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Volt Maintenance at NBS via $2e/h$: A New Definition of the NBS Volt*

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Abstract

This paper describes in detail the procedures, methods and measurements used to establish a new definition of the U.S. legal volt via the ac Josephson effect. This new definition has been made possible by the use of thin film tunnel junctions (capable of producing 10 mV outputs) and high accuracy voltage comparators. The Josephson junction is used as a precise frequency-to-voltage converter with a conversion factor equal to $2e/h$. A series of measurements of $2e/h$ has been carried out at NBS referenced to the as-maintained unit of emf based on a large group of standard cells. Measurements made at regular intervals over a one year period (1971 to 1972) indicate that the mean emf of this group of standard cells has decreased about 4 parts in 10^7. Primarily to remove the effects of this drift, on July 1, 1972 a new as-maintained unit was defined by choosing a value of $2e/h$ consistent with the existing unit of emf. The adopted value of $2e/h$ is 483593.420 GHz/V_{NBS}. The precision (one standard deviation) with which the new unit of emf can be maintained with the present techniques and apparatus is about 2 parts in 10^8. The accuracy of the present system is estimated to be 4 parts in 10^8. Comparisons of $2e/h$ systems at different national laboratories have been limited by uncertainties associated with the physical transfer of standard cells. In order to determine the relative agreement of the various $2e/h$ systems with precision better than 1 or 2 parts in 10^7, it appears desirable to compare $2e/h$ systems directly by transporting one of them.

1. Introduction

The ac Josephson effect has made possible the realization of a new voltage maintenance standard at the National Bureau of Standards. Critical to this realization is the role played by a Josephson junction which may be regarded here as a frequency-to-voltage converter, where the frequency-to-voltage ratio is precisely equal to the combination of physical constants $2e/h$ (e is the electron charge and h is Planck's constant). A variety of experimental tests (for material dependence, temperature dependence etc.) [1—5] and theoretical investigations [6—9] of the Josephson relation have been made which indicate that for ordinary Josephson devices (particularly tunnel junctions) with conventional current-voltage lead configurations the ratio is exact to at least a few parts in 10^8. However, further experimental investigation of this question appears desirable.

Since the first high precision measurements of $2e/h$ by Parker, Taylor and Langenberg [10], the potential significance of a precision voltage standard based on $2e/h$ has been recognized throughout the world [1, 2, 11—14]. It was first demonstrated by Finnegan, Denenstein, and Langenberg (FDL) that standard cells could be maintained with a precision of 10^{-7} via a Josephson $2e/h$ apparatus over extended periods of time (5 months) [1]. Establishing a unit of emf based on a fundamental physical phenomenon such as the ac Josephson effect removes many of the inherent difficulties in using a large group of standard cells to maintain a unit of emf. One of the most important of these difficulties is the gradual long term drift characteristic of the emf's of standard cells.

In this paper we present a detailed account of the experiments involved in establishing a working Josephson-effect voltage maintenance standard at NBS. Much of the apparatus and procedures are essentially identical with those described by FDL [1]. Section II contains a description of the Josephson devices and their performance. In Section III, we briefly describe the microwave and Josephson-device bias equipment. Section IV contains descriptions of the two dc voltage comparators including estimates of their respective accuracies. The experimental procedures used to compare a standard cell with the Josephson voltage are described in Section V. This section also contains $2e/h$ data for a local group of standard cells. In Section VI, the history of the NBS voltage maintenance and dissemination program based on standard cells is briefly reviewed. Section VII contains the NBS $2e/h$ results including a discussion of the overall experimental uncertainties. A comparison of recent (1971 to 1972) values of $2e/h$ is presented in Section VIII. Finally in Section IX, the procedures used for the NBS voltage maintenance standard based on $2e/h$ are outlined and its current precision noted.

2. Josephson Device Fabrication and Performance

All of the $2e/h$ measurements made at NBS have utilized resonant thin-film tunnel junctions. These junctions are more difficult to manufacture than point-contact junctions, and couple to the microwave power only over a limited frequency range; however, they can be used to achieve higher step voltages. The ability to use higher dc voltages is a significant advantage since it minimizes the effect of thermal emf's generated in the cryostat and the junction voltage measuring leads, and requires less sensitivity in the voltage null detector. Furthermore, thin-film junctions are permanent structures which require no mechanical adjustment before each experiment nor periodic cleaning and reconditioning.

The junctions we have used are of cross-type geometry with four junctions deposited on a single 2.54 cm square glass substrate, as shown in Fig. 1. The dimensions of the junctions are approximately 1 mm by 0.3 mm with the films approximately 150 nm (1500 Å) thick. This geometric structure has a resonance frequency at about 9 GHz. The junctions used

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for the $2e/h$ measurements have been of Pb-Pb oxide-Pb construction. Some Sn-Sn oxide-Sn junctions have been made but usable steps at the voltage required by our measuring instruments are not easily attained.

The junctions are fabricated with a thermal evaporation system. The first layer of Pb is evaporated on each glass substrate and then oxidized in 1/2 atm of oxygen at a temperature of about 40 °C. (The substrates are heated by radiation from infrared heat lamps external to the vacuum chamber.) The second layer of Pb is evaporated and the junction is overcoated with a layer of photoresist after removal from the evaporator. The junctions are then stored in liquid nitrogen dewars at 77 K.

Shortly after fabrication the dc I-V characteristic and normal-state resistance of the junctions are measured. Junctions with nearly identical I-V characteristics, however, can differ greatly in frequency response, coupling properties, and the rate of decrease of the maximum step height (current amplitude) with increasing dc voltage. Measurements of the dc junction characteristics are useful in detecting gross defects such as shorts bridging the oxide barrier which can markedly reduce the coupling to external microwave fields.

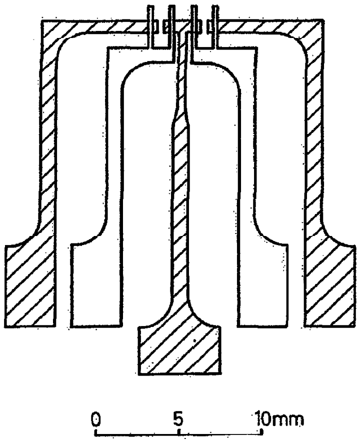
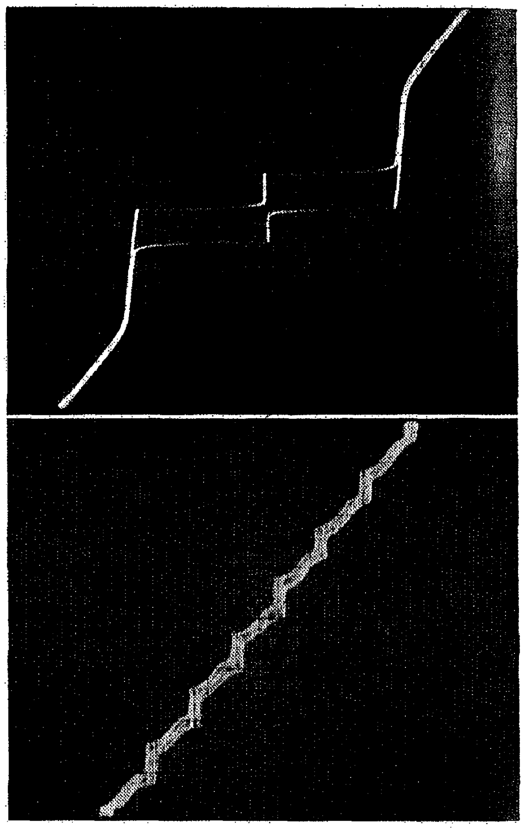


Fig. 1. Josephson-device geometry. The cross-hatched region indicates the oxidized film which is partially covered by the second film to produce four junctions

The normal resistance of the junction is, in theory, inversely proportional to the zero voltage current which in turn is related to the current amplitude of a given step. Therefore the use of low resistance junctions should provide higher step amplitudes. Unfortunately, in going to lower resistance junctions (below 1/3 ohm) the maximum zero voltage current, we observe, increases monotonically, but becomes a significantly smaller fraction of the theoretical limit. Typical junctions with resistances of 0.1 and 0.05 ohm have maximum dc currents of 9 and 12 mA compared to the respective theoretical limits of approximately 20 and 40 mA. Some of this reduction may be attributed to the asymmetric self-field generated by the dc bias current flowing through the junction. In selecting junctions for voltage measurement, one must compromise on the choice of junction resistance; it should be small enough to yield a reasonable zero voltage current and consequently large step amplitudes, and yet be large enough to provide sufficient coupling for operation at reasonable step voltages and applied microwave powers. We have found that the use of junction resistances near 0.1 ohm is a good choice.

When a tunnel junction is irradiated with microwaves, at frequency ν, the I-V characteristic shown in Fig. 2 (a), is modified so that steps appear at discrete voltage intervals given by the relation $2eV_n = nh\nu$. The height of these steps decreases with increasing junction voltage (V_n). As the step amplitude get smaller it becomes progressively more difficult to remain biased on a step, due to drifts in the dc bias current and microwave power level. For our present apparatus steps smaller than 50 µA are considered unusuable. Our junctions respond to microwave power only near their resonance frequencies. Continuous adjustability of the junction voltages is made possible by the high step numbers used, despite the limited frequency range. The details of the coupling between external microwave fields and our resonant tunnel junctions are not yet clearly understood. Qualitatively better coupling is observed for higher resistance junctions.



jg. 2. Typical I-V characteristic of a Pb-Pb oxide-Pb tunnel unction. a) With no applied microwaves. Vertical scale: 10 mA/div.; horizontal scale: 1 mV/div. b) With applied microwaves; constant voltage steps induced at 5 mV. Vertical scale: 200 µA/div.; horizontal scale: ≈ 20 µV/div.

In order to get usable step amplitudes at 10 mV we have chosen to operate two junctions in series. For reasonable operating conditions we can tolerate a few tenths of a percent mismatch in the two resonance frequencies. However, a half percent mismatch often means that the junction combination is marginal. When using junctions connected in series in the same microwave field, we have found it advantageous to cascade junctions of nearly equal resistance.

If the induced microwave steps have a finite slope (i.e. $\mathrm{d}I/\mathrm{d}V \neq \infty$), the Josephson voltage is no longer well defined. The slope of the steps is known to be sensitive to external electromagnetic noise [15, 16] and extensive precautions have been taken (shielded room and equipment) to reduce this noise. The slope is regularly checked by slowly varying the bias current up and down the step and looking for a voltage deflection on the null detector used with the measuring instrument. We have never observed any finite step slope to within the resolution of our null detector (a few parts in 10^8).

3. Microwave and dc Bias Apparatus

In order to obtain an induced step at a desired voltage, sufficient microwave power at a well-defined frequency must be coupled into the junction and a stable dc bias current passed through it.

a) Mircowave Equipment

The microwave apparatus, as indicated in the block diagram in Fig. 3, includes a klystron tube mounted in an oil bath (with air cooling) for microwave stability. The klystron is phase-locked to a continuously-adjustable quartz-crystal oscillator for frequency stability. The short term frequency stability (15 min) is about 1 part in 10^9. The frequency is measured by a frequency counter with an internal converter and a resolution of 1 part in 10^9. The isolator, shown in the diagram adjoining the main attenuator, prevents unwanted reflection of microwave power into the klystron. The microwave generation equipment and the cryostat containing the junction holder are grounded separately, and a dc block is placed in the waveguide to prevent circulating currents.

The accuracy of the counter time base is regularly checked against the U.S. frequency standard. A 100 kHz high stability oscillator is compared to the signal from WWVB using a VLF phase comparator. This oscillator, which is maintained within a few parts in 10^{10} of WWVB, is simultaneously used to check the counter time base. The drift in the counter time base is predictable and changes 2 parts in 10^{10}/day.

b) Junction Holder Description

The glass substrate on which the junctions are evaporated is mounted in the center of a piece of copper X-band waveguide. A slot is milled halfway through the waveguide and the substrate rests in this slot. A close fitting cover holds the substrate in place and provides continuous guide walls. The leads to the junctions are copper magnet wire soldered to the junctions using indium solder. The bias lead wires pass through small grooves in the substrate cover to Teflon standoffs outside the waveguide where they are soldered to leads from a vacuum tight electrical connector mounted in the top of the holder. The voltage leads are from a single spool of copper magnet wire and are kept in close thermal contact by running them to the voltage measuring instrument in a single piece of Teflon tubing. In the cryostat they are enclosed in a length of copper tubing that always crosses the helium level. From the copper tubing to the top of the cryostat the leads are enclosed in a thin-wall stainless steel tube. This arrangement minimized heat transfer and tends to keep the large temperature gradient at one location on the leads.

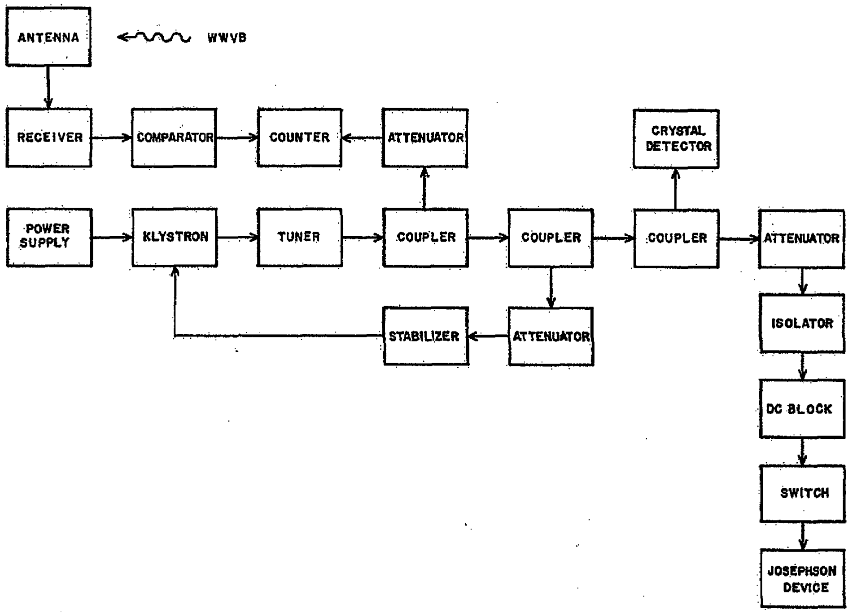


Fig. 3. Block diagram of microwave generation and frequency measuring equipment

In order to maximize the microwave electric field at the junction a shorting plug is placed in the waveguide about 4 cm below the substrate. Since placement of this short is extremely critical, it can be adjusted from the top of the cryostat while observing the step pattern on an oscilloscope. An iris placed above the substrate to form a cavity as described by FDL [1] was not used for our measurements.

c) *Bias Circuit*

The two junctions used for the $2e/h$ measurements are operated with independent bias current sources, similar to the ones described by FDL [1]. The individual supplies consist of two 14 ampere-hour mercury cells connected in parallel, and adjustable resistors connected in series with the junction to adjust the current. The current is reversible and has separate fine adjustment controls for the forward and reverse current so that small adjustments can be made in the bias current while in one direction without disturbing the settings for the other polarity. An I-V display on an X-Y oscilloscope with differential inputs is provided for each junction by monitoring the voltage across a resistor in the bias circuit and the voltage developed across each individual junction. Adjustable positional offsets in the display circuit are used to suppress the origin of the I-V curve to allow expansion of any portion of the curve for viewing. The offset for the junction voltage is calibrated so the proper step number can easily be determined.

The bias circuit normally supplies dc for use when measuring the junction voltage; however, for viewing the I-V characteristic an ac sweep is extremely useful. Two types of sweep circuits were constructed for use with our bias supply. A separate specially shielded transformer (connected to the 60 Hz power line) can be connected in place of the batteries to provide an adjustable ac sweep which is useful for observing the I-V characteristic with no microwaves applied and determining the critical current. The transformer is disconnected from the bias supply whenever measurements are to be made and a second incremental sweep circuit is used. The second circuit is battery operated and built into the bias supply. This sweep is superimposed on a dc level and is used to observe a small portion of the characteristic. The sweep consists of an oscillator with an active filter to remove all but the fundamental sine wave. During voltage balance both ac sweep circuits and the oscilloscope are completely disconnected from the dc circuitry so that the supply is isolated from grounded equipment with an insulation resistance greater than 10^{11} ohms.

4. Voltage Comparators

Two voltage comparators are presently in use at NBS. Both of these instruments provide a fixed 100 to 1 ratio and rely on the fact that the junction voltage is adjustable to exactly 1/100 of the standard cell voltage. These comparators were built and first used at the University of Pennsylvania and are described in greater detail in reference [1].

The use of a fixed 100/1 ratio comparator reduces the measurement uncertainty by eliminating the need for an adjustable resistance network since the junction voltage can be varied to achieve a null balance. Both instruments can be self-calibrated in less than an hour using no external resistance standards. Th use of two instruments operating on different principles with different major sources of systemati error is desirable since it allows us to perform a fina check on unsuspected sources of systematic error. The two instruments were periodically compared and were always found to agree within 3 ± 3 parts in 10^8, well within the estimated total instrument uncertainty of 4 parts in 10^8.

a) *Series-Parallel Comparator*

The design of the first voltage comparator (the one used for the $2e/h$ runs) is based on a method of double series-parallel exchange. If a group of n nominally equal resistors are connected first in series and then in parallel, the ratio of the resistances of the two combinations is n^2 with an error which is second order in the resistor mismatch. Figure 4 is a simplified circuit diagram of the comparator (SPC) showing the two sets of ten matched resistors, one set in series and one in parallel. If the two sets of resistors are exchanged (i.e., the set originally in series is reconnected in parallel, and the other set reconnected in series) and a second set of balances made, the effect of inequality of the total resistance of the two sets of resistors is reduced to second order by averaging the results of the two balances.

Tetrahedral junctions and compensating resistors (fans) for paralleling the network permit the use of commercial grade rotary switches despite their high contact resistance, while maintaining a high accuracy series-parallel transfer. A power supply using mercury batteries and regulated by a mercury battery under essentially no load, supplies stabilized current (1/2 ppm/h) to the resistance networks. The effects of thermoelectric voltages in the circuit are eliminated by reversing the current in the instrument, the standard cell, and the junction bias current. Although the 100/1 ratio can be determined to greater accuracy than that with which the individual resistors can be compared, the power dissipated in the networks changes by a factor of 100 when they are switched from series to parallel. To reduce the error resulting from self-heating the resistors are mounted in a thick walled aluminum can filled with oil. The entire instrument is enclosed in a temperature regulated air enclosure.

The instrument sources of uncertainty in a $2e/h$ measurement for the past year are essentially the same as reported by FDL [1] as the instrument was modified only slightly for use at NBS [12]. These estimated uncertainties are listed in Table 1 and are described briefly below.

a) and b) Checks on the matching of the main and fan resistors were carried out regularly. The uncertainties were estimated from the check data. In the case of the main resistor matching, the second-order corrections to the resistance ratio were calculated. The correction (as a result of periodic trimming of the resistors) was always negligible (<1 part in 10^9). The deviations for the fan resistors were also measured and found negligible. The uncertainties attributed to these two errors are 0.4 and 1 parts in 10^8 respectively.

c) The transfer resistance error due to tetrahedral junction asymmetries introduced a measured uncertainty of 4 parts in 10^9.

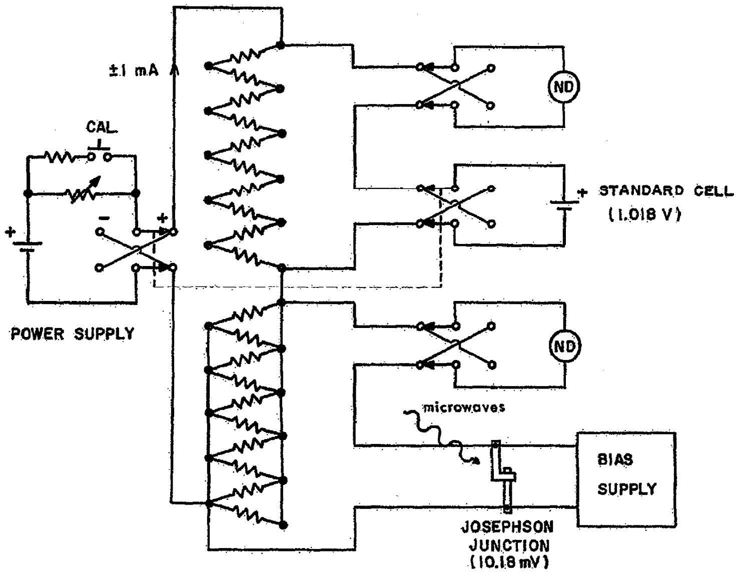


Fig. 4. Simplified circuit diagram of series-parallel voltage comparator

Table 1. Sources of uncertainty in $2e/h$ associated with the series-parallel instrument

	Uncertainty parts in 10^8 (one standard deviation estimates)
a) Main resistor mismatch	0.4
b) Fan resistor mismatch	1
c) Resistance of tetrahedral junctions	0.4
d) Main resistor heating effects	2
e) Comparator temperature stability	0.3
f) Working current stability	0.2
g) Calibrating signal accuracy	1
h) Leakage resistances	1
i) Dielectric polarization	0.2
j) Effects of thermal emf's	0.5
RSS total	2.8

d) The self-heating effects for the main resistors were measured *in situ* using the bridge within a bridge technique [17]. Using this procedure a correction of 3 parts in 10^8 was applied to the data with an uncertainty estimated to be 2 parts in 10^8.[1]

e) Since the series-parallel resistance ratio is not established simultaneously, any change in resistance between the measurements will cause a first order correction. The largest cause of this change is the change in internal temperature of the instrument. The temperature regulated oven changes slightly as ambient temperature changes and thus introduces an uncertainty of 3 parts in 10^9.

f) For the $2e/h$ measurements made before December 1971, a standard cell balance was made after the junction balance and a correction applied for the drift of the power supply. Since December we have begun regularly making standard cell balances both immediately before and after the junction balance and linearily interpolating the results to the time of the junction balance. The uncertainty contributed by non-linear drift in the power supply is estimated to be 2 parts in 10^9.

g) The balancing procedure requires that a calibrating signal be introduced to normalize the null-detector deflections. The uncertainty in calculating this signal is mainly due to resistor aging and results in a measurement uncertainty of 1 part in 10^8.

h) The effects of leakage resistance are estimated by measuring the individual leakage paths directly. The estimated uncertainty from this source is 1 part in 10^8.

i) Small leakage currents are induced in insulators due to a component of the insulator dielectric polarization, and polarization currents are induced due to piezoelectricity caused by mechanical stress on the insulators. The polarization currents were measured using an electrometer and contribute an uncertainty of 2 parts in 10^9.

j) The uncertainty due to the effects of thermal emf's is caused by variations of the thermal emf's in the instrument and non-linear changes in the thermal emf's in the leads from the junction to the instrument. Five parts in 10^9 is estimated for this uncertainty.

The root-sum-square total uncertainty is 2.8 parts in 10^8 and represents the total uncertainty associated with the series-parallel system exclusive of the random uncertainty of a $2e/h$ measurement.

b) *Cascaded-Interchange Comparator*

The second instrument develops a fixed 100 to 1 ratio by use of a voltbox optimized for self-calibration. A simplified circuit diagram of the cascaded-interchange comparator (CIC) is shown in Fig. 5. The calibration of the voltbox is accomplished by using a second identical voltbox as shown in the figure. With

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[1] The instrument is to be modified by replacing the main resistors with better matched, lower temperature coefficient resistors to significantly reduce the error due to self-heating. In addition the fan resistors have been replaced and the temperature control improved.

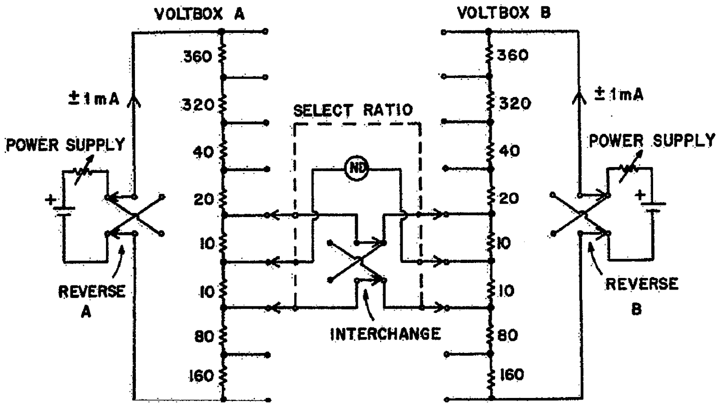

Fig. 5. Simplified circuit diagram of cascaded-interchange voltage comparator shown in the calibrate mode. The voltage developed across any one of the four 10 ohm resistors is 1/100 of the total voltage across the voltbox

Table 2. Sources of uncertainty in $2e/h$ associated with the cascaded-interchange comparator

	Uncertainty parts in 10^8 (one standard deviation estimates)
a) Random uncertainty of calibration measurement	2
b) Switch and power supply variations during calibration	2
c) Trimmer lead resistance error	0.7
d) Comparator temperature stability	0.3
e) Working current stability	1
f) Calibrating signal accuracy	0.5
g) Leakage resistances	0.4
h) Dielectric polarization	0.2
i) Effects of thermal emf's	0.5
RSS total	3.2

the switches set as shown, a 10 ohm equal-arm Wheatstone bridge is formed and the resistors are trimmed until a balance condition is achieved for both positions of the interchange switch. The next position of the "select-ratio" switch then forms a 20 ohm equal arm bridge using the two 20 ohm resistors and the four previously equalized 10 ohm resistors. Calibration is continued in this manner until both boxes are adjusted to a 100 to 1 ratio. By independently powering the voltboxes, the usual need for lead compensation is eliminated. The advantage of this method is that the resistors always operate at the same power so that the self-heating is negligible. However, the calibration procedure must be performed carefully as errors in these measurements contribute first order errors to the $2e/h$ measurement. Table 2 summarizes the sources of uncertainty in $2e/h$ associated with the CIC. Since this instrument was not modified the uncertainties are essentially the same as reported and discussed by FDL [1]. Because the SPC and CIC are of similar construction some of the sources of uncertainty for the CIC are the same as those for the SPC.

c) Null Detector Systems

Two independent null detector systems are used. Both systems consist of photocell galvanometer amplifiers modified to drive a stripchart recorder. The galvanometer amplifiers were: (a) modified to reduce thermal emf variations, (b) shielded electrostatically, and (c) placed on a anti-vibration platform. The amplifier used for the standard cell balance is operated in the series feedback mode and modified for high input impedance to reduce the off-null currents. The amplifier used for the junction balances is operated in the parallel feedback mode to reduce the Johnson noise. In the future we plan to use a superconducting galvanometer (SQUID) to make the junction balances.

d) Standard Cell Comparison System

To compare the standard cells in the $2e/h$ laboratory with other cells, the cells are connected in series opposition (negative leads connected together) and the small voltage difference measured with a commercial potentiometer. The null detector used with the potentiometer consists of a series feedback photocell galvanometer amplifier driving a secondary galvanometer.

The potentiometer system is regularly calibrated and a correction applied to the data. The systematic uncertainty of the correction is estimated to be less than 10 ppm of the voltage difference being measured. When an unsaturated cell is compared to a saturated cell, the difference is about 1000 μV and the systematic uncertainty in comparing the emf's of two cells is less than 0.01 ppm. The potentiometer is used with a resolution of 0.01 μV and the standard deviation of a single observation is about 0.01 μV, however, the use of a redundant statistical design reduces the random uncertainty by at least a factor of two.

5. Experimental Procedure

Prior to a $2e/h$ measurement, junction devices are tested and a suitable one is mounted in the waveguide holder. The device is replaced only if the junctions become defective, otherwise they are left in the cryostat between runs and are kept cold at liquid nitrogen temperatures. On the day of the run the photocell amplifiers are connected to 12 V batteries and allowed to stabilize. Standard cell comparisons are made using the commercial potentiometer, a photocell amplifier, and secondary galvanometer. The comarisons of cells are done using a redundant design of he type used in the NBS Volt Transfer Program [18]. iquid helium is transferred and it is pumped below K. The electrontic equipment is turned on, micro-vaves and bias current adjusted, and the system is eft to stabilize for approximately 1.5 h. Afterwards he bias current and frequency are adjusted to pre-iously selected optimum values and the thermal emf n the measuring leads is checked.

The $2e/h$ working group of cells contains three un-aturated standard cells mounted in a temperature egulated enclosure. On any day's run one of these ells is used throughout the entire run. The 1 V output f the voltage comparator is balanced against the cell nd the difference recorded on the strip-chart recorder. he low voltage output of the comparator is balanced gainst the junction and recorded. During all balances he input to the null detector is reversed. The micro-vave frequency is measured immediately before and fter the voltage balance. The counter is set so that it oes not sample during a junction balance as this ffects our measurements by disturbing the junctions. nother balance of the cell is then made against the omparator. These balances are interpolated to the ime of the junction balance to eliminate the effects of the linear drift of the current in the comparator. The polarity of the bias current, the standard cell, and the comparator current is reversed and the procedure is repeated. The series-parallel networks are interchanged and the procedure is repeated for each polarity. The pattern of polarity reversals (+, −, −, +) tends to cancel out the effects of first order drift of the thermal emf's in the measuring leads if the balances are evenly spaced in time. The four junction balances (and associated cell balances) combine to give one independent measurement of the standard cell emf in terms of $2e/h$ (or of $2e/h$ in terms of the standard cell voltage). Typically four or five independent measurements are made during one day's run. During the run small adjustments to the microwave power, microwave frequency, and bias current are made as necessary. At the conclusion of the run additional standard cell comparisons are made between the $2e/h$ working group and the check standards.

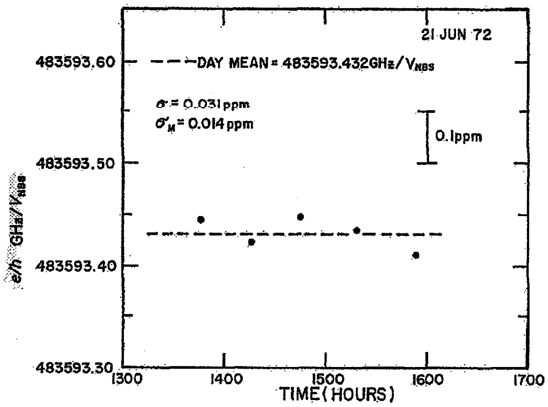

Fig. 6. $2e/h$ results of a typical day's run. Each point consists of four balances against the device voltage to compensate for thermal emf's and series-parallel resistor string inequalities

The result of a day's run consists of a recording of comparator balances and frequencies. Each balance is adjusted close to null and straight lines can then be fit by eye to the recording traces. A calibration signal is produced by causing a known change ($\simeq$ 1 ppm) in the current in the instrument to determine the normalized deviation. The normalized deviation represents the fractional difference between the 100:1 comparator ratio and the actual standard cell-junction ratio. One set of four comparator balances (including polarity and series-parallel reversals) combines to give

$$(2e/h)\cdot(V_S)=\beta n\nu$$

where V_S is the standard cell voltage, β is the measured voltage ratio V_S/V_J, V_J being the junction voltage, n is the step number, and ν is the microwave frequency. Using this equation, the product $(2e/h\cdot(V_S)$ can be calculated from the $2e/h$ run. If either $2e/h$ or V_S is assumed known then the other can be calculated. A plot of the results of a typical day's run is shown in Fig. 6.

In February 1972 six saturated cells in a temperature regulated enclosure (check standard 1) were placed in the $2e/h$ lab as a local voltage standard to estimate the precision with which a standard can be maintained via $2e/h$ measurements. This enclosure, which was designed by Cutkosky [19], maintains a stable temperature with short-term fluctuations of approximately 20 microdegrees Celsius. The mean emf of the six cells in the enclosure is shown in Fig. 7. (Here a constant value of $2e/h$ has been assumed.) The cell emf's are changing due to the large temperature shock encountered when installed in the box and normal cell aging, however, the emf's are very predictable and the standard deviation of a linear least-squares fitted line to the data in Fig. 7 is less than 0.02 μV.

6. NBS Voltage Maintenance and Dissemination Prior to July 1972

For many decades the U.S. legal volt has been maintained by a large group of standard cells [20]. Over the years groups of cells made at NBS were assembled and called the National Reference Group (NRG). From 1955 to 1969 the NRG consisted of 44 saturated cadmium sulfate (Weston) cells. The mean emf of the 44 cells was assumed to remain constant in time. In 1963, monitoring of a second group of 18 saturated cells designated the Secondary Reference Group (SRG) constructed in 1958 was begun. After the move of NBS from Washington to Gaithersburg in 1966, both groups of cells were put in two stirred temperature-regulated oil baths at 28 °C. In these baths, both groups are exposed to the moving oil, and electrical connections to the cells are made by opening the bath lid and inserting copper stabbers into mercury amalgamated copper cups. The temperature of each oil bath is read with a calibrated platinum resistance thermometer and Mueller bridge. The bridge and thermometer are calibrated monthly, the latter at the triple point of water.

By December 1969 the emf's of several cells in the NRG showed large instabilities due to the formation of gas bubbles. In order to maintain the stability of the legal volt, a new mean for the NRG was calculated (neglecting the unstable cells) using well established procedure [20].

Measurements of the reference cells were made using the "pivot cell" technique whereby all cells are read against only one cell (the pivot or favorite cell). In May 1970 a different procedure for comparing the reference cells was started. This procedure provides equal precision in determining any cell emf with respect to the mean, as opposed to the pivot cell method which provides high precision in determining the pivot cell and low precision in determining the other cells with respect to the mean. At the same time, a more accurate instrument with better resolution (about 0.01 μV) was used for all comparisons. Both methods of intercomparison were carried out for several months until final conversion to the new method was completed in September 1970. The new method allowed greater flexibility in using any cells of the NRG or SRG for calibration purposes. In practice, the Volt Transfer Program calibrations prior to July 1972 were all made using a subset of 6 cells of the SRG. Since June 1970, *all* calibrations have been related to the NRG via the SRG subset.

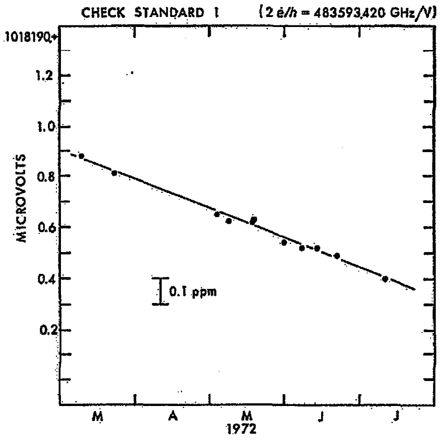

Fig. 7. The mean emf of six saturated cells assigned assuming an arbitrary value of 2*e*/*h*. The cells are mounted in a temperature regulated enclosure located in the 2*e*/*h* laboratory

Two major improvements were made to one of the oil baths: (a) installation of a new temperature regulating system, and (b) installation of a selector switch for the SRG cells so that the bath lid would not have to be disturbed. These two changes, made in March 1971 by Eicke, lowered the random uncertainty of a standard cell comparison involving these groups by a factor of four [21].

Over the past 60 years, various methods have been employed to place limits on the stability and reproducibility of the NBS volt. The two most meaningful methods used prior to 1970 for determining these limits were (a) the voltage comparisons of national units at the Bureau International des Poids et Mesures (BIPM) conducted every 3 years [22]; and (b) numerous measurements of the gyromagnetic ratio of the proton, γ_p, at NBS since 1958 [23]. Inasmuch as the national units consisted of groups of saturated cells, the international comparisons only gave information on the relative drift of the various groups of cells and not on the absolute stability. Until very recently, the precision of the γ_p experiments permitted checks of the stability of the NBS volt to about 2 ppm. A possible annual drift in the mean emf of the NBS reference cells as large as several tenths of a ppm could have gone undetected. Since 1970, sub-ppm determinations of 2*e*/*h* at the University of Pennsylvania and NBS have provided checks on the stability of the NBS volt.

7. Determinations of 2*e*/*h* at NBS (1971—1972)

All determinations of 2*e*/*h* at NBS have been obtained by relating the Josephson junction voltage to the mean emf of the National Reference Group of standard cells. As discussed in Section V, direct 2*e*/*h* measurements were made on one of the cells of our working group. The emf of the working cell was related to the mean emf of a second group of standard cells by direct standard cell comparisons before and after each 2*e*/*h* run. This second group of cells in turn was compared to the Secondary Reference Group (which was directly assigned in terms of the NRG). The second group of cells was necessary, since substantial scatter (~0.2 ppm) in the mean emf of the SRG prevented a precise check of possible changes in the working cell during a 2*e*/*h* run.

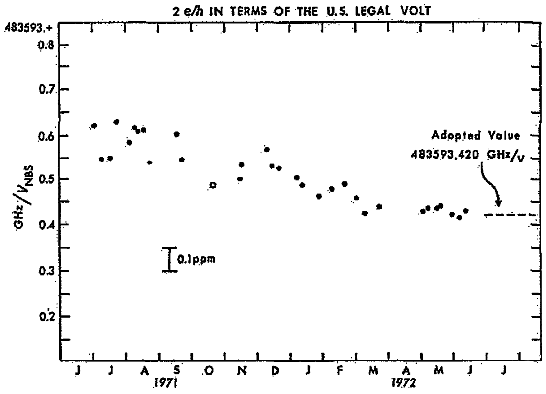

Fig. 8. Values of 2*e*/*h* measured at NBS referenced to V_{NBS}, the legal volt. Each point represents 1 day's run which usually consists of 3 to 5 independent determinations of 2*e*/*h*. The open circle indicates a run in which the standard cell used for the measurements changed an excessive amount (>0.1 μV) during the run. [Error bars indicating within-run standard deviation (~0.04 ppm) have been omitted for clarity.]

A series of 32 2*e*/*h* measurements were made at NBS between July, 1971 and July, 1972 to monitor the legal volt (i.e., the mean emf of the NRG) and to obtain sufficient data to permit a redefinition of the U.S. legal volt directly in terms of the ac Josephson effect. These 2*e*/*h* results are shown in Fig. 8. The within-run standard deviation of the mean of a typical point is about 0.025 ppm. A least-squares linear fit to the data implies an apparent drift of about −0.41 ± 0.03 ppm year in the legal volt during this period. Comparing the results of the last determination of $2e/h$ at the University of Pennsylvania (May, 1970) with the first reported value at NBS (July to August, 1971), we find an apparent drift of -0.22 ± 0.14 ppm/year in the legal volt for 1970 to 1971 assuming the legal volt alone has changed during this period. The relative agreement of these two numbers suggests that the U.S. legal volt has been decreasing for the period 1970 to 1972.

For the NBS measurements (see Fig. 8), various changes were made from time to time in the procedures used to relate the Josephson volt to the legal volt. These changes primarily involved the use of different standard cells. For runs 1 through 14, the $2e/h$ working cell was one of three saturated cells mounted in a commercial temperature-regulated enclosure at 30 °C. For subsequent runs, the working cell was one of three *unsaturated* cells mounted in the same enclosure. The unsaturated cells were used because changes in emf of the saturated cells, due ostensibly to temperature changes of the enclosure, were limiting the within-run precision of the $2e/h$ measurements. Standard cell comparisons made before and after the $2e/h$ runs indicated a typical change of about 0.04 μV for the saturated cells but a change of only 0.02 μV for the unsaturated cells.

Several different intermediate groups were used to relate the $2e/h$ working group to the Secondary Reference Group of cells. All intermediate groups, the SRG, and the NRG were located in a separate shielded room next to the shielded room in which the $2e/h$ measurements were carried out. For the early $2e/h$ runs (prior to September, 1971), an air enclosure containing four saturated cells was used as the intermediate group. This intermediate group was compared to the SRG weekly but not necessarily on the same days as $2e/h$ runs. Since September 1971, an NBS-built air enclosure containing six saturated cells (which we define as "check standard 2") has been used as the intermediate group. In Fig. 9, we have assumed an arbitrary value of $2e/h$ and plotted the effective mean emf of four of the cells using our $2e/h$ data. The standard deviation of a single point about the fitted line is 0.04 ppm. After January, 1972, comparisons of this intermediate group with the SRG were made on the same day (while the $2e/h$ run was in progress) rather than on arbitrary days.

In order to facilitate the comparisons of large numbers of standard cells, we installed several rotary selector switches which permitted rapid connection of different cells (from the various groups) to the potentiometer. These switches, which were operated in air, were electrostatically and thermally shielded. The thermal emf's present in these switches were on the order of a few nanovolts.

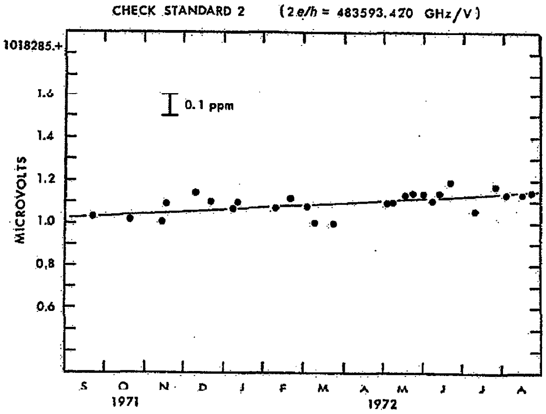

Fig. 9. The mean emf of four cells, assigned assuming an arbitrary value of $2e/h$. This enclosure is located in a separate shielded room containing the NBS reference group of cells

The sources of uncertainty in our $2e/h$ determinations can be divided into two categories: (a) the random and systematic uncertainties associated with the $2e/h$ measurements, and (b) the uncertainties in relating the voltage of the $2e/h$ working cell to the legal volt (i.e., the NRG). A summary of these sources of uncertainty and the corresponding one-standard-deviation estimates is listed in Table 3. The following comments apply. The random uncertainty arises from random variations in the thermoelectric voltages, day-to-day fluctuations in the local and reference (i.e. the intermediate, SRG, and NRG) groups of cells and any other randomly varying experimental parameters present in a $2e/h$ experiment. The standard deviation for a *single* run referenced to the legal volt (i.e. NRG) was of order 0.04 ppm. The estimated uncertainty in the measurement of the frequency of the applied radiation is 5 parts in 10^9 and thus essentially negligible. The systematic uncertainty in relating the local volt (the $2e/h$ working cell) to the legal volt has been ascribed to thermoelectric emf's in the measuring leads, temperature variations in the standard cell enclosures, and possible undetected changes in the working cell during $2e/h$ measurements.

Table 3. Summary of sources of uncertainty in $2e/h$ for April 1972

	Uncertainty parts in 10^8 (one standard deviation estimates)
1. Measurement uncertainties	
a) Random uncertainty of the predicted value	0.9
b) Frequency measurement and stability	0.5
c) Low-voltage comparison (series-parallel comparator)	2.8
2. Local volt uncertainty in V_{NBS69} (April 1972)	3
RSS total	4

A value of $2e/h$ based on the first nine runs shown in Fig. 8 has been reported [12]. The result was:

$$(2e/h)_I = 483593.598 \pm 0.024\ \mathrm{GHz}/V_{NBS}\ (0.05\ \mathrm{ppm})\,.$$

The random uncertainty of the mean of these nine measurements was 2.3 parts in 10^8. This determination was related to the results of other workers [2, 13, 14] via direct standard cell comparisons carried out between NBS and other national laboratories under the auspices of BIPM during the summer of 1971.

In the spring of 1972, a second series of similar volt comparisons was carried out. A value of $2e/h$ referenced to the legal volt for April, 1972 (approximately the central date of this latter series of comparisons) has been obtained by linearly fitting all the $2e/h$ data from January to July, 1972. The result is:

$$(2e/h)_{\text{II}} = 483593.444 \pm 0.019 \text{ GHz}/V_{\text{NBS}} \ (0.04 \text{ ppm}) .$$

The random uncertainty of 9 parts in 10^9 (as indicated in Table 3) was obtained by calculating the standard deviation of the interpolated result.

The Josephson voltage is directly proportional to the frequency of the applied radiation with the proportionality constant precisely equal to the physical constant $2e/h$. Since no other method of determining this physical constant with an accuracy comparable to that of the ac Josephson effect exists, we can use it only to establish a very stable and precise voltage standard but not to establish an absolute one. In order to implement such a standard at NBS, we have decided to adopt a value of $2e/h$ consistent with the assumed value of the mean emf of the National Reference Group on July 1, 1972. This value of $2e/h$ was obtained by fitting the $2e/h$ data shown in Fig. 8 from January to July, 1972. The (extrapolated) result is:

$$(2e/h)_{\text{III}} = 483593.420 \pm 0.019 \text{ GHz}/V_{\text{NBS}} \ (0.04 \text{ ppm}) .$$

The uncertainties in this result are essentially indentical to those of the April value.

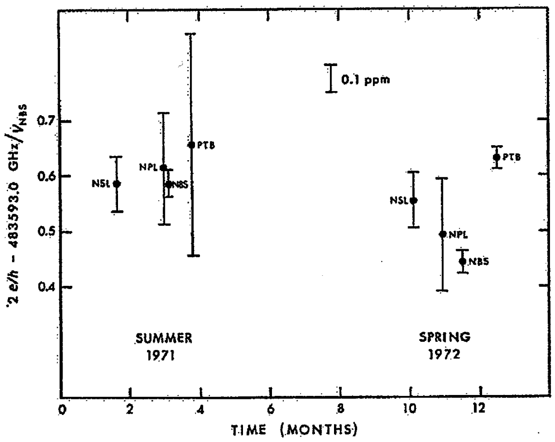

Fig. 10. Values of $2e/h$ as determined by workers at various national laboratories. All values have been expressed in the NBS unit of voltage (V_{NBS}) using the results of direct standard cell comparisons between each laboratory and NBS. (See Ref. [24].)

8. Comparison of Recent Values of $2e/h$ (1971—1972)

Workers at various national laboratories have conducted and reported experimental determinations of $2e/h$ referenced to their particular national unit of voltage. Each of these units has been defined as the mean emf of a different group of standard cells and therefore the relationships between the national units must be determined by comparison experiments. Traditionally these comparison experiments are conducted triennially at BIPM (Sèvres, France). In order to better determine the relationships of the units in laboratories carrying out high precision $2e/h$ experiments, two series of direct volt transfers between NBS and each of these laboratories were completed about 8 months apart. An individual transfer experiment involved the following: (a) calibration of an air enclosure in terms of the NBS reference cells and shipment of the temperature-controlled enclosure to the second laboratory, (b) calibration of the enclosure at the second laboratory and shipment back to NBS, and (c) calibration at NBS. Each transfer experiment lasted about 6 weeks. These transfer experiments provide a good basis for comparing the values of $2e/h$ obtained at the various national laboratories.

In Fig. 10, we have plotted values of $2e/h$ obtained by the various workers applicable to the time[2] of the transfers [2, 13, 14]. The results presented have been normalized to the NBS volt (V_{NBS}) using the data from the direct volt comparisons. Each error bar indicated the one standard deviation uncertainty assigned by the respective workers in determining $2e/h$ relative to their particular national unit of emf. No additional allowance for the uncertainty of the volt transfers has been added to the workers' estimated

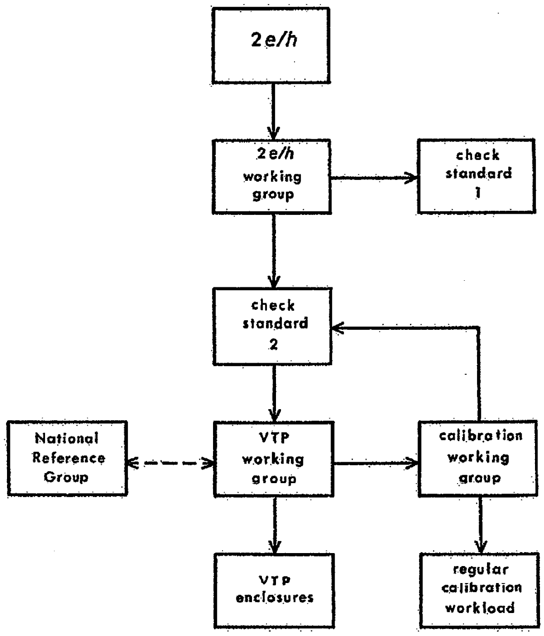

Fig. 11. A block diagram outlining the principle steps in the present (1972) NBS voltage maintenance and dissemination program using $2e/h$ via the ac Josephson effect

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[2] The PTB result shown for the summer of 1971 is based on a $2e/h$ determination made about $^1/_2$ year earlier and is the only reported value available for comparison with the 1971 direct standard cell transfer experiment.

uncertainties. The uncertainty in each of these volt transfer experiments has been estimated to be about 0.2 ppm [24]. The results are in fair to good agreement when the additional uncertainty associated with each volt transfer is included. Critical comparisons of present (1972) determinations are limited by the transfer of standard cell enclosures. The development of an improved portable voltage standard (for example, a portable Josephson standard) should permit meaningful comparisons of $2e/h$ experiments at different laboratories with transfer uncertainties comparable to local $2e/h$ uncertainties of a few parts in 10^8.

9. NBS Volt Maintenance Via the Josephson Effect

In July, 1972, NBS began maintaining and disseminating a unit of emf based on the ac Josephson effect. To define this new unit it was necessary to choose a value of $2e/h$. This new unit was defined to be equal to the apparent mean emf (on July 1, 1972) of the National Reference Group of standard cells. The value of $2e/h$ chosen for this purpose is the NBS $2e/h$ result for July, 1972 previously discussed in section VIII, namely

$$2e/h = 483593.420\ \mathrm{GHz}/V_{\mathrm{NBS}}\,.$$

Thus, the NBS as-maintained unit of voltage is now directly related by this constant (which is assumed to be exact) to the unit of frequency.

The procedures used to maintain and disseminate the new unit are essentially the same as those used in the $2e/h$ measurements already described in this paper. A diagram indicating the principle steps in the NBS $2e/h$ voltage dissemination program is shown in Fig. 11. Periodically, the Josephson apparatus is used to "calibrate" the emf of one of the standard cells in the $2e/h$ working group. This cell is compared with two other groups of cells (check standards 1 and 2 in Fig. 11) immediately before and after the $2e/h$ measurements. If the observed within-run standard deviation of the $2e/h$ measurement is less than twice the expected value 2σ (presently $\sigma \cong 0.04$ ppm), the assigned emf of the $2e/h$ working cell is used to obtain the emf's of the cells in the two check standards.

The mean emf of each check standard is plotted versus time (as shown in Fig. 7 and 9). The $2e/h$ measurements are made at regular intervals (about every 2 weeks for the data presented here) and mean emf's of check standard 2 and a second (VTP) working group of cells are obtained for use in calibrating the various transport standards and other groups of cells by averaging the respective results of the five most recent $2e/h$ runs. For calibration purposes, values for these mean emf's are calculated for up to several weeks ahead by applying small corrections for the long term (3 to 6 months) drift of the check standard and working group means[3].

10. Conclusions

The *precision* with which the mean emf of a single group of standard cells can be maintained using the present Jospehson apparatus is about 2 parts in 10^8 and is a measure of how reproducibly we can calibrate a group of standard cells over an extended period of time. The accuracy with which the emf's of a group of cells can be determined in terms of a unit based on an adopted value of $2e/h$ is about 4 parts in 10^8 and includes allowances for systematic effects in the present measurement system. This is an estimate of how well the present system would agree with another totally independent $2e/h$ system.

The agreement between the NBS $2e/h$ system and systems in operation at other national laboratories has been tested indirectly via the shipment of standard cells. The results are inconclusive in determining the relative agreement of the various $2e/h$ measuring systems at their current level of precision (<0.1 ppm). Differences as large as 0.4 ppm between $2e/h$ results and the corresponding cell transfers have been observed. These differences have been attributed primarily to uncertainties in the standard cell transfers.

One way to compare $2e/h$ systems at precisions approaching a few parts in 10^8 is to use a portable $2e/h$ system rather than standard cells. Our present system (particularly the dc instrumentation) is portable and can be used in such a comparison experiment. The application of cryogenic techniques to dc instrumentation (e.g. superconducting galvanometers and cryogenic dividers) and the development of an improved (long lived and durable) Josephson junction should permit the development of a compact cryogenic $2e/h$ system. Finally, with the use of cryogenic instrumentation, it appears that the accuracy of the $2e/h$ voltage ratio measurements can be improved at least an order of magnitude.

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[3] Generally, an average of five $2e/h$ runs is used; however, this number may change depending on the time intervals between $2e/h$ runs. The data from a given $2e/h$ run are only used for calibration if the corresponding value for each check standard mean is within 0.1 ppm of the expected value for the mean, and analysis of the individual cell emf's of the check standards shows no anomalous behavior. The small drift corrections (which may be negligible) are applied to the check standard and working group averages (for calibration purposes only) on a weekly basis.

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