4. The indirect calculations involving the $Fe-H_2O-H_2$ equilibria fall principally into two groups, the one agreeing fairly well with the directly measured values, the other being some 40% higher.

Summary

The value of the equilibrium constant $K_7 = CO_2/CO$ for the reaction $CoO + CO = Co + CO_2$ has been determined by a flow system at 450, 515 and 570°, to be 489.6, 245.9 and 148.4, respectively. Combination of these values with the previously determined constant $K_6 = H_2O/H_2$ for the reaction $CoO + H_2 = Co + H_2O$ gives indirect values for the water gas constant $K_{wg} = (CO)(H_2O)/(CO_2)(H_2)$ that are in good agreement with the values determined directly by Neumann and Köhler. The present status of the disagreement between some of the indirectly determined values for K_{wg} and the direct values of Neumann and Köhler is summarized.

WASHINGTON, D. C.

[CONTRIBUTION FROM THE LABORATORIES OF THE ROCKEFELLER INSTITUTE FOR MEDICAL RESEARCH]

A SCREENED BRIDGE FOR THE MEASUREMENT OF ELECTROLYTIC CONDUCTANCE. I. THEORY OF CAPACITY ERRORS. II. DESCRIPTION OF THE BRIDGE

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Introduction

Kohlrausch's classical method for measuring the electrical conductance of solutions has had the benefit of numerous improvements by many workers. The researches of Washburn[1] were particularly valuable in stimulating accurate conductance work in this country. Morgan and Lammert[2] have discussed some of the sources of error in the electrical arrangement used in the method, with valuable references to previous work. Of particular importance from the standpoint of precision measurements has been the comparatively recent introduction of vacuum tube alternating current generators and amplifiers for providing currents of symmetrical wave form, on the one hand, and increasing the sensitivity of the detector on the other.[3] Jones and Josephs[4] have described in a very detailed paper a direct reading alternating current bridge embodying these new features.

[1] Washburn and Bell, THIS JOURNAL, **35**, 177 (1913); Washburn, *ibid.*, **38**, 2431 (1916); Washburn and Parker, *ibid.*, **39**, 235 (1917).

[2] Morgan and Lammert, *ibid.*, **48**, 1220 (1926).

[3] Hall and Adams, *ibid.*, **41**, 1523 (1919); Jones and Bollinger, *ibid.*, **51**, 2407 (1929).

[4] Jones and Josephs, *ibid.*, **50**, 1049 (1928).

Their paper also includes a valuable and comprehensive study of various sources of error from the electrical standpoint in the Kohlrausch method as it has been generally used.

Important features of Jones and Josephs' bridge are the abandoning of the circular slide wire (which is capable of introducing a disturbing unsymmetrical inductance in the measuring circuit) and the use of a suitable earthing device for the bridge for minimizing disturbing earth capacity effects. They have, however, condemned the use of electrostatic screening of the bridge.[5] The use of screening, when properly designed, for the entire bridge has decided advantages. Since the readings are unaffected by the movements of the observer, a screened bridge is more convenient to operate than an unscreened one. Without adequate shielding, delicate balances are difficult to make due to shifting capacities introduced by the hands of the observer, etc. Also, with suitable screening, measurements of high precision are possible under conditions existing in modern laboratories in which other electrical work is certain to be in progress. Under such conditions the use of an unshielded bridge is at times troublesome if not impossible.

In Part I of this paper the theory of disturbing capacity effects in an alternating current Wheatstone bridge circuit is discussed, with reference to the underlying principle of the apparatus as a measuring instrument. Also, the basis for designing proper screening is developed.

In Part II, a shielded alternating current bridge for measuring electrolytic conductance with a high degree of precision is described. The main problem in the design of such a bridge is the fixing and the proper balancing of "stray couplings" in the apparatus.

PART I. THE THEORY OF EARTH CAPACITY ERRORS IN THE A. C. WHEATSTONE BRIDGE

1. **Stray Couplings.**—When a direct current flows through a conductor, leakage can take place only through inadequate insulation. With alternating currents, the case is more complicated because the current may also leak away through electrostatic and electromagnetic linkings, commonly known as "stray couplings" with the surroundings. Such stray couplings may be electrostatic capacities between the parts of the circuit and capacities between these parts and the ground. There may also be mutual inductive effects due to linkages with stray magnetic fields. The effects produced by these couplings vary with the frequency, being more troublesome at higher frequencies.

Stray electromagnetic couplings are particularly important in the case

[5] Their conclusions are based on tests made with a screen placed near one branch of the bridge network, which introduced an *unbalanced* earth capacity effect into the circuit. Such a test does not prove, however, that electrostatic screening cannot be used without error if it is properly designed.

of parts of circuits, such as transformer coils, which have appreciable inductance. These mutual inductive couplings may be reduced by using materials of high permeability in the cores of the transformers, by shielding stray fields with screens of high permeability, or by sufficiently separating the branches of the circuit having high inductances from each other. In the case of a Wheatstone bridge for measuring electrolytic conductance, the only branches in the network capable of very serious inductive coupling with each other are the detector and the oscillator. The best plan is to avoid the necessity of electromagnetic screening, which is always difficult and seldom completely satisfactory. This is readily accomplished by removing the oscillator to a sufficient distance from the detector, which is more conveniently located near the bridge, and avoiding as much as possible the introduction of stray inductance in the bridge itself. A distance of 10 to 15 feet between the detector and the oscillator is usually sufficient.

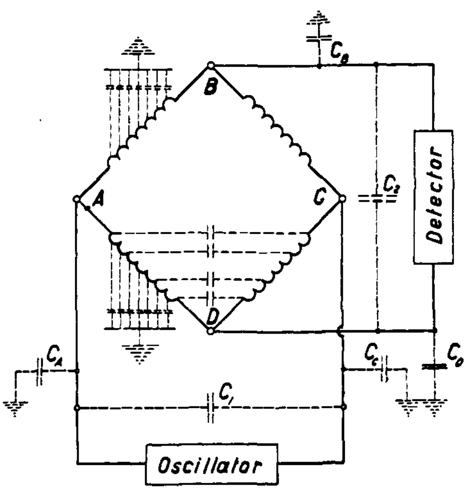

Fig. 1.

Electrostatic couplings existing between various branches of a circuit, directly or to ground, cannot be eliminated entirely in this simple manner without introducing another difficulty. The difficulty is that excessive separation of all the branches of the bridge from each other and from ground, besides being inconvenient, introduces additional inductance into the network because of the increased length of leads required. The result of this increased looping is that although capacitative couplings are reduced, inductances capable of disturbing the bridge balance are thus added, since the bridge balance may be changed by the inductive effect of varying stray fields enclosed.

In Fig. 1 is shown a diagram of a bridge supplied with alternating current, indicating the position of some of the capacitative couplings. The capacity paths from one lead of the oscillator to the other, either directly (C_1) or through ground (C_a and C_c in series), merely shunt the current input, and do not affect the bridge balance. Similarly, the coupling between the leads to the detector does not influence the bridge reading, merely shunting the detector. However, couplings are possible which may disturb the balance of the bridge. For example, current leaking from the branch AD, through CB to the terminal B, and back to the oscillator through the branch BC, would have an effect on the bridge balance. (It should be pointed out that the bridge terminals A, B, C and D include the leads appended to them since if they are not too long their resistance is usually negligible.) Although some of these numerous possible paths will tend to neutralize each other, the effects of these paths must be controlled; otherwise, the bridge readings will depend on the relative positions of the units in the circuit and on the surroundings.

Precise measurements are not possible unless these troublesome couplings are neutralized by being made symmetrical with respect to the terminals of the detector. It is not possible to avoid electrical asymmetry entirely in the construction of the apparatus, particularly if the bridge is used for measurements with various frequencies of current, requiring readjustments in the oscillator, or perhaps different oscillators. Neither is it practicable to reduce these couplings so as to make them negligible, especially at the higher frequencies, and in the measurement of dilute solutions having large resistances. For these reasons it is necessary to provide means for controlling and balancing these disturbing effects. This is accomplished (a) by properly designed shielding[6] and (b) by the "Wagner earthing device," both of which will be discussed below. Shielding makes it possible to fix definitely and to control the possible interbranch capacities. Before discussing the effect of capacity couplings on the bridge as a whole, it is first necessary to consider the effect on the impedance of a single branch due to the capacity between it and the ground (or a surrounding screen).

2. **Effect of Earth Capacity on a Conductor.**—In general, with a conductor carrying alternating current, there will be present a distributed capacity of total magnitude c to earth, or to a surrounding screen, as indicated in Fig. 2a, where OR is the conductor of impedance[7] R, and S is the ground or screen. In Fig. 2b is shown a special condition which will help in the consideration of a more general case. In this special case the total capacity from OR to S is concentrated at some point P, between O and R. Let $[x]$ be the impedance from O to P, $[y]$ the impedance from P to R and $[z]$ the impedance from P to S. Let us now substitute for the

[6] The necessity of electrostatic screening for measurements at frequencies of, say, above 10,000 cycles is generally recognized. See for example G. A. Campbell, "The Shielded Balance," *Electrical World*, April, 647 (1904); W. S. Shackelton, "A Shielded Bridge for Inductive Impedance Measurements," *Bell System Technical Journal*, **6**, 142 (1927); J. G. Ferguson, "Shielding in High Frequency Measurements," *ibid.*, **8**, 560 (1929).

[7] Ohm's law can be applied to sinusoidal alternating currents if vector symbols instead of scalar symbols are used. On this basis the impedance operator, which is analogous to resistance in D. C., is defined as the vector voltage divided by the vector current. See B. Hague, "A. C. Bridge Methods," pp. 32–35; R. M. Wilmotte, *Phil. Mag.*, **6**, 788 (1928).

arrangement connecting the points O, **R** and S as in Fig. 2b, the arrangement shown in Fig. 2c. which we shall prove can be made equivalent by the "Kennelly $\tau - \pi$ transformation."[8] In Fig. 2c $[\alpha]$, $[\beta]$ and $[\gamma]$ are the impedances connecting the three terminals of interest, O, R and S. By equivalence of the two circuits (shown in Figs. 2b and 2c) is meant that the potentials of O, R and S are the same at any instant in both arrangements. Thus, for example, the impedance operators $x + y$ must be equal to α and $\beta + \gamma$ in parallel. (The letters in brackets $[x]$, $[\alpha]$, etc., refer to impedances; x, α, etc., refer to the corresponding impedance operators.) We consequently get the following relations

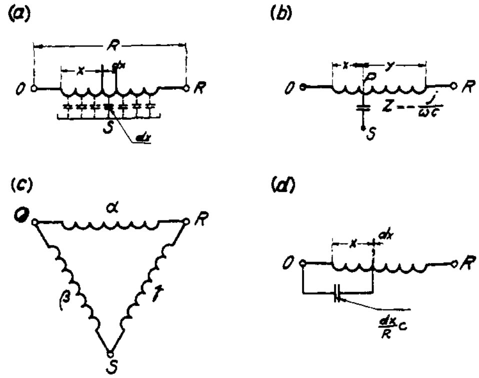

Fig. 2.

$$\frac{1}{x + y} = \frac{1}{\alpha} + \frac{1}{\beta + \gamma} \tag{1}$$

$$\frac{1}{x + z} = \frac{1}{\beta} + \frac{1}{\alpha + \gamma} \tag{2}$$

$$\frac{1}{y + z} = \frac{1}{\gamma} + \frac{1}{\alpha + \beta} \tag{3}$$

Solving, we obtain the equations

$$\alpha = x + y + \frac{xy}{z} \tag{4}$$

$$\beta = x + z + \frac{xz}{y} \tag{5}$$

$$\gamma = y + z + \frac{yz}{x} \tag{6}$$

(a) **Capacity Concentrated at the Midpoint.**—Now, referring again to Fig. 2b, if we consider R a resistance with its total capacity to the ground (S) concentrated at the midpoint, $x = y = R/2$; $z = -j/\omega c$, where c is the total capacity to ground. $\omega/2\pi$ is the frequency and j is the "reactance" operator.[9] Substituting these values in (4), (5) and (6) we obtain

$$\alpha = R + j\,\frac{R^2\omega c}{4} \tag{7}$$

$$\beta = \gamma = \frac{R}{2} - j\left(\frac{1}{\omega c/2}\right) \tag{8}$$

[8] This transformation has been used by Butterworth [*Proc. Phys. Soc.*, **33**, 312 (1921); *ibid.*, **34**, 8 (1922)] and more recently by Bartlett [*J. Sci. Instruments*, **6**, 277 (1929)] in dealing with the effects of earth capacities.

[9] $(j)^2 = -1$. The reactance due to a capacity c is $-(j/\omega c)$; the reactance due to an inductance L is $j\omega L$. See, for example, B. Hague, "Alternating Current Bridge Methods," p. 35.

That is, due to earth capacity effects, the resistance R between the points O and R is modified by a reactance $R^2\omega c/4$ (this may be considered to be an inductance of magnitude $R^2c/4$ in series with the resistance R) and by the impedances (8) from O and R to ground (S) (these may be considered to be capacities of magnitude $c/2$ in series with a resistance $R/2$).

(b) **Capacity Uniformly Distributed.**—The more general case of a distributed capacity, as shown in Fig. 2a, is somewhat more complicated to deal with rigorously. However, the values of α, β and γ for this case are approximately represented by Equations 7 and 8. This assumes, of course, the approximation that the total distributed capacity is represented by a single capacity from the middle of the arm to the screen. If the capacity is uniformly distributed, the effect on α due to the differential capacities $(\mathrm{d}x/R)(c)$ from the differential proportions $\mathrm{d}x/R$ (see Fig. 2) is obtained from Equation 4 to a first approximation by integration as follows[10]

$$\mathrm{d}\alpha = x + R - x + j\int \frac{x(R-x)\omega c\mathrm{d}x}{R} \qquad (9)$$

$$\alpha = R + \int_0^R \frac{x(R-x)\omega c\mathrm{d}x}{R} = R + j\,\frac{\omega R^2 c}{6} \qquad (10)$$

Equation 10 shows that the resistance of OR, due to the distributed earth capacity effect, behaves as a resistance R in series with an inductance $R^2c/6$.

(c) **Impedance Directly Connected to Earth or Screen.**—Another case of interest is one in which the ground or screen S is connected to one terminal of the impedance (Fig. 2d), since screens are often so connected, and bridges are frequently grounded directly from one terminal. The effect due to the capacity from a differential section to the screen S (or earth) is a shunting impedance [dz]. As before, $-j(R/\omega c\mathrm{d}x) = \mathrm{d}z$.

The total impedance operator, then, from O to R is

$$Z_{(\mathrm{OR})} = \frac{1}{\frac{1}{x} + j\,\frac{\omega c\mathrm{d}x}{R}} + R - x = x - j\;\omega c x^2\mathrm{d}x + R - X = R - j\,\frac{\omega c x^2\mathrm{d}x}{R} \qquad (11)$$

neglecting terms of higher order.[11] Integrating from x = O to x = R

$$Z_{\mathrm{OR}} = R - j\,\frac{\omega c r^2}{3} \qquad (12)$$

[10] For a more rigorous treatment of this uniformly distributed case, see A. E. Kennelly, "Electric Lines and Nets," McGraw-Hill Book Co., New York, pp. 61, 395. The method of integration (Equations 9 and 10) used below for obtaining α in this distributed case amounts to neglecting higher order terms in the rigorous treatment which involves the use of hyperbolic functions. However, no such approximations are involved in obtaining Equations 7 and 8.

[11] This derivation involves the approximation that the differential capacity effects act independently. For a more rigorous derivation see R. Davis, *J. Sci. Instruments*, **5**, 306 (1928).

In this case we see that the earth capacity effect introduces a negative inductance in series with it of magnitude $R^2c/3$.

3. Earth Capacity Effect on the Bridge Circuit.—In the light of the discussion in the previous section we may now view the effect of "stray couplings" on the bridge network. We shall assume that *direct* couplings between the branches have been avoided by shielding. Assuming, then, that the branches of the bridge are so shielded from each other by screens, and making the Kennelly $\tau - \pi$ transformation for every branch, the bridge with its capacity couplings to ground can be represented as in Fig. 3. The segments L_1, L_2, etc., represent the inductive effects discussed above produced in the branches by the earth capacities. AE, BE, CE and DE are the impedances from the four bridge terminals to ground at E. Each of these impedances includes the separate earth capacity effects from the three branches (corresponding to the various β and γ terms, Equation 8) meeting at each terminal of the bridge network. In addition, there are the capacities to earth from the terminals (and leads) A, B, C and D. For instance, (1) is a resistance in series with a capacity due to AB; (2) is a similar, though not necessarily equal, impedance due to AD; (3) is another one due to the oscillator branch; and (4) is a capacity from A to E, due largely to the lead from the oscillator. All these in parallel constitute AE.

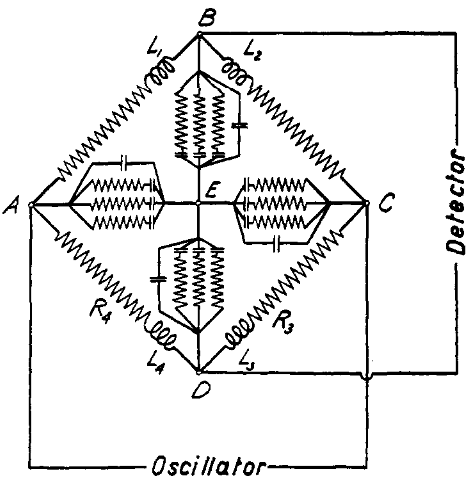

Fig. 3.

It should be noted that the representation of the bridge in Fig. 3 takes into account the distributed dissipations of current from the branches in the circuit to the screens and earth. The advantages of the artifice used in this representation are that it shows the effects produced on the branch impedances from the standpoint of the four terminals of the bridge, making clear the necessary conditions for proper bridge balance, and shows the limitations which must be observed in designing suitable screening so as not to introduce errors in the measurements.

When the bridge is balanced, the terminals B and D are at the same potential, both in magnitude and in phase. That is, the potentials are equal at every instant and no current flows between the two points through the detector. Referring to Fig. 3, if V is the potential between two points at balance

$$V_{AB} = V_{AD} \text{ and } V_{BC} = V_{DC} \tag{a}$$

This gives by the Vector Ohm's Law[12]

$$\frac{I_{AB}Z_{AB}}{I_{BC}Z_{BC}} = \frac{I_{AD}Z_{AD}}{I_{DH}Z_{DC}} \tag{b}$$

where I is the current and Z the impedance. Now, if the points B and D are brought to the same potential as the ground E, there will be no current flowing in either BE or DE, and the conditions

$$I_{AB} = I_{BC} \text{ and } I_{AD} = I_{DC} \tag{c}$$

will be fulfilled. (There are only three possible paths for current from B or D, when no current flows in the detector.)

Then

$$\frac{Z_{AB}}{Z_{BC}} = \frac{Z_{AD}}{Z_{DC}} \tag{d}$$

If no errors are to be introduced into the measurements, the ratio arms (AD and CD) should be identical in all respects in the case of a direct reading (equal ratio) bridge ($Z_{AD} = Z_{DC}$). Not only must the resistances R_4 and R_3 be equal, but the inductances L_4 and L_3 must also be equal. The latter need not, however, necessarily be negligible, since it is quite feasible to have two equal coils, of similar construction, similarly screened so that, practically, $R_4 = R_3$ and $L_4 = L_3$, in which case $Z_{AD} = Z_{DC}$. Nevertheless, slight differences, in resistance particularly, are likely to occur. This, as well as slight unbalances in the L terms due to screen capacity, are automatically corrected for if two readings are taken, one with the ratio arms reversed. The average value (strictly speaking, the geometric mean) gives the correct measurement.

However, the characteristics of the measuring branch and of the unknown (cell) cannot be considered identical as in the case of the ratio arms. That is, it is not possible to shield the two with relatively close screens, and feel assured that the capacity effects are similar in both cases. However, shielding is desirable from the standpoint of screening out external influences which may affect the circuit. The correct procedure, therefore, is to shield these branches not closely, but at a sufficient distance to make the effect of the capacity on the impedance negligible under the limiting conditions existing in measurements. If the upper frequency range does not exceed 4000 cycles, direct test showed that a separation of 2.5 inches between the coils of the resistance box (or cell) and the shield introduces a negligible error. That is, the terms L_1 and L_2 in Fig. 3 are negligible.

If these conditions for the ratio arms and the other two branches in the bridge are fulfilled (L_1 and L_2 negligible, $L_3 = L_4$, $R_4 = R_3$, no current in BE or DE) then Equation d reduces to

$$Z'_{AB} = Z'_{BC} \tag{e}$$

[12] See Hague, Ref. 9, p. 32.

(Z' is the impedance free from earth or screen effect)[13] which is the correct balance condition for an equal ratio bridge without error. Jones and Josephs[4] state in their paper that the necessary condition for the validity of Equation e is that no current whatever escape from any of the bridge parts. Of course, if that is so, correct balance is obtained at once. Practically this is not possible. However, as shown above, correct balance, without error in the measurements, is quite attainable when the proper precautions are observed in spite of a certain amount of current leakage from at least some of the branches.

4. The Wagner Earthing Device.—One of the conditions for the validity of Equation e is that the terminals B, D and E (Fig. 3) be at the same potential. This may be done by adjusting the earth impedances AE and CE until no current flows in the detector connected from E to B (or D), when the main bridge (ABCD) is also balanced. That is, $Z_{AE}/Z_{CE} = Z_{AB}/Z_{CB} = Z_{AD}/Z_{CD}$. This is the principle of the device. Since Z_{AE} and Z_{CE} are mixed impedances, consisting of resistance and capacity, the adjusting impedance must similarly comprise a variable resistance and reactance. The reactance may be either a capacity or an inductance, or both, since any impedance may be balanced by such combinations. It is merely necessary to adjust the impedances Z_{AE} and Z_{CE} to the proper ratio.

The scheme used by Jones and Josephs,[4] who, however, do not discuss the theoretical basis of the device, is a very convenient one. It consists of shunting AE and CE with resistances permitting of sufficient variation in adjustment, and a variable condenser from A to E, or C to E, as required. The advantage of their method lies principally in the fact that for the same delicacy of adjustment condensers of lower capacity can be used than would be required with series resistance and capacity combinations.[14]

An examination of Fig. 3 shows the limitations of connecting the ground point E directly to B or D, and securing balance by the adjustment of a condenser in parallel with the necessary branch. Evidently, except in the case of accidental balancing between AE and CE, the bridge reading will not be free from error. The magnitude of the error will depend on the magnitudes of AE and CE and on the extent of their unbalance. It is, however, possible to determine the unbalance between AE and CE, and then to calculate the error thus introduced in the measurements.

[13] This impedance may be a pure resistance. The somewhat more complicated case of a cell for measuring electrolytic conductance will be discussed in a later paper. However, if the cell impedance is of sufficiently low-phase angle, it can be regarded as a resistance.

[14] Jones and Josephs deserve the credit for describing the proper use of the earthing device for balancing the earth admittances in a conductance bridge for work with solutions, although the underlying principle of the method is due to Wagner.

This scheme, though feasible in certain types of impedance measurements, is inconvenient since it requires an estimation of the earth capacity with subsequent calculations. For a bridge designed to measure electrolytic conductance the Wagner device is simpler and preferable.

PART II. A SCREENED ALTERNATING CURRENT WHEATSTONE BRIDGE

The shielded bridge, which was discussed from the theoretical standpoint in Part I, is shown diagrammatically in Fig. 4. The detector and oscillator are connected to the bridge by duplex cables inclosed in flexible copper shielding which is grounded. The oscillator and the earthing circuit W_R, W_C are connected directly to terminals of the measuring branch and of the conductivity cell, at M and N.

1. **Balancing Condensers.**—A twin (double) variable air condenser K is connected across the measuring resistance (MS) and the cell (BN) as shown, for balancing out the reactance of the cell, due to polarization at the electrodes. The ordinary type of single variable condenser has a disadvantage. It is sometimes impossible to get complete balance in the bridge with it, owing to the fact that the residual zero capacity is too large for the required setting. The twin type, which makes it possible to remove capacity from one side, adding it to the other, avoids this difficulty, and does not require a switch for shifting the condenser from one branch to the other. The entire condenser K consists of two such twin condensers. One is of $250\mu\mu$f. capacity, easily reconstructed from the "tandem type" condenser made by the General Radio Co. The other, connected in parallel with the first, is similarly constructed from two micro condensers. The latter has a maximum capacity of about $10\mu\mu$f. and it is provided with a "Vernier" control knob, allowing of very delicate adjustment.

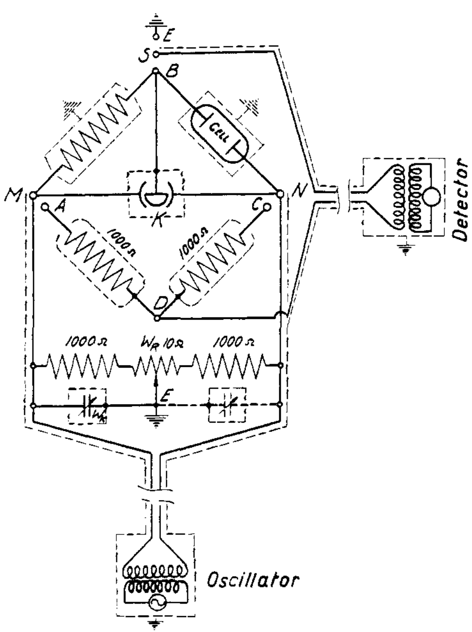

Fig. 4.

2. **Ratio Arms.**—The ratio arms are connected to the bridge by means of a double pole double throw reversal switch (not shown in Fig. 4). In making determinations the mean of readings with the ratio arms in the two reversed positions is taken. This procedure corrects for slight variations in the resistances (and reactances) of the ratio coils, and avoids the necessity of adjusting them to perfect equality. The ratio coils are surrounded by local symmetrical shields connected to the junction point D. The shield localizes the total distributed capacity of the ratio arms at point D, and avoids the possibility of any stray couplings directly with these important branches of the bridge.

The ratio arms consist of two closely matched Ayrton–Perry coils of 1000 ohms resistance which are wound on flat bakelite cards. It has been shown in Part I that the effect of the distributed capacity in these coils will add an inductance of magnitude $-cR^2/_3$ to them. For this reason it is important to make shielding the same around the two ratio arms. In our arrangement the flat coils are mounted parallel to each other, symmetrically between three parallel copper plates spaced 1.5 inches apart. The plates are soldered to a copper strip joining the two resistance coils.

3. **The Detector.**—The detector consists of a two-stage audio transformer coupled amplifier with sensitive telephones. The output from the bridge is fed into the primary winding of the first transformer. By means of the switch S in Fig. 4, the detector may be connected across DB, for recording the balance in the main bridge, or across DE, for the earthing adjustment.

4. **The Earthing Circuit.**—The earthing circuit consists of two 1000-ohm bifilar coils (Leeds and Northrup) and a 10-ohm rheostat (W_R) connected as shown in Fig. 4 to the ratio arm extremities, and to ground. In addition, there is a variable air condenser, with a "Vernier" control knob connected between the earth E and the point A (or C, as required).

Various parts of the bridge, including the oscillator and detector, are shielded from external electrostatic disturbances by the earthed metal shields surrounding them. The various earth points E are all brought together by soldered connections.

The ratio arms, earthing resistances, condensers K, and the reversal and detector switches ("Federal Anti-capacity Switches") are mounted in a grounded copper screened box, as shown diagrammatically in Fig. 5. The top of the box consists of a brass plate in which the terminals are mounted with adequate insulation of transparent bakelite.

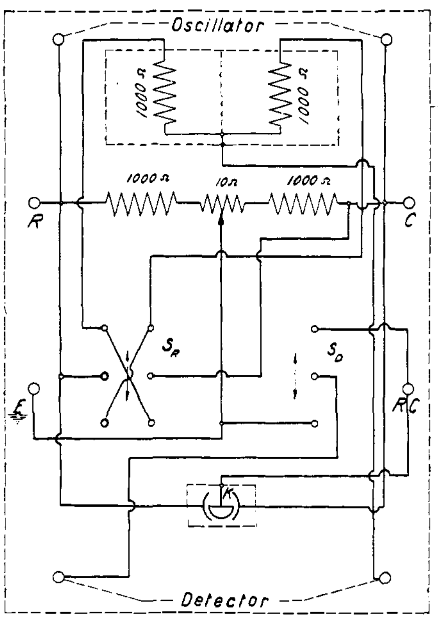

Fig. 5.

5. **Measuring Resistance.**—The resistance standard MB (Fig. 4) consists of three parts. A five-dial box of bifilar coils containing decades of 1/100, 1/10, 1, 10 and 100 ohm steps, is mounted in a shielded box. The screening in the box has a clearance of not less than 2.5 inches from any of the coils or contacts. This spacing proved to be sufficient by actual test to make the effect of the screen capacity on the resistance negligible for our purposes. The control knobs for operating the resistance dials are on the outside of the box, over a brass plate which forms a part of the shielding. They are fastened to the dials through stout bakelite rods. Complete shielding of these lower resistance dials as well as of the condenser K (Fig. 5) is of great convenience in entirely eliminating "hand effects" in measurements.

The effect of temperature on the resistance coils of higher values is not negligible in work requiring readings to 0.01 ohm and is not the same on every coil, so that corrections are not readily made. For this reason we found it desirable to control the temperature of the 1000-ohm step decade and the 10,000-ohm coils. These coils, of a woven type, forming one loop, are made by the Leeds and Northrup Co. They are practically reactance-free, compact and more constant in resistance than the card-wound type, being subject to very slight mechanical strain.

The 1000-ohm decade is mounted in air in a glass jar which is immersed in the metal shielded, oil-filled thermostat which holds the conductivity cell. The 10,000-ohm coils are mounted separately in large test-tubes, which are sufficiently spaced in a wooden frame, and also immersed in the thermostat. The 1000-ohm decade is permanently connected to the resistance box with a stiff heavy wire, avoiding close screening. The required connections in the thermostat, of the cell and measuring resistance are made with short heavy strands of bare copper wire through mercury cups. To avoid appreciable "dead end effects" the 10,000-ohm coils are appended one at a time as needed. Connections to the "bridge box" (Fig. 5) of the various units are made with flexible copper screened stranded wire, the screening being grounded.

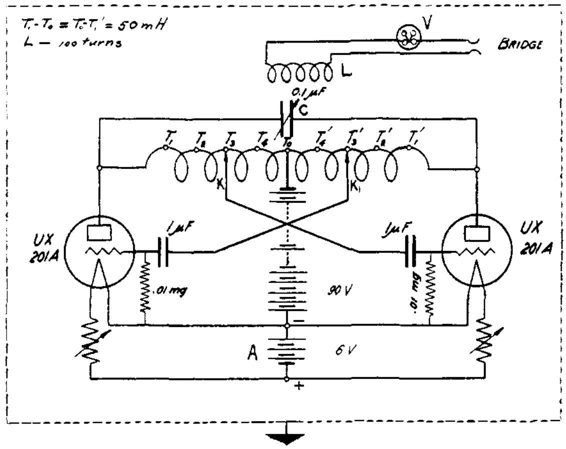

Fig. 6.

6. **The Oscillator.**—We are indebted to Dr. N. Frank of the Massachusetts Institute of Technology for furnishing us with the specification for an improved type of vacuum tube oscillator, designed by Eccles and Jordan. It consists of a double balanced oscillating circuit which has the advantage of giving an alternating current of very good wave form and of more constant frequency and intensity than that generated by the usual type of one-tube oscillator. The circuit is shown in Fig. 6. In varying the magnitude of the capacity C, which is made up of mica condensers which can be thrown in parallel by a system of switches (not shown in Fig. 6), the instrument can be made to give currents of frequencies ranging from about 600 to about 8000 cycles. The filament supply from the 6-volt storage battery A can be thrown on or off by means of a switch located near the bridge, so that the oscillator can be started or stopped conveniently during the measurements. The voltage supplied may be varied by looser coupling of the "pick up" coil L, or by changing the connections of K and K′ to the taps T_1, T_2, T_3 and T_1', T_2', T_3', respectively. It is important to use separate batteries for the oscillator and detector circuits; otherwise, troublesome inductive couplings will occur. A calibrated vacuum thermocouple (V) is included in the apparatus for measuring the current supplied to the bridge.

7. **Tests and Calibrations.**—The resistance box, 100-ohm step decade, and the 10,000-ohm coils were calibrated with direct current against Bureau of Standards re-

sistance standards, by the Carey Foster method, using an auxiliary resistance box. This was done directly with the bridge described above, using a high sensitivity galvanometer, and then checked on a well calibrated direct current Wheatstone bridge. The individual 10,000-ohm coils and various parallel combinations of them were also measured with the shielded bridge, at frequencies of 1000, 2000 and 3000 cycles, and with direct current. The variations from the direct current values obtained were less than 0.002% at 3000 cycles for 10,000 ohms, and entirely negligible at 1000 cycles, or for lower resistances.

The quality of the insulation, which is particularly important for the higher resistance measurements, was tested by connecting a 45-volt battery between the various binding posts, leads and screens, with a sensitive galvanometer in series. It was found to be well over 500 megohms across the important paths. The resistances of the metal contacts, important for the comparatively low resistance measurements, were also tested. A film of vaseline on the terminals and switch points made the resistance of the contacts reproducible and negligible (under 0.01 ohm).

In using the bridge, measurements are made by alternately adjusting **R** and K for the main balance, and W_R and W_K in the earthing circuit, with the detector in the correct position for each. The unknown and standard are then interchanged by throwing the reversed switch, and the procedure is repeated. The mean of the two readings gives the desired value.

No difficulty is found in making the adjustments, which may be made rapidly with a sensitivity of 0.001% directly without interpolation in measuring resistances of 1000 ohms or over. It is possible to use the bridge for measurements of high precision under conditions in which the use of an unshielded bridge would be quite difficult or impossible due to disturbances from other electrical circuits.

Measurements made with this bridge on the conductance of mixtures of potassium and sodium chlorides have already been reported.

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Summary

Part I. The theory of earth and shield capacity effects on alternating currents is discussed, and the results are applied to the Wheatstone bridge. The principles for the design of an electrostatically screened bridge for precision work are developed.

Part II. An alternating current, shielded bridge for precise electrolytic conductance measurements is described.

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