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# *Possible Changes in the U.S. Legal Units Of Voltage and Resistance*

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The Consultative Committee on Electricity of the International Committee on Weights and Measures is considering adopting sometime in the future 1) a new value for the Josephson frequency-voltage ratio $2e/h$ ($e$ is the elementary charge and $h$ is the Planck constant) and 2) a value for the quantized Hall resistance $R_H \equiv h/e^2$. Both values are to be chosen as consistent with their International System of Units (SI) values as possible and would be used by every national standards laboratory which employs the Josephson and quantum Hall effects to define and maintain their national or legal units of voltage and resistance. Based on current knowledge, this would lead to an increase in the U.S. Legal Volt of about nine parts-per-million (ppm) and an increase in the U.S. Legal Ohm of about 1.5 ppm. Comparable changes would be required in the voltage and resistance units of most other national, governmental, and industrial standards laboratories throughout the world. Many high-precision instruments would also have to be readjusted to make them consistent with the new units. It is the purpose of this paper to review in some detail the basis for these proposed and potentially significant changes.

**Key words:** electrical units; Josephson effect; ohm; quantum Hall effect; volt.

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## 1. Introduction

The dominant system of units used throughout the world to express the results of physical measurements is *Le Système International d'Unités* or International System of Units, abbreviated SI. The seven *base* units of the SI from which all other units are *derived* are the meter (m), kilogram (kg), second (s), ampere (A), kelvin (K), mole (mol), and candela (cd) [1][1]. These are, respectively, the unit of length, mass, time, current, temperature, amount of substance, and luminous intensity.

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[1] Numbers in brackets indicate literature references.

The SI electrical units most commonly used in practice are those of potential difference (or electromotive force) and resistance; the volt (V) and ohm (Ω). These two units are derived from the three SI base mechanical units (m, kg, s) and the SI base electrical unit (A), the specific relationships being

$$1\ \mathrm{V} = 1\ \mathrm{m}^2 \cdot \mathrm{kg} \cdot \mathrm{s}^{-3} \cdot \mathrm{A}^{-1} \tag{1}$$

$$1\ \Omega = 1\ \mathrm{m}^2 \cdot \mathrm{kg} \cdot \mathrm{s}^{-3} \cdot \mathrm{A}^{-2} \tag{2}$$

Because the SI definitions of the volt and ohm embodied in eqs (1) and (2) are extremely difficult to realize with high accuracy, national standards laboratories such as NBS have historically used practical representations of them to serve as the

national or legal electrical units. For example, the mean emf of a particular group of electrochemical standard cells of the Weston type (each with an emf of order 1.018 V) has traditionally been used to define a laboratory or as-maintained national unit of voltage $V_{LAB}$, and the mean resistance of a particular group of precision wire-wound resistors of the Thomas or similar type (each with a resistance of order 1 Ω) has similarly been used to define a laboratory or as-maintained national unit of resistance $\Omega_{LAB}$. The national unit of current $A_{LAB}$ is then defined in terms of $V_{LAB}$ and the $\Omega_{LAB}$ by means of Ohm's law, $A_{LAB}=V_{LAB}/\Omega_{LAB}$, and does not require its own separate representation.

A laboratory or as-maintained national system of practical electrical units immediately raises two questions: 1. How does one ensure that $V_{LAB}$ and $\Omega_{LAB}$ are *constant in time* when they are based on artifacts? 2. How does one ensure that $V_{LAB}$ and $\Omega_{LAB}$ are *consistent with their SI definitions*? Problem 1 leads to the idea of monitoring or *maintaining* laboratory units while Problem 2 to the idea of carrying out *absolute realizations* of the SI electrical units. Ideally one would like to solve both problems simultaneously, that is, to maintain a laboratory unit constant in time and consistent with its SI definition by the same means and at the same time, and at a level of accuracy which is in keeping with the inherent stability of the artifacts used to define it. However, because this stability is at the level of parts in $10^7$ per year (or for some very well aged cells and resistors at the level of parts in $10^8$ per year), it has not yet proved feasible to do so in most laboratories.

It is important to recognize that Problems 1 and 2 *both* require solution. If the various national units of voltage and resistance (and hence current) *vary with time*, it will be difficult to make reproducible and consistent electrical measurements within a particular country as well as between different contries. If the units are *inconsistent with their SI definitions*, electrical and mechanical measurements of force, energy, and power will not yield the same results. While there are no practical situations at present where measurement accuracy is high enough to make visible the known inconsistencies between the SI mechanical and as-maintained electrical units, it is inevitable that such situations will arise as science and technology advance. Moreover, if all national units are consistent with the SI they will be consistent with each other. This will help ensure that electrical measurements made throughout the world are compatible.

## 2. Maintaining Laboratory Units

### 2.1 Josephson Effect

The national standards laboratories of most major industrialized countries now use the Josephson effect [2] to define their unit of voltage and maintain it constant in time. A low-temperature, solid-state physics phenomenon, the Josephson effect occurs when two superconductors separated by 1–2 nm (achievable with an oxide layer) are cooled below their transition temperatures. If such a Josephson junction is exposed to microwave radiation of frequency $f$, current steps appear in its current-voltage curve at discrete or quantized values of voltage. The voltage $V_n$ of the $n$th step and the frequency $f$ are related by $2eV_n=nhf$ where $e$ is the elementary charge and $h$ is the Planck constant. A Josephson junction can thus be viewed as a perfect frequency-to-voltage converter with the constant of proportionality being the invariant fundamental constant ratio $2e/h$. Numerically, $2e/h \approx 484$ MHz/μV. Hence, the spacing between steps for applied radiation of 10 GHz, a commonly used frequency, is $\approx 20$ μV. The amplitude of the current steps decreases with increasing $n$ and there are practical limitations on the minimum useable size of a current step due to electrical noise. The maximum step number $n$ is thus usually restricted to $\approx 250$ for a single Josephson junction, corresponding to a maximum junction voltage of $\approx 5$ mV. Because frequencies can be readily measured to very high accuracy, the Josephson effect can be used to define and maintain $V_{LAB}$ to an accuracy limited only by the uncertainty with which the voltage across the Josephson device can be compared with the 1.018-V emf of a standard cell. Typically this is in the range 0.01 to 0.1 parts-per-million or ppm. (Throughout this paper all uncertainties are meant to correspond to one standard deviation estimates.) The standard cell now serves only as a "flywheel," that is, as a means of preserving or storing $V_{LAB}$ between Josephson effect measurements.

The defining equation for $V_{LAB}$ based on the Josephson effect is

$$(2e/h)_{LAB} \equiv 48359?\ \mathrm{GHz}/V_{LAB} \quad , \tag{3}$$

where $(2e/h)_{LAB}$ is the specific value of $2e/h$ adopted by the laboratory to define $V_{LAB}$. The question mark is meant to indicate that several different values are in use at the various national laboratories. For example, since 1 July 1972 NBS has defined $V_{NBS}$ and maintained it constant in time

with an uncertainty of 0.031 ppm using the value [3]

$$(2e/h)_{NBS} \equiv 483593.420 \text{ GHz}/V_{NBS} \quad . \qquad (4)$$

This particular number was chosen in order not to introduce a discontinuity in the U.S. Legal Volt when on this date NBS officially converted from standard cells to the Josephson effect as the basis for $V_{NBS}$. In contrast, a large number of national laboratories, including the National Research Council (NRC), Canada, the National Physical Laboratory (NPL), U.K., the Physikalisch-Technische Bundesanstalt (PTB), Federal Republic of Germany, and the Electrotechnical Laboratory (ETL), Japan, as well as the International Bureau of Weights and Measures (BIPM), use

$$(2e/h)_{LAB} \equiv 483594.000 \text{ GHz}/V_{LAB} \quad , \qquad (5)$$

a value recommended in October 1972 by the Consultatative Committee on Electricity (CCE) of the International Committee on Weights and Measures (CIPM) [4]. This means that the unit of voltage of these countries and of the BIPM is 1.20 ppm larger than that of the U.S.

The CCE value of $2e/h$ was chosen to be consistent with the unit of voltage of the BIPM as it existed on 1 January 1969 based on a group of standard cells. Acting upon a 1968 CCE recommendation, on this same date BIPM decreased its unit of voltage by 11.0 ppm to bring it into agreement with the SI unit [5]. Thus the CCE value of $2e/h$ was intended to be consistent with the SI. The 11 ppm decrease recommended by the CCE was initially obtained from the results of NBS and NPL current-balance absolute realizations of the SI ampere with the help of a number of calculable inductor and capacitor absolute realizations of the SI ohm [6]. (It was later supported by results from certain fundamental constant determinations [7,8].) Most national laboratories also lowered their voltage unit on 1 January 1969 [8], the size of the decrease being determined by the difference between $V_{LAB}$ and $V_{BIPM}$ obtained in the 1967 triennial international comparison of national units of voltage carried out under CCE auspices at the BIPM by transporting standard cells [7]. For example, on 1 January 1969 the NBS unit was reduced by 8.4 ppm since in 1967 $V_{NBS}$-$V_{BIPM}$ was found to be $-2.6$ ppm.

Two other values of $2e/h$ are also in use: the Central Laboratory of the Electrical Industries (LCIE), France, employs [9]

$$(2e/h)_{LCIE} \equiv 483594.64 \text{ GHz}/V_{LCIE} \qquad (6)$$

while the All-Union Scientific Research Institute of Metrology (or Mendeleyev Institute of Metrology, IMM), U.S.S.R., uses [10]

$$(2e/h)_{IMM} \equiv 483596.176 \text{ GHz}/V_{IMM} \quad . \qquad (7)$$

The French and U.S.S.R. units are thus 2.52 and 5.70 ppm larger than the U.S. unit, respectively. The French value of $2e/h$ was chosen for the same reason as was the U.S. value, that is, to prevent a discontinuity in the French volt when converting from standard cells to the Josephson effect as the basis for $V_{LCIE}$. The U.S.S.R value was selected in the late 1970's to make $V_{IMM}$ more consistent with the SI unit and stems from an IMM analysis of certain fundamental constant determinations (to be touched upon later).

### 2.2 Quantum Hall Effect

The quantum Hall effect (QHE) promises to do for resistance-unit definition and maintenance what the Josephson effect has done for voltage-unit definition and maintenance [11]. Like the Josephson effect the QHE is a low-temperature, solid-state physics phenomenon. However, the materials involved are semiconductors rather than superconductors. The QHE is characteristic of a two-dimensional electron gas (2DEG) realized, for example, in classic Hall-bar geometry, high-mobility semiconductor devices such as silicon MOSFETs and GaAs-$Al_xGa_{1-x}As$ heterostructures when in an applied perpendicular magnetic field of order 10 T and cooled to a few kelvin. Under these conditions the 2DEG is completely quantized and there are regions in the curve of Hall voltage vs. gate voltage for a MOSFET, or Hall voltage vs. magnetic field for a heterostructure, where the Hall voltage remains constant as the gate voltage or magnetic field is varied. On these so-called Hall plateaus the Hall resistance $R_H(i)$, defined as the ratio of the Hall voltage of the ith plateau $V_H(i)$ to the current $I$ through the device, $R_H(i)=V_H(i)/I$, is quantized and given by $R_H(i)=h/(e^2 i)$ with the quantum integer i equal to the plateau number. Numerically, $h/e^2 \approx 25812.8\ \Omega$ and hence the resistance of the readily obtainable $i=4$ plateau is $\approx 6453.2\ \Omega$. A QHE device can thus be viewed as a resistor whose resistance depends only on the fundamental-constant ratio $h/e^2$. As such it can be used to define and maintain $\Omega_{LAB}$ to an accuracy limited only by the uncertainty with which the resistance of the device (when on a plateau) can be compared with the 1-$\Omega$ resistance of a standard

resistor. Eventually this is expected to be in the range 0.01 to 0.1 ppm for all laboratories; 0.022 ppm is the smallest uncertainty reported to date [12]. In analogy with the standard cell and the Josephson effect, the standard resistor would serve only to store $\Omega_{LAB}$ between QHE measurements.

The defining equation for $\Omega_{LAB}$ based on the quantum Hall effect may be written as

$$(h/e^2)_{LAB} \equiv 25812.8?\ \Omega_{LAB} \quad , \tag{8}$$

where in analogy with eq (3) $(h/e^2)_{LAB}$ is the specific value of $h/e^2$ adopted by the laboratory to define $\Omega_{LAB}$. (In this case the question mark means that a specific value has yet to be adopted by any laboratory.) The combination of constants $h/e^2$ has been termed the quantized Hall resistance $R_H$. It is related to the inverse of the fine-structure constant $\alpha$, the dimensionless coupling constant or fundamental expansion parameter of quantum electrodynamic theory (QED), by

$$h/e^2 \equiv R_H = \mu_0 c \alpha^{-1}/2 \quad . \tag{9}$$

Here $\mu_0$ is the magnetic permeability of vacuum and exactly equal to $4\pi \times 10^{-7}$ N/A$^2$. (Note that 1 N$=1$ m $\cdot$ kg $\cdot$ s$^{-2}$ and that in the SI the ampere is related to the meter, kilogram, and second in such a way that $\mu_0$ is an exact constant). The quantity $c$ is the speed of light in vacuum and as a result of the recent redefinition of the meter [13] is an exact constant given by $c \equiv 299792458$ m $\cdot$ s$^{-1}$. Since both $\mu_0$ and $c$ are defined constants, if $\alpha^{-1}$ is known from some other experiment with a given uncertainty, $R_H$ will be known with the same uncertainty.

All of the major national standards laboratories as well as the BIPM are currently putting into place the apparatus necessary to define and maintain their unit of resistance using the QHE. However, as of this writing no laboratory has officially converted to the QHE; most national units of resistance are still based on the generally time-dependent, mean resistance of a particular group of wire-wound resistors. For example, in the U.S. $\Omega_{NBS}$ is still defined in terms of the mean resistance of five specific Thomas one-ohm resistors and, as will be noted later, is decreasing relative to the SI unit by about 0.06 ppm per year [14,15]. Since the drift of the unit of resistance of a number of other countries and of the BIPM is comparable [15], in analogy with the present state of the various national units of voltage brought about by the Josephson effect, implementation of the QHE will at the very least lead to the various national units of resistance remaining constant relative to the SI unit and one another, and to their differences always being well known.

## 3. Absolute Realizations

While the Josephson and quantum Hall effects allow $V_{LAB}$ and $\Omega_{LAB}$ to be maintained constant in time with an uncertainty between 0.01 and 0.1 ppm, thereby solving Problem 1 above, unless $2e/h$ and $R_H$ are known in SI units to the same level of accuracy, the as-maintained and SI systems of electrical units will not be consistent and Problem 2 above will remain unsolved. In practice there are two general approaches to determining $2e/h$ and $R_H$ in SI units. The first is to carry out experiments to realize *directly* the SI definitions of V, $\Omega$, and A or equivalently, experiments which use electromagnetic theory in combination with the SI definitions; the second is to carry out experiments to determine various fundamental constants from which V, $\Omega$, and A may be *indirectly* derived. As it will shortly be shown, the latter approach can yield uncertainties comparable with or smaller than those of the former.

### 3.1 Direct Determinations

The following is a brief summary of some of the ways the SI volt, ohm, and ampere are being directly realized at present [16].

*Volt.* By measuring the force between electrodes to which a voltage known in terms of $V_{LAB}$ has been applied, and the capacitance between the electrodes (determined in SI units via a calculable cross capacitor as discussed below), the ratio $V_{LAB}/V$ can be obtained. In practice, determining this ratio is what is meant by the terms "absolute realization of the volt" or "realization of the SI volt." Defining $(K_V)_{LAB} \equiv V_{LAB}/V$ and recognizing that $(2e/h)_{LAB}$ is used to define $V_{LAB}$, we may write

$$(K_V)_{LAB} \equiv V_{LAB}/V = (2e/h)_{LAB}/(2e/h) \ . \tag{10}$$

A realization of the SI volt is thus equivalent to determining $2e/h$ in SI units [recall that $(2e/h)_{LAB}$ is an adopted number with no uncertainty]. The smallest uncertainty reported to date for the direct realization of the SI volt is about 0.3 ppm [17], at least an order of magnitude larger than the uncertainty with which $V_{LAB}$ may be maintained via the Josephson effect.

*Ohm*. The SI ohm may be realized using a so-called Thompson-Lampard calculable cross capacitor [16] which allows the capacitance of a special configuration of electrodes to be calculated (in SI units) to very high accuracy from a single length measurement and the permittivity of vacuum $\epsilon_0$. (Since $\epsilon_0 = 1/\mu_0 c^2$ and $\mu_0$ and $c$ are exactly known constants, $\epsilon_0$ is also exactly known.) The impedance of the calculable capacitor is compared with the resistance of the one-ohm standards which represent $\Omega_{LAB}$ using a complex series of bridges. Defining $(K_\Omega)_{LAB} \equiv \Omega_{LAB}/\Omega$ and assuming $(R_H)_{LAB}$ is used to define $\Omega_{LAB}$, we may write

$$(K_\Omega)_{LAB} \equiv \Omega_{LAB}/\Omega = R_H/(R_H)_{LAB} \ . \qquad (11)$$

A realization of the SI ohm is thus equivalent to *determining $R_H$ in SI units, which in turn is equivalent* to determining the inverse fine-structure constant [see eq (9)]. The uncertainty of such an experiment is on the order of 0.03 to 0.1 ppm, comparable to the yearly stability of good resistance standards and the accuracy with which $\Omega_{LAB}$ may be currently maintained via $R_H$. However, because of the complexity of the experiment only one laboratory in the world has yet been able to maintain its unit of resistance consistently via the calculable capacitor. It would thus appear that the QHE will become the method of choice in most laboratories.

*Ampere*. By measuring the force between coils *of known dimensions carrying a current known in* terms of $A_{LAB}$, the ratio $A_{LAB}/A$ can be determined. Defining $(K_A)_{LAB} \equiv A_{LAB}/A$, we may write

$$(K_A)_{LAB} \equiv A_{LAB}/A = (K_V)_{LAB}/(K_\Omega)_{LAB} \ . \qquad (12)$$

A realization of the SI ampere measures neither $2e/h$ or $R_H$ but the product $(2e/h)R_H$ [see eqs (10 and 11)], which is equivalent to measuring the ele*mentary charge $e$ in SI units. The smallest uncer*tainty claimed to date for such an experiment is 4 ppm [18], about two orders of magnitude larger than the uncertainty with which $A_{LAB}$ can be maintained via the Josephson and quantum Hall effects.

It should be noted from eq (12) that the determination of any pair of the three quantities $(K_A)_{LAB}$, $(K_V)_{LAB}$, and $(K_\Omega)_{LAB}$ is sufficient to yield a value for the third. Hence, accurate measurements of all three can provide a useful check of their consistency.

### 3.2 Indirect Determinations

As indicated above, $(K_V)_{LAB}$, $(K_\Omega)_{LAB}$, and $(K_A)_{LAB}$ may also be obtained from appropriate combinations of various fundamental physical constants. In addition to $\mu_0$, $c$, $(2e/h)_{LAB}$, and $(R_H)_{LAB}$ discussed above, these include (with the smallest uncertainty currently achieved shown in parenthesis [15,19,20]), the Rydberg constant for infinite mass $R_\infty$ (0.00055 ppm), the magnetic moment of the proton in $H_2O$ in units of the Bohr magneton $\mu_p'/\mu_B$ (0.011 ppm), the molar mass of the proton $M_p$ (0.012 ppm), the ratio of the proton mass to electron mass $m_p/m_e$ (0.020 ppm), the inverse fine-structure constant $\alpha^{-1}$ (0.038 ppm), the Faraday constant measured in laboratory electrical units $F_{LAB}$ (1.3 ppm), the gyromagnetic ratio of the proton in $H_2O$ measured by the low and high field methods in laboratory electrical units $\gamma_p'(\text{low})_{LAB}$ and $\gamma_p'(\text{high})_{LAB}$ (0.21 ppm and 1.0 ppm, respectively), and the Avogadro constant $N_A$ (1.3 ppm).

It should be recognized that the electric-unit-dependent constants in the above group have not all been measured in the same national standards laboratory and thus in terms of the same set of national electrical units. It is possible, however, to re-express all such quantities in terms of a single set of laboratory units, for example, those of BIPM, with little loss in accuracy by using the known values of $(2e/h)_{LAB}$ and the results of direct resistance-unit comparisons carried out by means of transportable resistance standards. [If the national laboratories carrying out the measurements had been using the quantum Hall effect to define and maintain their unit of resistance, the required resistance-unit differences could have been readily obtained from the known values of $(R_H)_{LAB}$ adopted by the different national laboratories.]

As might be imagined, there are a number of different combinations of these constants which yield values of the three quantities $(K_V)_{LAB}$, $(K_\Omega)_{LAB}$, and $(K_A)_{LAB}$ [14,19,20]. For example, for the volt one has

$$(K_V)^2_{BIPM} = \frac{\mu_0 c^2 M_p (2e/h)^2_{BIPM}}{16 R_\infty (m_p/m_e) \alpha^{-1} N_A} \ , \qquad (13)$$

where we have assumed all electric-unit-dependent quantities have been expressed in terms of the laboratory units of BIPM. Based on the uncertainties given above for the relevant constants entering eq (13), it yields an indirect value of $(K_V)_{BIPM}$ with an uncertainty of about 0.65 ppm, only about twice that of the most accurate direct SI volt realization reported to date [17]. [Equation (13) was used by the U.S.S.R. to derive the value of $(2e/h)_{IMM}$ given in eq (7).]

For the ohm one may write

$$(K_\Omega)^3_{BIPM}=\frac{\mu_0^2c^3(\mu_p'/\mu_B)(2e/h)_{BIPM}}{16R_\infty(R_H)^2_{BIPM}\gamma_p'(low)_{BIPM}} \quad , \quad (14)$$

which yields an indirect value of $(K_\Omega)_{LAB}$ with an uncertainty of about 0.07 ppm. This is comparable with the uncertainty of direct calculable capacitor determinations.

For the ampere one has

$$(K_A)^2_{BIPM}=\frac{M_p\gamma_p'(low)_{BIPM}}{(m_p/m_e)(\mu_p'/\mu_B)\,F_{BIPM}} \quad , \quad (15)$$

gives an indirect value of $(K_A)_{BIPM}$ with an uncertainty of about 0.7 ppm. This is significantly less than the uncertainty of present-day direct current balance determinations which is in the range 4 to 10 ppm [7,8,16,18,19], and only about twice as large as that obtained from the relatively new approach of equating electrical and mechanical work [21].

## 4. Prognosis

Based on all of the data currently available, including both direct and indirect realizations of the SI electrical units as outlined above, there is strong evidence (first pointed out nearly a decade ago [22]) that the value of the Josephson frequency-voltage ratio adopted by the CCE in 1972 is smaller than the SI value by about 8 ppm with an uncertainty of about 0.3 ppm [14,15,17,19,21]. This means that the laboratory unit of voltage maintained by the BIPM and all of the other national standards laboratories which use the 1972 CCE recommended value of $2e/h$ is smaller than the SI unit by this same amount. For France and the U.S.S.R. the corresponding figure is about 6.7 and 3.5 ppm, respectively. Since $(2e/h)_{CCE}$ exceeds $(2e/h)_{NBS}$ by 1.2 ppm, the SI volt exceeds the U.S. Legal Volt by about 9.2 ppm. Thus, to bring the U.S. unit into agreement with the SI unit would require that the U.S. unit be increased by this amount. The observant reader will notice that this would bring the U.S. unit essentially back to where it was (within 1 ppm) prior to its 8.4 ppm decrease on 1 January 1969.

In a similar manner, based on all of the data currently available [14,15,19], there is strong evidence that the BIPM unit of resistance is about 1.6 ppm smaller than the SI unit with an uncertainty of about 0.1 ppm and that the BIPM unit is decreasing relative to the SI unit at a rate of about 0.06 ppm per year. The U.S. unit of resistance is smaller than the SI unit by approximately the same amount and is decreasing at about the same rate as the BIPM unit. Most other national units of resistance also differ from the SI unit by less than 2 ppm and are drifting relative to the SI unit by less than 0.1 ppm per year.

Because of the relatively large differences between national voltage and resistance units and the SI, and the rapid development of the quantum Hall effect as a resistance standard, the CCE is considering adopting in the future 1) a new value, consistent with the SI, for the Josephson frequency-voltage ratio $2e/h$ to be used by *every* national standards laboratory which employs the Josephson effect to define and maintain its laboratory unit of voltage; and 2) a value for the quantized Hall resistance $R_H$, consistent with the SI, to be used by *every* national standards laboratory which employs the quantum Hall effect to define and maintain its laboratory unit of resistance.

## 5. Conclusion

If the results of new, more accurate experiments currently underway are consistent among themselves and reaffirm the results of the earlier experiments upon which the differences given above are based, then an increase in the U.S. Legal Volt of approximately 9 ppm and in the U.S. Legal Ohm of approximately 1.5 ppm could be expected sometime within the next five years, along with the implementation at NBS of the quantum Hall effect to define and maintain the U.S. unit of resistance. Similar changes would be made by other national standards laboratories as well as the BIPM. The end result would be that most major national standards laboratories would have in place two quantum phenomena, the Josephson and quantum Hall effects, to define and maintain their national electrical units in terms of invariant fundamental constants of nature to within an uncertainty of 0.01 to 0.1 ppm. Since all laboratories would use the same values for these constants and these values would be consistent with their SI values to within an uncertainty of 0.1 to 0.3 ppm, the practical electrical units for voltage, resistance, and current of most major industrialized countries would be equivalent to within an uncertainty of 0.01 to 0.1 ppm and consistent with their SI definitions to within an uncertainty of 0.1 to 0.3 ppm. This would clearly represent a major advance in ensuring the compatibility of electrical measurements made throughout the world and their consistency with the SI.

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