

The equipment for measuring the temperature and pressure is also new. A calibrated platinum resistance thermometer is located in a fixed position in the oil bath containing the transfer standards and the resistors to be measured. The reference junctions of 12 copper-constantan thermocouples are closely coupled thermally to the thermometer. The second junction of each thermocouple pair is placed in the thermometer well of a resistor in the bath. Temperature differences between the thermometer and the oil at the centres of the resistors are determined from digital nanovoltmeter readings. The estimated type A uncertainty is 0.25 mK. (All uncertainties here are one-standard-deviation estimates.) The atmospheric pressure is measured with an uncertainty of about 10 Pa with a calibrated digital manometer, Crouzet model 2100, equipped with an IEEE-488 bus.

Because of the importance of $\Omega_{69\text{-BI}}$ as an international reference used, for example, as an auxiliary constant in the adjustment of the fundamental physical constants [5], it was considered advisable to compare results obtained with the new CCC-based bridge with those from the BIPM's old double bridge. This was done in a comparison of one-ohm travelling standards from the NPL, in April 1987. Mean results from the two systems differed in relative value by less than 1×10^{-8}, an amount rather less than the uncertainty of the double bridge. The final result, deduced from the CCC measurements, of three travelling standards was that, on April 24, 1987 [6] :

$$\Omega_{\text{NPL}} - \Omega_{69\text{-BI}} = (0.34 \pm 0.02)\ \mu\Omega.$$

The uncertainty is the root-sum-square of the combined type A and type B components. It is an indication of the accuracy we expected to achieve in the present comparison.

C. *Procedure for comparison of two resistors*

The comparison of two resistors begins with the measurements of the depth of oil above the top plates of the resistors in order to calculate the pressure of the oil. Then the platinum resistance thermometer is read, followed by readings of the two thermocouples and the manometer. The electrical measurement sequence consists in setting up the 50 mA current in the normal polarity and reading the voltage difference on a picovoltmeter, integrating over about two minutes. The current polarities are then reversed and the voltage measurements repeated. With the current polarities back in the original directions, a third set of voltage measurements is obtained. Using a linear interpolation technique, the resistance ratio is calculated. Polarity reversals are continued until a total of nine sets of voltage measurements are completed. Statistically these are considered as three independent determinations of the resistance ratio. In a typical run, the standard deviation of the mean of the three determinations is about 1 to 2×10^{-9}. The temperature and pressure measurements are repeated, the final results calculated and the data are stored.

The high resolution of the BIPM bridge allowed us to identify anomalous behaviour associated with low leakage resistance (as little as 20 MΩ) in some one-ohm travelling standards.

D. *Complete comparison scheme*

Measurements of the travelling standards were carried out from September 24 to November 17, 1987. The mean date, to which all results were referenced, is October 20, 1987. Each travelling standard was compared to the two transfer standards five times at intervals of about 11 days. A linear least-squares fit was calculated for the ratios of the resistance of each travelling standard to each transfer resistor. For 34 of the 37 participating resistors the average of the standard deviation of the predicted value of a travelling standard with respect to the transfer standards on the mean date of the comparison is 3.4×10^{-9}. Similar least-squares fits were made to data from seven comparisons of the resistors forming $\Omega_{69\text{-BI}}$ with the two transfer standards. The drift rates, relative to $\Omega_{69\text{-BI}}$, and their uncertainties were (-0.23 ± 0.11) nΩ/d and (0.014 ± 0.08) nΩ/d. The standard deviations from the predicted values in $\Omega_{69\text{-BI}}$ of the transfer resistors on the mean date were 2.3 nΩ and 1.5 nΩ. The fact that these uncertainties are comparable in magnitude to the type A uncertainty of a single comparison run implies that no significant random scatter arises from influences such as temperature and pressure which generally vary from run to run. To verify the absolute stability of the transfer standards they were compared with a relative uncertainty of about 1×10^{-8} with the BIPM's quantum Hall resistance [7]. The result indicated changes of about 0.01 μΩ and 0.02 μΩ in the two standards. The relative drift of these two resistors throughout the comparison was confirmed by repeated direct comparisons.

It is difficult to generalize the type B uncertainties to assign to the measurement of a 1 Ω resistor in terms of $\Omega_{69\text{-BI}}$ because of the great variation (factors of 500 or more) among temperature or pressure coefficients. In general, for rather good quality resistors we estimate equivalent 1-σ uncertainties of about 10 nΩ for effects of temperature and 10 nΩ for uncorrected influences of pressure. The uncertainties due to leakage resistance and the winding ratio are less than 1 nΩ. The uncertainty in the calibration of the resistive divider used to equilibrate the CCC by injecting a known current into the compensation winding is about 5 nΩ. This gives a total type B uncertainty of about 15 nΩ.

III. Results

Table I gives the results of the comparison of the one-ohm travelling standards with $\Omega_{69\text{-BI}}$. Deviations from unity of the initial and return values of the travelling standards in terms of Ω_{LAB} are listed in columns 2 and 3. In column 4 we give the corresponding values of the travelling standards in Ω_{LAB} on 1987-10-20. These are obtained using a linear interpolation between the initial and return measurements for all but two laboratories ; NBS and OFM provided predicted values of their travelling standards on 1987-10-20 based on linear least-squares fits to results of measurements made before and after the BIPM measurements. The initial and return results for NBS were calculated from separate sets of 28 and 32 measurements carried out before and after the measurements at BIPM. Column 5 lists the deviations from unity of the travelling standards in $\Omega_{69\text{-BI}}$ on 1987-10-20, as measured at BIPM using the procedure described in sections II.C and II.D. Column 6 gives the individual and mean values of $\Omega_{\text{LAB}} - \Omega_{69\text{-BI}}$ deduced from columns 4 and 5. The standard deviation of the mean value, s_{M}, is listed in column 7.

Table II summarizes the results of the comparison and the determinations of R_{H}. Data in the second column were supplied by the laboratories and should have been referred to October 20, 1987. In those cases where R_{H} in Ω_{LAB} was not referred to this date by the laboratory, we have specified the reference date. We assume that the change in Ω_{LAB} between the two dates is negligible. Two laboratories (OFM and PTB) reported values of R_{H} from measurements reported in 1986 [8] and extrapolated by those laboratories to the central date of the comparison. In a departure from previous practice, the CSIRO reported its values of R_{H} and the travelling standards in terms of an Ω_{LAB} maintained by standard resistors. Previously, they had reported values in terms of the CSIRO's realization of the ohm by the calculable capacitor. The ETL does not maintain Ω_{ETL} in the form of standard resistors. The uncertainty listed for them in column 2 is that for the determination of R_{H} in terms of a set of one-ohm resistors. Column 3 lists the value of $\Omega_{\text{LAB}} - \Omega_{69\text{-BI}}$ at the standard conditions of temperature, pressure and power dissipation stated in Section I.A. The uncertainties are combinations of type A and type B uncertainties and correspond to those of column 6 of Table III. In column 4 we give the value deduced for R_{H} in $\Omega_{69\text{-BI}}$ on the central date of the comparison. The values and uncertainties are deduced from the two previous columns except for the uncertainty for the LCIE, who measured the transfer standards directly in terms of R_{H}.

The results of column 4 are presented graphically in Fig. 1 along with a value of the weighted mean and standard deviation. The weights

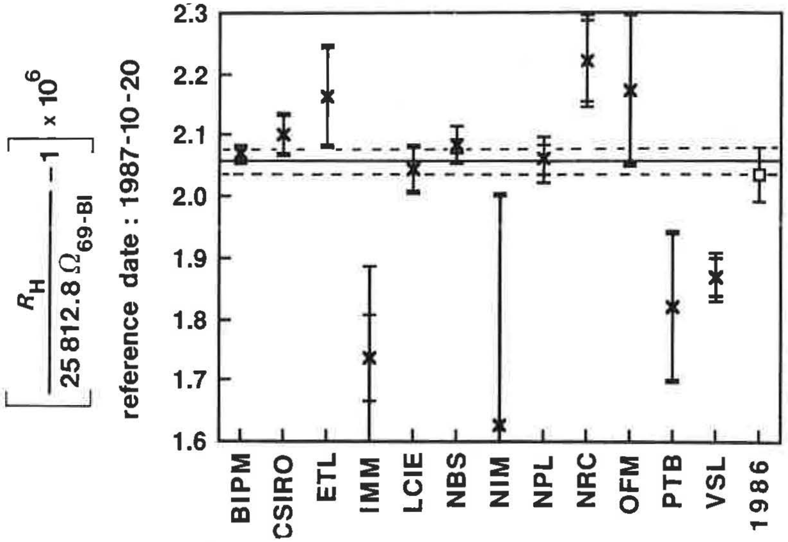

Fig. 1. — Values of R_H in $\Omega_{69\text{-BI}}$ on 1987-10-20 expressed as fractional deviations from 25 812.8 $\Omega_{69\text{-BI}}$. The error bars surrounding each datum represent the uncertainty of R_H in Ω_{LAB} (smaller) and the uncertainty of R_H in $\Omega_{69\text{-BI}}$. The solid horizontal line and parallel dashed lines represent the weighted mean and standard deviation. The datum represented by an open square and bar is the weighted average and standard deviation of the corresponding 1986 value extrapolated using the known drift of $\Omega_{69\text{-BI}}$.

were the reciprocals of the variances from column 4 of Table II. The final result is

$$R_H = 25\,812.8\ [1 + (2.059 \pm 0.021) \times 10^{-6}]\ \Omega_{69\text{-BI}} \text{ on } 1987\text{-}10\text{-}20. \quad (1)$$

The above calculation gives a heavy weight to the BIPM's determination of R_H since its transfer uncertainty is zero. Recalculating a weighted mean and standard deviation without the BIPM results gives

without BIPM :

$$R_H = 25\,812.8\ [1 + (2.048 \pm 0.031) \times 10^{-6}]\ \Omega_{69\text{-BI}} \text{ on } 1987\text{-}10\text{-}20, \quad (2)$$

i.e. a result practically identical with that obtained with the BIPM values included. We see no reason to delete the BIPM results and we take the first value for the final result of this comparison.

The value of R_H in (1) can be compared with the corresponding weighted mean value from the results in [8] which are referred to the date 1986-01-01. For the OFM and the PTB, the 1986 results are already included in (1); so we deleted them in the calculation of the

1986 value. To extrapolate $\Omega_{69\text{-BI}}$ from 1986-01-01 to 1987-10-20 we use the results of (6) below. This gives for the 1986 R_H value extrapolated to 1987-10-20:

$$R_H = 25\,812.8\,[1 + (2.034 \pm 0.044) \times 10^{-6}]\ \Omega_{69\text{-BI}} \text{ on 1987-10-20.} \quad (3)$$

This is in good agreement with the 1987 value in (1).

The uncertainties listed in column 3 of Table II were derived from the components given in Table III. Data in the third column were provided by the participants. The fourth column gives the standard deviation of the mean calculated from the values of $\Omega_{LAB} - \Omega_{69\text{-BI}}$ deduced from each travelling standard. The type B uncertainties are estimated as described in Section II.D.

The histogram in Fig. 2 indicates the scatter in the value of $\Omega_{LAB} - \Omega_{69\text{-BI}}$ obtained from travelling standard *i* with respect to the mean value of $\Omega_{LAB} - \Omega_{69\text{-BI}}$ deduced from all travelling standards from a given laboratory. The two travelling standards from one laboratory are deleted since one of them, we do not know which one, underwent an unusually large change. For the data in Fig. 2, the pooled standard deviation is 0.034 μΩ. This is an estimate of the transfer uncertainty of the travelling standards. It is noteworthy that if the same analysis is made using only the results from the seven transfer standards made by the CSIRO, the corresponding pooled standard deviation is 0.010 μΩ.

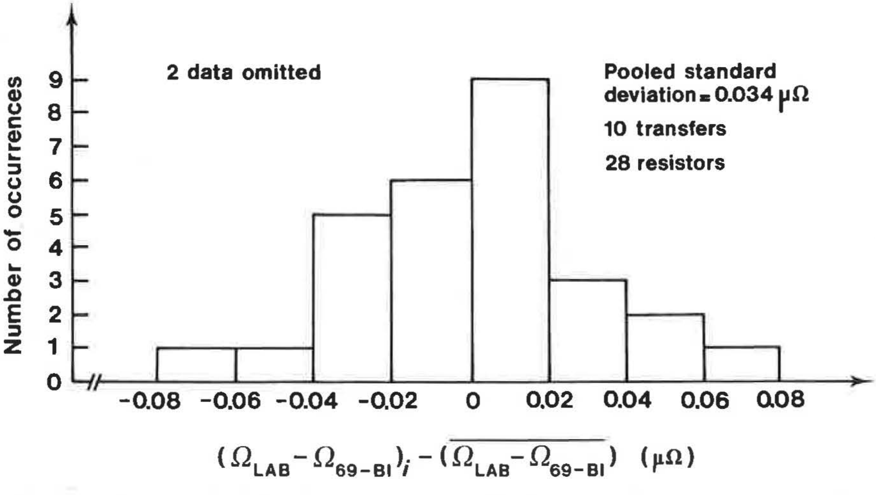

Fig. 2. — Dispersion of $\Omega_{LAB} - \Omega_{69\text{-BI}}$ for the 1987 limited international comparison of resistance.

The value of $\Omega_{LAB} - \Omega_{69\text{-BI}}$ on 1987-10-20 from the CSIRO, combined with the values of Ω_{LAB} in terms of the CSIRO realization of the ohm by the calculable capacitor, namely, $\Omega_{LAB} - \Omega = (0.030 \pm 0.005)\ \mu\Omega$, allows us to calculate a value for $\Omega_{69\text{-}BI}$ in Ω, based on the CSIRO determination of the ohm, for 1987-10-20. The value is

$$\Omega_{69\text{-}BI} - \Omega = -\ (1.731 \pm 0.017)\ \mu\Omega. \tag{4}$$

The above uncertainty is only that component of the total uncertainty (types A and B combined) which is expected to vary in time. From previous results [9], we would have expected

$$\Omega_{69\text{-}BI} - \Omega = -\ (1.738 \pm 0.011)\ \mu\Omega, \tag{5}$$

a remarkably good agreement. From the results and uncertainty in (4), and all of the previous data linking $\Omega_{69\text{-}BI}$ to the CSIRO determination of the ohm [9], we have recalculated a weighted, linear, least-squares fit. The result is

$$\Omega_{69\text{-}BI} - \Omega = a + bt, \tag{6}$$

where $a = -\ (1.733 \pm 0.007)\ \mu\Omega$,
$b = -\ (0.0614 \pm 0.0011)\ \mu\Omega/\mathrm{a}$,
t is time, in years, measured from 1987-10-20,

and all uncertainties are of type A only.

The data are shown in Fig. 3. The error bars represent the *total* uncertainties assigned by the CSIRO to each point. The results in (6)

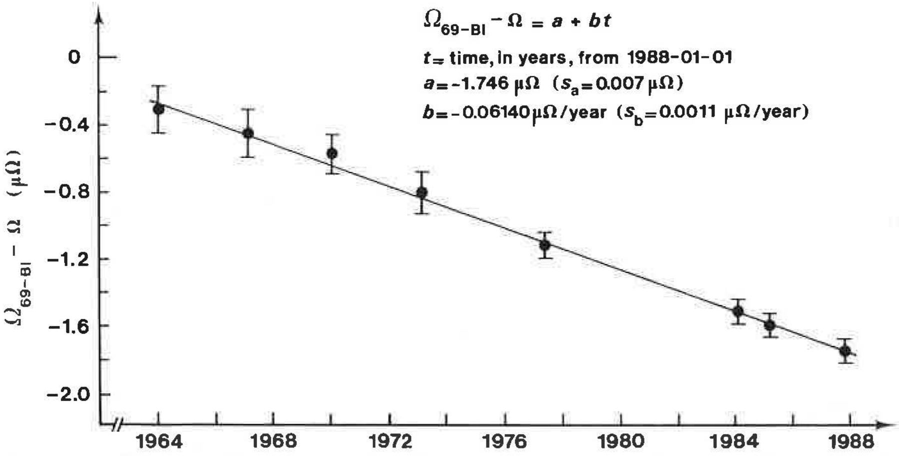

Fig. 3. — Variation in time of $\Omega_{69\text{-}BI}$ deduced from determinations of the ohm at the CSIRO. The error bars represent the total combined uncertainty of each determination. The line results from a weighted fit taking into account only the component of the total uncertainty that is expected to vary in time.

can be used to express the result of the weighted value of R_H from (1) in Ω. The result is

$$R_H = 25\,812.8\,[1 + (0.326 \pm 0.067) \times 10^{-6}]\ \Omega, \qquad (7)$$

where we have included the type B uncertainty of 0.062 μΩ estimated by the CSIRO for its ohm determination [10].

IV. Conclusions

The limited international comparison of one-ohm resistance standards yields values of $\Omega_{LAB} - \Omega_{69\text{-}BI}$ having typical total uncertainties of about 0.03 μΩ, a value nearly equal to the typical random scatter of 0.034 μΩ. The comparison with the CSIRO resulted in a value for $\Omega_{69\text{-}BI}$ in Ω based on the CSIRO determinations of the ohm, which was very close to the anticipated value, reconfirming the predictability of $\Omega_{69\text{-}BI}$ with a completely new measurement system at the BIPM.

The weighted mean and standard deviation of the values of R_H in $\Omega_{69\text{-}BI}$, deduced from measurements of R_H in Ω_{LAB} made in the 12 participating laboratories are :

$$R_H = 25\,812.8\,[1 + (2.059 \pm 0.021) \times 10^{-6}]\ \Omega_{69\text{-}BI} \text{ on 1987-10-20.}$$

The values of R_H for five of the six laboratories claiming a relative uncertainty of 3.6×10^{-8} or less in their measurements of R_H in terms of Ω_{LAB} as well as the extrapolated value of the weighted mean of R_H from 1986 all lie within an interval of 6.6×10^{-8}. This excellent agreement demonstrates that it is now possible to use the quantum Hall effect to realize a representation of the ohm having a world-wide reproducibility and a stability in time of a few parts in 10^8.

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Notes added in proof. — In order to reduce the type A uncertainty in the value of $\Omega_{IMM} - \Omega_{69\text{-}BI}$, a new bilateral comparison between the IMM and the BIPM is being arranged. Also, a new, post-deadline, result has become available [11] from the PTB, namely, on 1988-09-21,

$$R_H = 25\,812.8\,[1 + (0.793 \pm 0.065) \times 10^{-6}]\ \Omega_{PTB}.$$

Based on determinations of the ohm at the CSIRO, it was estimated [11] that, on 1988-09-21,

$$\Omega_{PTB} - \Omega = (-\,0.498 \pm 0.066)\ \mu\Omega,$$

which, when combined with (4), gives, on 1987-10-20,

$$R_H = 25\,812.8\,[1 + (2.026 \pm 0.094) \times 10^{-6}]\ \Omega_{69\text{-}BI}.$$

This is in good agreement with (1).

TABLE I

Deviations from unity of the values R of the travelling standards in Ω_{LAB} and $\Omega_{69\text{-}\mathrm{BI}}$ and corresponding values, in μΩ, of the differences $\Omega_{\mathrm{LAB}} - \Omega_{69\text{-}\mathrm{BI}}$ on 1987-10-20

s_{M} is the standard deviation of the mean, in μΩ, of the differences $\Omega_{\mathrm{LAB}} - \Omega_{69\text{-}\mathrm{BI}}$.

	$\left(\frac{R}{\Omega_{\mathrm{LAB}}} - 1\right) \times 10^6$			$\left(\frac{R}{\Omega_{69\text{-}\mathrm{BI}}} - 1\right) \times 10^6$	$\Omega_{\mathrm{LAB}} - \Omega_{69\text{-}\mathrm{BI}}$ in μΩ	
Standard	Initial	Return	1987-10-20	1987-10-20	1987-10-20	s_{M} in μΩ
			PTB			
	1987-09-24	1987-12-15				
730951	− 25.670	− 25.880	− 25.736 6	− 24.505 7	+ 1.230 9	
730955	− 23.363	− 23.396	− 23.373 5	− 22.075 0	+ 1.298 5	
692273	− 20.016	− 20.199	− 20.074 0	− 18.846 4	+ 1.227 6	
					+ 1.252 3	0.023 1
			CSIRO			
	1987-09-02	1988-01-01				
S-60650	+ 29.411	+ 29.510	+ 29.450 2	+ 31.213 7	+ 1.763 5	
S-60657	− 1.470	− 1.427	− 1.453 0	+ 0.305 2	+ 1.758 2	
S-64144	− 9.976	− 9.899	− 9.945 5	− 8.184 7	+ 1.760 8	
					+ 1.760 8	0.001 5
			NRC			
	1987-08-26	1987-12-27				
336435	− 3.19	− 3.39	− 3.279	− 4.771 0	− 1.492	
336436	− 5.10	− 5.34	− 5.207	− 6.722 3	− 1.515	
336437	− 4.11	− 4.27	− 4.182	− 5.649 9	− 1.468	
					− 1.492	0.014
			NIM			
	1987-08-27	1988-02-04				
127BZ13	− 11.55	− 11.72	− 11.607 0	− 11.236 4	0.371	
601BZ13	− 26.20	− 26.32	− 26.240 2	− 25.803 7	0.436	
645BZ13	− 23.77	− 23.69	− 23.743 2	− 23.245 7	0.498	
					0.435	0.037
			NIST (ex. NBS)			
	1987-08-22	1988-01-05				
77	+ 5.966	+ 5.892	+ 5.934	+ 6.128 5	+ 0.194 5	
S-60659	+ 2.349	+ 2.342	+ 2.346	+ 2.595 0	+ 0.249 0	
S-60906	+ 6.708	+ 6.718	+ 6.712	+ 6.987 2	+ 0.275 2	
					+ 0.239 6	0.023 8
			LCIE			
	1987-08-10	1988-01-25				
732525	− 22.690	− 22.688	− 22.689	− 21.577 6	+ 1.111 4	
732530	− 22.880	− 22.885	− 22.882	− 21.782 4	+ 1.099 6	
732532	− 22.660	− 22.652	− 22.657	− 21.559 2	+ 1.097 8	
					+ 1.102 9	0.004 3

ETL

	1987-09-05	1988-02-04				
70C111	+ 0.938	+ 0.688	+ 0.864 0	+ 2.825 0	+ 1.961 0	
70C122	+ 5.248	+ 5.088	+ 5.200 6	+ 7.093 4	+ 1.892 8	
72C202	− 2.622	− 2.802	− 2.675 3	− 0.779 4	+ 1.895 9	
					+ 1.916 6	0.022 2

VSL

	1987-10-25	1988-04-23	1987-11-16	1987-11-16	(1987-11-16)	
1773191	− 24.277	− 24.347	− 24.285 5	− 23.689 6	+ 0.595 9	
1805643	− 21.814	− 21.879	− 21.821 9	− 21.207 4	+ 0.614 5	
					+ 0.605 2	0.009 3

NPL

	1987-09-04	1987-12-17				
L-713	+ 49.126	+ 49.145	+ 49.134 4	+ 49.448 0	+ 0.313 6	
S-60652	+ 54.156	+ 54.176	+ 54.164 8	+ 54.525 8	+ 0.361 0	
S-60656	+ 11.700	+ 11.714	+ 11.706 2	+ 12.078 0	+ 0.371 8	
					+ 0.348 8	0.017 9

OFMET

	1987-09-10	1988-01-17				
1624034	− 26.790	− 26.821	− 26.805	− 26.550 4	+ 0.254 6	
1844266	− 25.982	− 26.027	− 26.005	− 25.723 6	+ 0.281 4	
					+ 0.268 0	0.013 4

IMM

	1987-09-09	1988-03-09				
710	− 5.140	− 5.190	− 5.151	− 3.747 4	+ 1.403 6	
922	+ 12.760	+ 12.790	+ 12.767	+ 14.438 7	+ 1.671 7	
					+ 1.537 7	0.134 1

TABLE II

Values and uncertainties of Δ *in the equation* $R_{\mathrm{H}} = 25\,812.8\,(1 + \Delta \times 10^{-6})\,\Omega_{\mathrm{j}}$, *with* $\Omega_{\mathrm{j}} \equiv \Omega_{\mathrm{LAB}}$, *of* Ω_{LAB}-$\Omega_{\mathrm{69\text{-}BI}}$, *and (by derivation) of* Δ *with* $\Omega_{\mathrm{j}} \equiv \Omega_{\mathrm{69\text{-}BI}}$; *all referred to the mean date* 1987-10-20

LAB	Value and uncertainty for Δ, R_{H} in Ω_{LAB}, on 1987-10-20	Value and uncertainty for $\Omega_{\mathrm{LAB}} - \Omega_{\mathrm{69\text{-}BI}}$ on 1987-10-20, in μΩ	Value and uncertainty for Δ, R_{H} in $\Omega_{\mathrm{69\text{-}BI}}$, on 1987-10-20
BIPM	not applicable	not applicable	2.069 ± 0.015
CSIRO/NML	0.340 ± 0.030[a]	1.761 ± 0.015	2.101 ± 0.034
ETL[b]	0.247 ± 0.080	1.917 ± 0.027	2.164 ± 0.084
IMM	0.197 ± 0.070[c]	1.538 ± 0.136	1.735 ± 0.153
LCIE	0.942 ± 0.036	1.103 ± 0.037	2.045 ± 0.041[d]
NBS	1.843 ± 0.012	0.240 ± 0.028	2.083 ± 0.031
NIM	1.193 ± 0.372[e]	0.435 ± 0.050	1.628 ± 0.375
NPL	1.712 ± 0.025	0.349 ± 0.027	2.061 ± 0.037
NRC	3.711 ± 0.066	− 1.492 ± 0.036	2.219 ± 0.075
OFMET	1.906 ± 0.121	0.268 ± 0.032	2.174 ± 0.125
PTB	0.569 ± 0.120	1.252 ± 0.031	1.821 ± 0.122
VSL	1.263 ± 0.030[f]	0.605 ± 0.027[g]	1.868 ± 0.040

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[a] CSIRO reported its results in terms of an Ω_{LAB}; they deduced $\Omega_{\mathrm{LAB}} = 1\,\Omega + 0.030\,\mu\Omega$, with a type A uncertainty of 0.005 μΩ, for the period 1987-08-24 to 1988-03-02.

[b] ETL did not use an intermediate group of resistors corresponding to an Ω_{LAB}; values of their travelling standards were determined directly in terms of the QHE using $R_{\mathrm{H}} = 25\,812.806\,4\,\Omega_{\mathrm{ETL}}$.

[c] Using $\Delta = 0.190 \pm 0.070$ on 1988-04-21 and assuming (0.015 ± 0.010) μΩ/a for the drift rate of Ω_{IMM}.

[d] Relative uncertainties of 3.6×10^{-8} for R_{H} in terms of travelling standards and 2.0×10^{-8} for travelling standards in terms of $\Omega_{\mathrm{69\text{-}BI}}$.

[e] Referred to 1988-05-01.

[f] Referred to 1987-12-20.

[g] Referred to 1987-11-16.

TABLE III

Uncertainties in $\Omega_{\mathrm{LAB}} - \Omega_{\mathrm{69\text{-}BI}}$ *in parts in* 10^8

LAB	Value of $\Omega_{\mathrm{LAB}} - \Omega_{\mathrm{69\text{-}BI}}$ μΩ	Uncertainty for travelling standards, in Ω_{LAB}; type	Value of σ_m for the transfer; type A	Uncertainty for travelling standards, in $\Omega_{\mathrm{69\text{-}BI}}$; type B	RSS total uncertainty
CSIRO	1.761	1 A and B	0.2	1.1	1.5
ETL	1.917	0 —	2.2	1.5	2.7
IMM	1.538	1.5 A and B	13.4	1.5	13.6
LCIE	1.103	3.3 B	0.4	1.5	3.7
NBS	0.240	0.8 B	2.4	1.1	2.8
NIM	0.435	3 A and B	3.7	1.5	5.0
NPL	0.349	1.7 A and B	1.8	1.1	2.7
NRC	− 1.492	3 A and B	1.4	1.5	3.6
OFMET	0.268	2.5 A and B	1.3	1.5	3.2
PTB	1.252	2 A and B	2.3	1.5	3.1
VSL	0.605	2.1 B	0.9	1.5	2.7

Acknowledgement

We thank all of our colleagues in the national laboratories who participated in the resistance comparison and who provided values of R_H.

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APPENDIX E 6

Minutes of the fact-finding Meeting on Optical Fibres

(Organized jointly by the CCPR and the GT-RF of the CCE)

by J. BASTIE, Rapporteur

A fact-finding meeting on optical fibres, held jointly by the Comité Consultatif de Photométrie et Radiométrie (CCPR) and the Working Group on Radiofrequency Quantities (GT-RF) of the Comité Consultatif d'Électricité (CCE), took place at the Bureau International des Poids et Mesures (BIPM), at Sèvres, on Friday September 30, 1988.

Present were :

W. R. BLEVIN, President.

Delegates from the member laboratories :

Amt für Standardisierung, Messwesen und Warenprüfung [ASMW], Berlin (W. SCHLESOK).

Bureau National de Métrologie [BNM], Paris : Institut National de Métrologie [INM] du Conservatoire National des Arts et Métiers (J. BASTIE).

CSIR, Division of Production Technology [CSIR], Pretoria (M. L. du PREEZ).

CSIRO, Division of Applied Physics [CSIRO], Lindfield (W. R. BLEVIN, member of the CIPM, President of the CCPR).

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

Instituto de Optica Daza de Valdés [IOM], Madrid (A. PONS).

Laboratoire Central des Industries Électriques [LCIE], Fontenay-aux-Roses (L. ÉRARD, Chairman of the Working Group on Radiofrequency Quantities).

National Institute of Metrology [NIM], Beijing (J. M. ZHANG).

National Institute of Standards and Technology [NIST], Gaithersburg (E. AMBLER, Member of the CIPM, President of the CCE).

National Physical Laboratory [NPL], Teddington (D. H. NETTLETON, O. C. JONES).

National Research Council [NRC], Ottawa (J. VANIER).

Orszagos Mérésügyi Hivatal [OMH], Budapest (G. DEZSI).

Physikalisch-Technische Bundesanstalt [PTB], Braunschweig (K. MÖSTL, W. MÖLLER).
Statens Provningsanstalt [SP], Borås (L. LIEDQUIST).
Van Swinden Laboratorium [VSL], Delft (J. de VREEDE).

J. SCHANDA, Research Institute for Technical Physics, Budapest.
The Director of the BIPM (T. J. QUINN).

Also present at the meeting: P. GIACOMO, Director Emeritus; J. BONHOURE and T. J. WITT, senior staff; R. KÖHLER (BIPM).

Sent regrets:

Instituto Nacional de Tecnología Industrial [INTI], Buenos Aires (R. D. LOZANO).

Absent:

International Radioscientific Union [URSI].
Istituto Elettrotecnico Nazionale Galileo Ferraris [IEN], Turin.
Office Fédéral de Métrologie [OFMET], Wabern/World Radiation Center, Davos Dorf.
Optical and Physical Measurements Research Institute [VNIIOFI] Moscow.
Telecommunications Institute [IRT], Budapest.
A. E. BAILEY, Milford-on-Sea.

The President opens the session and welcomes all present. Following the introduction of each participant, Mr. Bastie is designated Rapporteur.

After adding a seventh item (Publication of the findings of the meeting) the agenda is approved.

1. Reports on metrological work in the national laboratories that is specifically related to or in support of optical-fibre technology

This item on the agenda formed the subject of written replies summarized in the working document RFO/88-1-R, to questions 1 and 2 of the preliminary questionnaire (Document RFO/88-1).

In practice, most of the laboratories have the necessary equipment to measure characteristics of sources (radiant power output, spectral power distribution, etc.) and detectors (spectral responsivity, linearity, etc.); only some of them are equipped to measure characteristics of monomode and multimode fibres (e.g. attenuation). All laboratories anticipate the development of future facilities as users' needs require.

2. Identification of the national and international organizations, other than the Convention du Mètre and the BIPM, that already provide avenues for collaboration in optical-fibre metrology

2.1. National organizations

This question was the subject of written answers (Document RFO/88-1-R) from the majority of the participants. We observe that the national standards laboratories generally play an important rôle but there are other organizations as well: the ASMW and Kammer der Technik in the German Dem. Rep., the BNM and the Union Technique de l'Électricité in France, the National Calibration Service in South Africa, the ETL, the Japan Machinery and Metals Inspection Institute and the Optoelectronic Industry and Technology Development Association in Japan, the NIST and the Electronics Industries Association in the USA, the NPL, the Optical Fibre Measurement Club and the British Standards Institution in the UK, the Deutscher Kalibrierdienst and the Standardizing Committee DIN DKE in the Fed. Rep. Germany, the SP in Sweden.

Next, Mr. Schanda is asked to describe the situation in his country. In Hungary, the OMH is responsible for the basic metrology of optical radiation. Practical measurements are conducted at the Research Institute for Technical Physics which is active in practically all the measurements enumerated in the questionnaire.

2.2. International organizations

In the replies received, the two most often cited entities are the Comité Consultatif International Télégraphique et Téléphonique (CCITT) and the International Electrotechnical Commission (IEC).

Information given chiefly by Messrs. Jones, Nettleton, Nemoto, Ambler, Vanier and Quinn indicates that the CCITT, a permanent organ of the International Telecommunication Union, has published a book of specifications for assuring consistency in the use of optical fibres in telecommunications and has developed a number of reference methods for carrying out tests. Numerous characteristic parameters of optical fibres have « CCITT reference methods » and many countries employ CCITT recommendations in placing their orders for telecommunications materials. Although some metrology laboratories participate in the activities of the CCITT, it does not seem that its major concerns are metrological.

The rôle of the IEC is to establish standards. Mr. Nettleton indicates that this body is presently preparing some standards for calibration methods in the field of fibre optics, particularly for power measurements. Mr Jones adds that the CCITT would probably adopt the IEC standards if they were made ready more quickly.

Mr. Schanda points out that the International Commission on Illumination (CIE) does not have a committee for fibre optics specifically but deals only with radiometry.

In Europe a number of bodies are interested, to a varying degree, in the problem of optical fibres. These include the Comité Européen de Normalisation (CEN), the Comité Européen de Normalisation Electrotechnique (CENELEC), the Coopération Européenne Scientifique et Technologique (COST), the Bureau Communautaire de Référence (BCR) and EUROMET.

The President finishes the discussion on this point by noting that the international body which seems to be the most active at present is the CCITT ; the latter provides evaluation methods covering most industrial needs for the characterization of optical fibres.

3. Discussion of any needs and/or advantages for the BIPM and the Convention du Mètre to provide additional avenues for collaboration in optical-fibre metrology, particularly between the national standards laboratories

The majority of the responses to the preliminary questionnaire show that the laboratories want the rôle of the CIPM to be limited to fundamental measurements. Only the ASMW and the CSIR would envisage a much wider activity for the CIPM ; they agree, however, that the fundamental subjects are sources and detectors, and more particularly the measurement of power. Thus the result of this initial consideration of the problem is that the CIPM should concern itself with measurements on optical fibres in areas which have to do with standards, but not with the technology of optical fibres.

Mr. Nettleton then poses the problem of high-precision measurements of the dimensions of very small objects ; Mr. Érard adds that it would also be desirable to measure attenuation as well as parameters of sources and detectors.

After this general discussion, the discussion focuses on the study of the table of replies to Question 6 (Document RFO/88-1-R) in order to determine more precisely the rôle of the CIPM in the field of optical fibres.

Sources : The first two points, radiant power and spectral distribution, are in the area of responsibility of the CIPM. In contrast, the third point, modulation characteristics, appears to be more the concern of the national laboratories or of industry.

Detectors : Spectral sensitivity, linearity, frequency response and spatial uniformity fit into the CIPM's activities.

Fibres in general : Core and sheath diameters are important parameters for industry ; they pose the problem of dimensional metrology of very small objects. Mr. Quinn observes that this problem encompasses a much broader range of activities than just optical fibres because it is part of the field of « nanotechnologies ». That can be a subject of interest to the CIPM.

Monomode fibres : Problems pertaining to monomode fibres do not seem to fall within the purview of the CIPM.

Multimode fibres : The GT-RF is currently organizing a comparison of attenuation in this type of fibre, with the ETL as pilot laboratory and 5 participating laboratories (comparison GT-RF/86-5). This is therefore an area in which the CIPM already has an activity.

Characteristics of other apparatus : This is a very important point for industry and involves the problems of calibrations and traceability but does not concern the CIPM directly.

From this discussion it becomes clear that the members of the CCPR are much more inclined towards a more fundamental rôle of the CIPM and towards basic references whereas the GT-RF leans much more towards the industrial aspects. Mr. Ambler explains that there is an historical reason for this orientation.

For the President, the most important point is to ensure that the national laboratories are in good agreement among themselves before undertaking activities of a more industrial nature. Mr. Quinn adds that it would be important to know how close are the needs of users to the capabilities of the best present standards and measurement techniques.

In order to complete the information on this point of the agenda, the President asks Mr. Nemoto to give a brief summary of the progress to date in the comparison GT-RF/86-5. Mr. Nemoto says that the first phase of the comparison with a multimode fibre (light-emitting diode ; 0.85 µm) is just now starting ; a second phase is suggested for 1989 with a monomode fibre (laser diode ; 1.3 µm).

From the discussion it emerges that, for the present, the activities of the CIPM in the field of optical fibres should be limited to sources, detectors and attenuation, leaving open the question of other characteristics.

Concerning the assignment of activities among the different consultative committees, it is clear that a close collaboration between the CCPR and the GT-RF is highly desirable. It is therefore proposed that matters concerning measurements of power and associated quantities become the responsibility of the CCPR but that the GT-RF be consulted and invited to participate in comparisons. Since attenuation measurements are chiefly of interest to the GT-RF, they are placed under its responsibility and, in a fashion comparable to the above arrangement, the members of the CCPR should be consulted on, and invited to participate in, any proposed comparisons.

As the problem of dimensional measurements (nanotechnologies) is not the responsibility of either the CCPR or the GT-RF, it will be brought to the attention of the CIPM.

4. Progress report on present International Comparison of Optical-Fibre Power Measurements (pilot laboratory : NIST)

In the absence of Mr. Gallawa, Mr. Nettleton presents the progress report for the comparison. A preparatory meeting took place on September 18, 1987 at Braunschweig (Fed. Rep. Germany). This comparison is divided into two parts. The first is intended for the preparation of the detectors and the second consists of the comparison itself which, to save time, will proceed in three parallel branches. Four laboratories, the NIST, the NPL, the PTB and the CSIRO, are involved in the first part and fourteen laboratories in the second. Work in the first part is under way and the detectors should be ready by about April 1989. The time required for the circulation of standards is estimated to be one year.

The President thanks Mr. Nettleton for his report and the NIST, the NPL and the PTB for the work already completed. Joint discussions of the results will be undertaken by the CCPR and the GT-RF.

Following this presentation, a brief discussion takes place on the practical problems connected with the transportation of detectors and customs formalities. As in the case of other comparisons, the BIPM recommends the use of the ATA carnet, a customs document permitting free temporary importation of material.

5. Responsibility for future international comparisons of radiometric measurements on lasers

Mr. Jones proposes that the CCE be responsible for pulsed or high-power lasers and that the CCPR take responsibility for CW, low-power lasers. In case of doubt, a discussion between the Presidents of the two consultative committees should allow any problem to be resolved. This solution satisfies all the participants.

6. Miscellaneous subjects

Taking up a proposal by the ETL, the conferees study the possibility of creating a joint Working Group, CCPR and CCE, on opto-electronic components. The President asks if there will be enough activity to justify creation of such a Working Group. For Mr. Nettleton, it seems that some forum for discussing these problems would probably be of interest ; another solution would be to create a small working group for each specific subject, such as a comparison, considered. As for the preparation of documents, discussions and agreements could proceed by correspondence, without having to arrange international meetings.

Mr. Schanda describes an international comparison organized by the CIE, dealing with the photometric and radiometric characteristics of light-emitting diodes. Temperature-regulated diodes have been sent to various laboratories which were asked to measure the luminous intensity, the luminous flux, the spectral distribution and the trichromatic coordinates of the diodes. The results obtained were not very satisfactory and, at present, two of the participating laboratories have begun to repeat the measurements after having made improvements aimed at trying to remove ambiguities found earlier. Another comparison is planned, on a larger scale, with new diodes. Would such a comparison, extended into the infrared, be of interest to the members of the CCPR and the GT-RF ?

7. Publication of the minutes of the meeting

The participants would like the minutes to be published as an appendix to the report of the 1988 meeting of the CCE and of the 1990 meeting of the CCPR.

The President thanks all the participants for the work completed and closes the session.

TABLE DES MATIÈRES

COMITÉ CONSULTATIF D'ÉLECTRICITÉ

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Annexes

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