a 30-element SPIR, a Josephson junction showing steps to only 1 mV would be adequate for calibrating standard cells. This could be a very simple point contact type, either fixed or adjustable in liquid helium, and would require only about 1 mW of microwave power rather than the 75–500 mW presently needed for 10-mV junctions. The 1 mW is easily available from a compact solid state source, even at 36 GHz.

The ultimate system at 3 K might produce 1 V with a source impedance of 10 Ω, offering a precision of 4 parts in 10^{11}, 100 times better than a standard cell. However, a portable system for calibrating standard cells with the best possible accuracy could be made in a simpler way by extending the techniques described in this paper.

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Maintaining the Unit of Voltage at PTB via the Josephson Effect

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***Abstract*—In Section I a report on high precision voltage comparisons between the mean EMF of the former PTB voltage standard (consisting of a group of 39 saturated Weston cells) and the Josephson reference voltage is presented. The experiments were carried out with a total uncertainty (1 σ) of 4 parts in 10^8. The measured rate of change of the mean EMF during a $1\frac{3}{4}$-year period was -1.3×10^{-7} V per year. This voltage stability is sufficient to maintain the unit of voltage by this group of standard cells for several months until a new comparison with the Josephson reference voltage becomes necessary. Due to the effects of thermal EMF's in the millivolt circuit of the measuring system used at present, the Josephson reference voltage ($\approx$3 mV) is only stable during a short time.**

In Section II a prototype cryogenic voltage standard developed at PTB is described. By immersing the main measurement components into the superfluid liquid helium bath, a long term voltage stability can be achieved. These components include the cryogenic resistive divider, consisting of a new copper alloy, and the SQUID null detector. The resistance ratio of the cryogenic resistive divider of 320:1 is determined by a ten-decade inductive voltage comparator operating at $8\frac{1}{3}$ Hz. The effects of power dissipation introduce only errors of second order because the currents in the calibration mode and the measurement mode are the same.

INTRODUCTION

FOR MORE THAN 60 years the unit of voltage has been maintained at the Physikalisch-Technische Bundesanstalt (PTB) and in all other standard laboratories throughout the world via groups of saturated Weston cells kept at constant temperature. In order to obtain worldwide consistency, the Bureau International des Poids et Mesures (BIPM), Sèvres, France, carries out international comparisons of standard cells in periodic intervals of about three years. Cells are kept at a nominal temperature of 20°C and recently have also been held at 30°C in thermo-regulated enclosures in air.

In recent years the ac Josephson effect, a physical phenomenon between two weakly coupled superconductors, has become a new basis for maintaining the unit of voltage in various standard laboratories [1]–[6]. The dc voltage produced by this effect is of high stability and depends only on a microwave frequency and on fundamental constants $2e/h$, where e is the electron charge and h is Planck's constant. Unfortunately, this ratio is not known with the desirable accuracy in SI units. For metrological purposes, the Comitè Consultatif d'Electricitè in 1972 recommended a frequency value of 483 594.0 GHz for the realization of the unit of voltage.

PRESENT SYSTEM OF MAINTAINING THE VOLT

The experimental setup which we have used until the present time has been described in [1], [2]. In the first part of this paper we give results of the long term stability of the former PTB voltage standard consisting of 39 saturated Weston cells. Because voltage comparisons with

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the Josephson reference voltage are very time consuming it is necessary to have, in addition, a working voltage standard for maintaining the volt between periodic Josephson measurements.

A block diagram of this measurement system is shown in Fig. 1. The 39 standard cells are held at 20°C and are located in a large air enclosure, surrounded by two additional thermal insulation shells (see I in Fig. 1). Unfortunately, this air bath is not as well shielded against stray electrical fields as the much smaller thermo-regulated enclosures held at 30°C (see II in Fig. 1), so that two comparisons become necessary. To avoid disturbing the Josephson reference voltage, the EMF of some cells in enclosure II are first calibrated by the Josephson dc voltage. Subsequently, the EMF's of these cells will be compared with the mean EMF of the 39 cells in enclosure I. The enclosures I and II are located at a distance of 10 m from the Josephson measurement system. Due to the different temperatures in the enclosures, a voltage difference of about 500 μV exists between the EMF's of the cells in the enclosures I and II. This has to be compensated by means of a potentiometric circuit (see Fig. 1). Because the temperature coefficient of the cell EMF at 20°C is -4×10^{-5}/K, the uncertainty of the temperature measurement in enclosure I has to be less than 0.25 mK in order to achieve a voltage uncertainty of 1 part in 10^8. These high precision measurements require that the exact temperature be known over a time of about two years. In order to guarantee this, the temperature was continuously recorded using a platinum resistance thermometer which was recalibrated at the triple point of water every six months. No temperature measurement is necessary for enclosure II because only a short term stability is required during the measuring time (a few hours).

The comparisons of the Josephson reference voltage with the mean EMF of the 39 standard cells of enclosure I (via the cells of enclosure II) have been carried out since 1972. Before discussing the final results we present detailed information and data concerning calibration of the resistive divider.

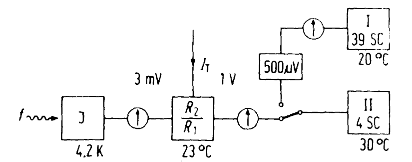

Fig. 1. Block diagram of circuit used for comparing the dc Josephson voltage (J) with the EMF of standard cells (SC). f is the microwave frequency; I_T is the dc current through the resistive divider of ratio R_2:R_1.

Calibration of the Resistive Divider

The dc voltage across the point contact junctions was approximately 3 mV. This voltage is balanced by means of a resistive divider of fixed nominal ratio $R_2/R_1 = 350\ \Omega/1\ \Omega$ against the EMF of a standard cell ($\approx$1 V). The 1-Ω resistor is composed of ten 10-Ω coils in parallel including a compensation network (Hamon device), while the 350-Ω resistor consists of 35 coils of the same type in series. The values of all single resistors are matched within $\pm 10^{-6}$, the relative temperature coefficient of the ratio at the 23°C bath temperature was found to be 2×10^{-7}/K, and self-heating effects in the oil bath are smaller than 5×10^{-9} at divider currents of up to 10 mA (nominal value 3 mA). The possible error in the determination of the resistance ratio consists of two main parts: the error in establishing a 1-Ω to 100-Ω ratio by parallel-series interchange in the Hamon network, and the error originating from comparisons of 100-Ω resistors and also of 50-Ω resistors. The maximum theoretical relative error of the 1:100 ratio is estimated to be 8 parts in 10^9 (this also takes into account effects of current distribution in the shorting bars).

Two independent measurements were carried out to determine the maximum error of the 1:100 ratio experimentally. One was the Riley method [7] where the voltage differences between the coil terminals and the bridge unbalances in the network yields an upper limit of the transfer accuracy smaller than 1 part in 10^8. This result was confirmed by a second independent measuring procedure using the accurate self-calibrated 1:10 ratio of a Kusters comparator potentiometer [8]. By comparing the 1-Ω resistor (Hamon parallel mode) with an intermediate 10-Ω resistor and later on comparing the same 10-Ω resistor with the 100-Ω resistor (Hamon series mode), one obtains the 1:100 ratio with an uncertainty of 1 part in 10^8.

The measurements of the 100-Ω and 50-Ω resistors are carried out with the same accuracy. We compared them in a potentiometric substitution method using the aforementioned Kusters comparator. All resistors that establish the 350:1 ratio have been kept in an oil bath at 23°C for more than two years. The constancy of that ratio was checked at each run and the scatter from day to day was, in general, smaller than 1 part in 10^8. The long term stability of each resistor relative to the 1-Ω resistor was about $\pm 10^{-7}$ per year, whereas, the rate of change of the 350:1 ratio was found to be 2 parts in 10^8 per year. It is interesting to note that one group of resistors shows a dependence on air pressure of a few parts in 10^8.

Discussion of the Results

Fig. 2 shows the results of all comparisons between the mean EMF values of the 39 standard cells in enclosure I and the Josephson reference voltage during a period of 21 months. Each point represents a mean value of a measurement series comprising usually 10 independent measurements. The total uncertainty (1 σ) for a period of 14 days (about 15 measurement series) is 4 parts in 10^8, as pointed out in [2].

The mean EMF of the cells is converted to 20.000°C and U_0 is the value of the EMF at the last international comparison at BIPM in February, 1973. The mean EMF of the saturated cells seems to drift almost linearly with time at a rate of -1.3×10^{-7} V per year. The voltage stability of this group of cells is sufficiently high, so that

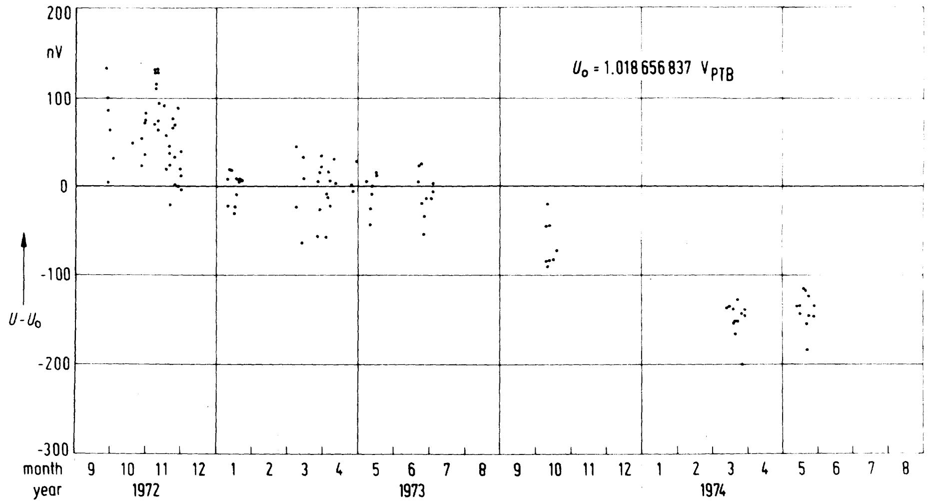

Fig. 2. Results of the comparisons between the mean EMF of 39 saturated standard cells and the dc Josephson voltage during a period of 21 months. U is the EMF of the cells converted to 20°C and U_0 is the value of the EMF at the last international comparison in February 1973.

new comparisons with the Josephson reference voltage need be made only at intervals of a few months.

A NEW CRYOGENIC VOLTAGE STANDARD

The main disadvantage of the measurement system previously described (see Fig. 1) is that the thermal EMF's between the Josephson junction and the divider are only stable for short time periods and thus a compensating EMF must be continually added to these leads. In order to reduce this effect and to maintain the unit of voltage with a long term stability, we have developed and built a prototype cryogenic voltage standard. Besides the Josephson junctions, two other components, a cryogenic resistive divider and a superconducting quantum interference device (SQUID) are contained in the superfluid liquid helium bath at 2 K. In the following paragraphs we present the principles of operation and calibration of the cryogenic resistive divider. Other cryogenic dividers are described in [4], [9].

Principle of Operation

Fig. 3 shows a simplified circuit diagram of the cryogenic voltage standard in the measurement mode. The Josephson reference voltage of 3 mV is produced by irradiating two point contact junctions at a microwave frequency of 70 GHz and then biasing to the appropriate microwave-induced steps as described earlier [1], [2]. While feeding a constant dc current of 30 mA through the resistive divider, the voltage drop across the 0.1-Ω resistor can be compared with the dc Josephson voltage by means of the null detector. At present this null detector system consists of a SQUID picovoltmeter[1] with a sensitivity of about 10 pV and an input resistance of 0.1 Ω, so that a balance of 3 parts in 10^9 can be achieved in the 3-mV circuit.

The voltage of interest at the 1-V level appears across the total resistance of 32 Ω. The thermal EMF's due to the temperature gradients on the 1-V potential leads are compensated by adding a Lindeck circuit, as shown in Fig. 3. By shorting the potential leads in the helium bath (not shown in the figure) the thermal EMF's are compensated by adjusting the resistance r (Fig. 3) and monitoring the balance by connecting a galvanometer across the 1-V leads. Thermal EMF drift rates of 10^{-10} V/min were measured which would introduce an error of 1 part in 10^8 in about $1\frac{1}{2}$ h in the worst case, assuming a unidirectional drift. Depending on the desired precision of the voltage stability, this compensating procedure can of course be repeated in shorter or longer periods.

By closing the loop between the SQUID readout and the constant current source (CCS), as shown in Fig. 3, the EMF at the 1-V level can be regulated relative to the Josephson EMF so long as the resistance ratio does not change by aging effects.

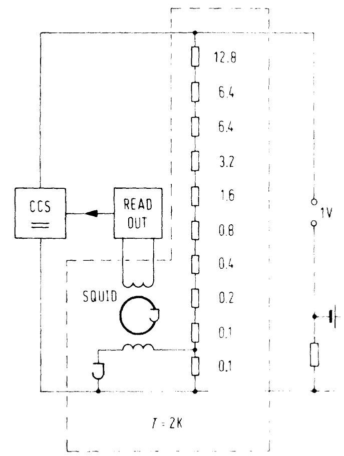

Fig. 3. Simplified circuit diagram of the cryogenic voltage standard operating at a temperature of 2 K. The CCS is automatically controlled by the readout voltage of the SQUID null detector. The thermal EMF's on the potential leads are compensated by adjusting the resistor r. The numbers at the resistors are nominal values in ohms. The reversing switches are not shown.

[1] Made by the S. H. E. Manufacturing Corporation, San Diego, Calif.

Cryogenic Resistive Divider and Its Calibration

The cryogenic resistive divider establishes a maximum ratio of 320:1 and consists of 10 resistors connected in series. These resistors are bifilar wound of a new ductile copper germanium alloy [10],[2] which has a relative temperature coefficient of the resistance (TCR) at 2 K of -5.4 parts in 10^6/K.

The TCR of this resistance material, composed of 94-percent copper and 6-percent germanium, was -2.6 parts in 10^6/K at 4.2 K and $+5.1$ parts in 10^4/K at 300 K. At 2 K the material has a resistivity of 16 $\mu\Omega \cdot$cm, whereas, at 300 K the resistivity is about 15 percent larger. The wire diameter was 0.6 mm and the wire length, for 1 Ω is 1.8 m. Assuming a Kapitza conductance of 0.2 W/cm^{2}K [11] for the Cu–Ge alloy, we obtain a power coefficient for a 1-Ω resistor of -7.4 parts in 10^{10}/mW.

The temperature of the superfluid helium bath at 2 K is controlled to better than 10^{-3} K, but such control is not essential since temperature change affects the ratio only in second order. The potential leads were brazed to the resistors in order to avoid any current dependence which would appear at the interface of the alloy and a superconducting solder. The divider ratio is calibrated with a ten-decade inductive voltage comparator (IVC), shown in principle in Fig. 4 operating below 10-Hz frequency which was developed by Fuhrmann [12], [13]. The input impedance of the IVC achieved by electronic means is larger than 10^8 Ω. The cryogenic divider is ac driven by a constant voltage source (CVS) with an rms value of 1-V and $8\frac{1}{3}$-Hz frequency. Fig. 4 shows an example of one of the nine 1:1 ratios that must be measured in order to determine the total divider ratio. The ac null detector has an rms noise voltage of 35 pV assuming a 1-Hz bandwidth and a source resistance of 0.5 Ω.

This ac system has several advantages.

1) Thermal EMF's do not affect the comparison, so that, for instance, the switch which connects the IVC with the cryogenic divider can be located at room temperature.

2) The effects of temperature coefficient, power coefficient, and current distributions in the resistors are reduced to second order because the power dissipation during the measurement and the calibration are the same. These errors are first order when current comparator systems or Hamon networks are used.

3) Matching of the resistances is only necessary to about 4 parts in 10^3 because this IVC can determine deviations from a 1:1 ratio up to this level.

As with the IVC, the 1:1 ratios can also be determined by a direct comparison of the dc voltage on each of the unit resistors with the dc Josephson voltage (using the SQUID as a sensitive null detector) by adjusting the divider current. Both techniques can thus be used to calibrate the divider; however, the ac comparisons are more accurate for ratios of high value resistors, because of the larger voltage drop across the resistors. The intercomparison with the Josephson junction provides better results for the low value resistors (because noise voltage is smaller in this case). Combining both calibration measurements, the estimated uncertainty for the total 320:1 ratio is about 5 parts in 10^9.

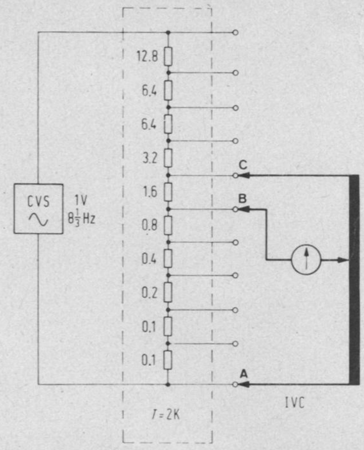

Fig. 4. Simplified circuit diagram of the cryogenic resistive divider at 2 K and the IVC in the calibration mode. The divider is supplied by a CVS with an rms value of 1 V at $8\frac{1}{3}$-Hz frequency. The potential leads (A,B,C) of the IVC are connected for measuring the 1.6-Ω:1.6-Ω ratio.

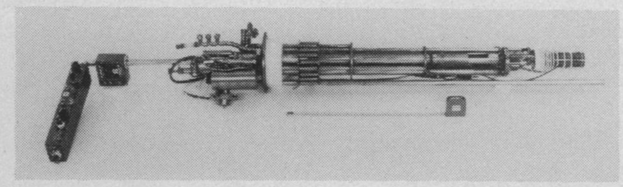

Fig. 5. Cryogenic devices consisting of the resistive divider, the Josephson junctions, and the SQUID null detector (total view).

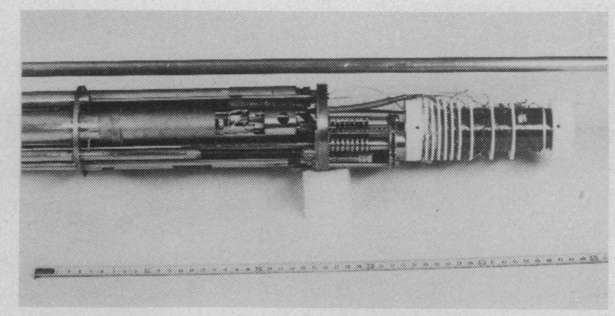

Fig. 6. Josephson junctions, switches, and cryogenic resistive divider (partial view).

Although we have obtained only preliminary results with the apparatus shown in Fig. 5 and Fig. 6, it appears that this cryogenic voltage standard may prove to be a very reliable, easy to use, and extremely accurate one. The stability of such a system should depend only upon the stability of the Josephson EMF and the divider components, but not on the stability of an electrochemical system.

[2] We appreciate very much the help and discussion of F. R. Fickett and D. B. Sullivan of the National Bureau of Standards, Boulder, Colo., in the first stage of making the Cu–Ge alloy. We acknowledge the effort of K. Thielmann, Isabellenhütte, Heusler KG, Dillenburg, Germany, for manufacturing this special wire.

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The AC Josephson Effect Monitoring of the Unit of EMF in Canada

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***Abstract*—The experimental program outlined is directed toward the utilization of the ac Josephson effect to maintain surveillance of the unit of EMF in Canada. Preliminary results indicate a weighted mean value of $2e/h = 483\,593.0 \pm 0.2$ (0.4 ppm) GHz/$V_{\mathrm{NRC}(73)}$ which is, at present, not precise enough to detect the small drifts normally encountered in the mean value of the standard cell group upon which V_{NRC} is based.**

I. INTRODUCTION

It is now well known that when a finite dc voltage V is developed between two weakly coupled superconductors, the supercurrents flowing between them oscillate at a frequency $\nu_J = (2e/h)V$, where h is Planck's constant, and e is the electronic charge. This phenomenon, named the ac Josephson effect after its discoverer [1], has been extensively studied both theoretically and experimentally and is believed to be free of corrections to better than a part in 10^8. As illustrated in Fig. 1, this high-frequency supercurrent is usually detected by irradiating a junction with microwaves at frequency ν_o and observing the resulting dc sidebands which are manifested as constant-voltage current steps in the current–voltage characteristic. The voltage V_n at which the nth step occurs is given by the important relation

$$V_n = n(h/2e)\nu_o.$$

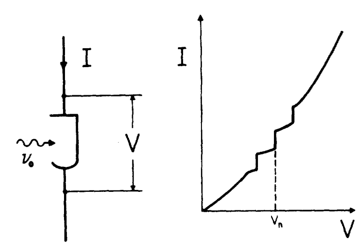

Fig. 1. Schematic current–voltage characteristic of a Josephson junction showing microwave radiation-induced constant-voltage current steps.

The implications of this result for the maintenance of standards of electromotive force (EMF) were first described by Taylor *et al.* [2] in 1967. In essence, the approach taken since then has been to induce current steps in a Josephson device at some convenient voltage, usually 1–10 mV, and compare this to the potential of a standard cell by means of a stable voltage divider whose ratio r is accurately known. As it is relatively easy to measure frequency to parts in 10^9, a knowledge of ν_o, r, and n makes a high precision determination of $2e/h$ in terms of a local EMF standard (V_{std}) quite straightforward in principle. Problems such as control of thermal emf's encountered in the 4 to 300 K temperature range spanned by

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