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APPLICATION OF THE THERMIONIC AMPLIFIER TO CONDUCTIVITY MEASUREMENTS.[1]

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The use of the thermionic amplifier as an aid in making conductivity measurements is an outgrowth of the necessity for accurate work under restricted conditions. We have been confronted with the need of making resistance measurements on saturated solutions of electrolytes in cells whose volume is small and whose electrodes are limited in area to approximately 2 sq. mm. Under these conditions, to avoid heating effects during a measurement, and to minimize polarization at the electrodes, as far as possible, the current through the cell should be made as small as is compatible with a correct bridge setting; and the lower limit to the value of the current is determined by the sensitivity of the telephone.

Ordinarily the conductance cell is designed to meet the requirements of the telephone which is to be used with it. A good telephone has an audibility current of 10^{-8} or 10^{-9} amperes, audibility current being defined as the least current through the telephone which will produce an audible tone. For the majority of uses in connection with measuring conductivities this is sufficient sensitivity. If one is not confronted with limitations in the size and spacing of the cell electrodes, and can work in a quiet room, there is little difficulty in satisfactorily determining the minimum, for one can vary the current passing through the bridge until

termined by their content of the two diamino acids, lysine and arginine. It should not be concluded from this, however, that a protein containing no lysine or arginine would adsorb no acid at all. I believe that, owing to their amphoteric nature, all proteins would adsorb some acid, in the form of a double layer of hydrogen ion and acid ion; the electrostatic force set up by this double layer, however, would discourage further adsorption, and with increasing concentration of acid the adsorption would finally cease to increase. If now, lysine or arginine are present in the protein, the adsorbed acid will be mainly fixed by the strong forces produced by the free amino groups of these acids; after these forces are neutralized, further indiscriminate adsorption at places on the molecule having weaker forces will be prevented by the electrical charge which has been set up. On this basis we should expect the amount of acid adsorbed by ordinary proteins, containing lysine and arginine, to be determined mainly by the content of these diamino acids, as has been found by Mr. Bracewell.

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[1] Presented at the Buffalo meeting of the American Chemical Society, April 7–11, 1919.

it meets the requirements of the telephone. But even then, it is necessary to be very careful in regard to the heating effects caused by the current passing through the cell, and for this reason to follow a rather definite schedule in making bridge settings.[1] Further, increasing the current through the system, as a means of shortening as much as possible the region of absolute silence in making the bridge setting, in addition to increasing the heating effect, is disadvantageous in increasing any errors due to polarization; while decreasing the current to the lowest value compatible with an accurate setting renders the determination of the minimum point a continuous strain on the nerves. Since the dimensions of our conductivity cell were limited by the bomb in which we were working, it was necessary to increase appreciably the sensitivity of the telephone.

Different methods for increasing the sensitivity of the telephone have been discussed by Washburn.[2] (1) Mechanical tuning consists in so adjusting the diaphragm that its fundamental vibration period is the same as that of the current. In the telephones designed for wireless work, or for conductivity measurements, the diaphragm is usually adjusted by the makers to a frequency of about 1000 cycles per second, and for all ordinary work, this frequency is satisfactory. (2) Electrical tuning is said to be of twofold value in that the insertion of capacity in series compensates for the inductance of the telephone and at the same time is effective in damping out higher harmonic tones. Our experience with this type of tuning has been unsatisfactory both with a telephone of low resistance and low impedance, and one in which the resistance and impedance are high. We have found a condenser connected in *parallel* with the telephone to be of advantage, however, in damping out any tones higher than the fundamental. (3) The use of acoustical tuning presupposes a current of almost unvarying frequency, and consequently requires adjustment for any changes in frequency. (4) The use of the stethoscope has been suggested by Curtis[3] as an aid with the telephone. In any of these arrangements, the gain in sensitivity is not great, as the current through the telephone is at best near its allowable lower limit.

The Amplifier.—The thermionic amplifier places at our disposal a means of increasing the current through the telephone almost indefinitely without in any manner changing the current through the remainder of the system, or it allows us to decrease the current through the bridge network very considerably, without any sacrifice in the accuracy of locating the balance position on the bridge.

[1] Leeds & Northrup Co. *Catalog* 48, p. 29.

[2] THIS JOURNAL, 39, 235 (1917). The original references will be found here.

[3] Mentioned by Taylor and Acree, THIS JOURNAL, 38, 2406 (1916).

Reference to Fig. 1 will make plain the principle[1] upon which the amplifier works. V is an electron-tube generator or audion; it consists of an evacuated bulb containing (1) a heated filament F, which acts as a source of electrons; (2) a metal plate P; (3) a grid of fine wire G, placed between the plate and filament. When the filament is heated, it becomes a source of electrons; with their discharge it acquires a positive

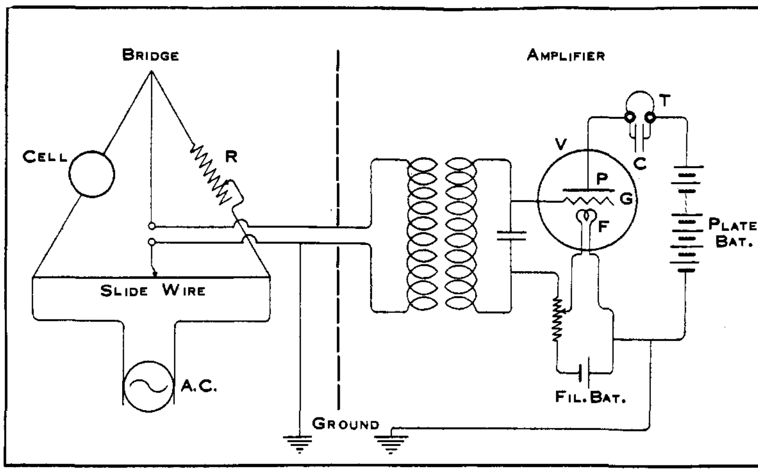

Fig. 1.—The Wheatstone bridge and the amplifier The amplifier is drawn on a considerably larger scale than the bridge.

charge. Finally this positive charge attains such a value that the electrons are attracted back at a rate equal to their rate of emission, and equilibrium ensues. If, however, the plate P is maintained at a positive potential relative to the filament F, as for instance by the plate battery shown in the figure, the electrons will move from F to P, and a direct current will flow in the plate battery circuit. The amount of this current depends upon the temperature of the filament, the voltage of the battery, and the characteristics of the grid. Fig. 2 illustrates the influence of the grid voltage on the plate current. If the potential of the grid has a sufficiently large negative or positive value, the electronic current is a minimum or maximum, respectively. For a large section of the curve on either side of zero potential, the plate current is a linear function of the impressed voltage. If now an alternating voltage is superimposed on the grid voltage, the current in the plate battery circuit is dependent upon whatever part of the curve we are working in. If the voltage of the grid corresponds to the point A, an increase in

[1] L. DeForest, *Electrician*, **73**, 842 (1914); *Elec. World*, **65**, 465 (1914); I. Langmuir, *Phys. Rev.*, [2] **2**, 450 (1913); *Gen. Elec. Rev.*, May, **1915**, 327–339; E. H. Armstrong, *Elec. World*, **64**, 1149 (1914); H. J. Van der Bijl, *Phys. Rev.*, [2] **12**, 171 (1918); M. Latour, *Electrician*, **78**, 280 (1916); Bur. Standards, *Circ.* **74**, 200 (1918).

negative potential will result in a diminution of current in the plate battery circuit, and a decrease in negative potential will result in a small augmentation of current, but the diminution and augmentation of current will not be equal. On the other hand, at zero potential of the grid, the same decrease and increase of voltage will produce corresponding equal changes in the values of the plate battery current. Oscillographs of the input and plate battery currents taken with the instrument working at this point of the curve, show them to be entirely in phase.[1] For amplification without distortion, then, the grid voltage must correspond to the linear section of the curve. In Fig. 1 it will be seen that the voltage of the grid is controlled by its connection to the negative terminal of the filament battery. Now as the high frequency current from the bridge induces periodic fluctuations of potential in G, the thermionic current between F and P changes simultaneously. Accordingly, the current in the plate battery circuit, and therefore in the telephone T, is periodically increased or decreased, the frequency remaining the same as in the primary current. "It is seen that the device functions broadly as a relay, in that variations in one circuit set up amplified variations in another circuit unilaterally coupled with the former."[2]

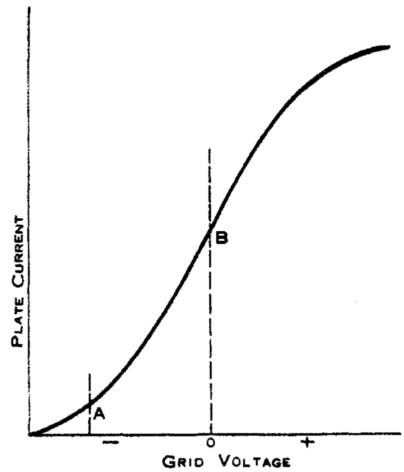

Fig. 2.—The relation of plate current to grid voltage in a 3-element vacuum tube. A characteristic curve.

The amplification which is desired determines the number of amplifier bulbs which shall be used. The instrument[3] which we are using (Fig. 3) is a two-step amplifier, manufactured by the Marconi Wireless Telegraph Company and used for wireless telephony in connection with airplane work. It consists of two audion bulbs,[4] connected in cascade, with the necessary transformers and condensers. As shown in Fig. 1, the leads which, in the ordinary conductivity apparatus, connect the telephone to the bridge, are now attached to the input terminals of the amplifier. The telephone may be connected so that either one bulb is used, or the full amplification of the two bulbs obtained. The plate voltage is maintained

[1] E. H. Armstrong, *Elec. World*, **64**, 1149 (1914).

[2] H. J. van der Bijl, *Loc. cit.*

[3] We are indebted to the Radio Laboratory of the Bureau of Standards for the loan of this instrument. It is now possible, with the end of the war, to purchase the instrument in the commercial market.

[4] V. T. 1 tubes, manufactured by the Western Electric Co.

by a battery of dry cells, and the filament current is furnished by a 6-volt storage battery.

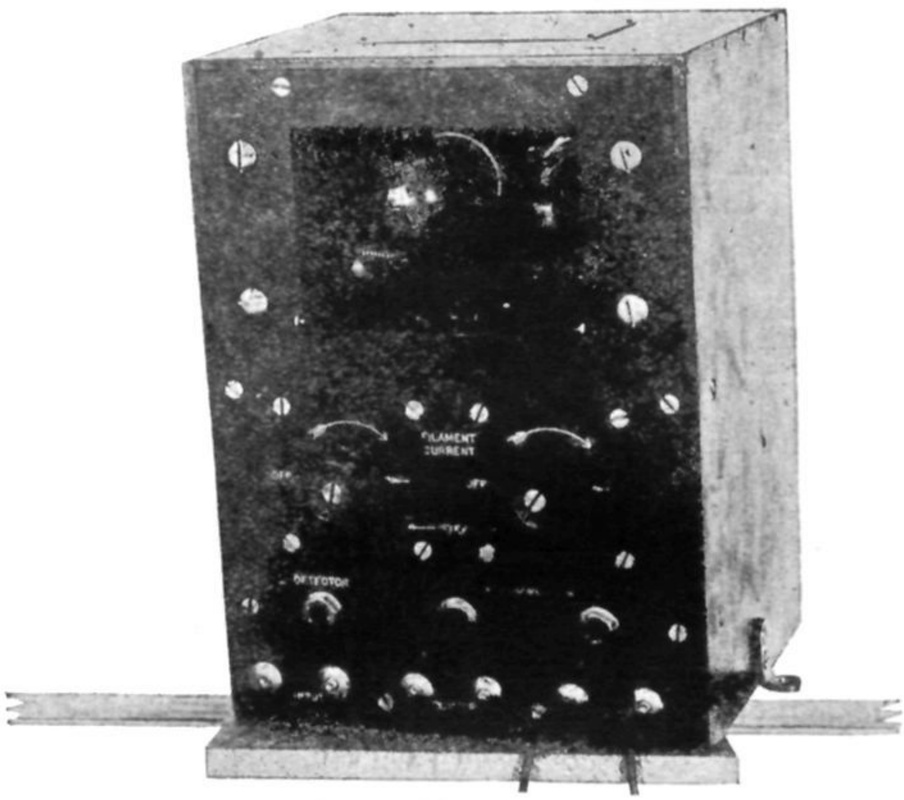

Fig. 3.—The amplifier.

The Gain in Sensitivity by the Introduction of the Amplifier.—The advantage to be gained in conductivity work through the use of the amplifier is shown by the series of measurements recorded in Table I. The current in the bridge circuit, measured by a vacuum thermocouple, was 0.4×10^{-3} ampere, except for one measurement with 0.2×10^{-3} ampere. Metallic, non-inductive resistances were used, and all measurements were made on the ordinary Leeds & Northrup circular slide-wire bridge, with the extension coils in. The figures in the second and third columns of the table represent the number of full divisions on the bridge wire between the points at which the minimum audibility current passes through the telephone; 0.05 division is the smallest unit which can be interpolated. The telephone, a Western Electric instrument, Type CW834, has a direct-current resistance of 2270 ohms. A qualitative determination of the resonance frequency[1] showed it to lie between 900 and 1100 cycles per second. At a frequency of 900 cycles, its effective resistance,[2] as measured in a Rayleigh bridge, is 7500 ohms, and its reactance is 16600 ohms. The telephone was connected to the amplifier so that the amplification from both tubes was obtained.

[1] A. E. Kennelly and H. A. Affel, *Proc. Am. Acad.*, **51**, 421 (1915).

[2] We are indebted to Dr. F. B. Silsbee, of the Bureau of Standards, for making this measurement for us.

TABLE I.

Improvement in audibility obtainable using an amplifier and a 2270 ohm telephone. Frequency: 1000 cycles. Plate battery voltage: 35. Current in bridge circuit: (I) 0.4×10^{-3} ampere. (II) 0.17×10^{-3} ampere.

	Resistance in arms of bridge R. Ohms.	Region of silence on bridge wire in scale divisions.		$I_T \times 10^9$ amperes.	
		Without amplifier.	With amplifier.	Without amplifier.	With amplifier.
	1000	3	0.05	0.85	0.014
	9500	5	0.05	1.43	0.014
I......	30000	6	0.05	1.28	0.011
	60000	10	0.40	1.46	0.058
II.....	30000	24	0.40	2.18	0.036
			Average,	1.44	0.027

The audibility current of a telephone according to Washburn[1] is given by the equation

$$I_T = \frac{\Delta R_B R I}{\left(\frac{R_B}{2} + R\right)\left(\frac{R_B}{4} + \frac{R}{2} + R_T\right)} \tag{1}$$

in which I_T is the current through the telephone I, that in the circuit, ΔR_B is one-half of the resistance of the section of wire ("region of silence") given in the table, R_B the resistance of the slide wire, R the resistance in the arms of the bridge, and R_T the effective resistance of the telephone. The expression $\left(\frac{R_B}{4} + \frac{R}{2} + R_T\right)$ represents the resistance of the telephone circuit; no term appears for the reactance, as this has presumably been eliminated by the insertion in series with the telephone of the proper capacity. If, however, the circuit has not been tuned to resonance in this way, its impedance will be given by the expression $\sqrt{\left(\frac{R_B}{4} + \frac{R}{2} + R_T\right)^2 + (L\omega)^2}$, in which $L\omega$ represents the reactance of the telephone at the frequency at which R_T was measured; and our equation for I_T becomes

$$I_T = \frac{\Delta R_B R I}{\left(\frac{R_B}{2} + R\right)\sqrt{\left(\frac{R_B}{4} + \frac{R}{2} + R_T\right)^2 + (L\omega)^2}} \tag{2}$$

With a telephone of low resistance and inductance, the use of either equation will give practically identical values for I_T; but if the resistance and inductance are high, as in our telephone, and the circuit is not tuned to resonance, the latter equation should be used.

Equation 2 has been used in making the calculations for the table. The average value of I_T, when no amplifier was used, is seen to be 1.44×10^{-9}; with the amplifier, it becomes 0.027×10^{-9}, *i. e.*, the telephone

[1] THIS JOURNAL, **38,** 2431 (1916); **39,** 235 (1917).

becomes apparently 50 times as sensitive. Of course, in the latter case, I_T does not represent the real current through the telephone, but is a measure of the effective sensitivity of telephone and amplifier combined. In other words, a current no greater than 0.027×10^{-9} ampere would produce an audible tone in a telephone whose sensitivity was equal to that of telephone and amplifier combined. It is readily seen that the introduction of the amplifier permits the current through the bridge to be reduced to $^1/_{50}$ of the value necessary when no amplifier is used, with no loss in accuracy in determining the null setting; or a reduction of the current to perhaps $^1/_{10}$ of its value, while still retaining the sensitivity of the telephone at several times the value it had without the amplifier.

It will be noted that the telephone used in these tests was a high resistance instrument. This should be the case for use with the amplifier, as it develops the greatest power when working into a resistance of several thousand ohms. However, tests were made on several other telephones of varying resistance, the results of which are shown in Table II. It will be seen that in every case, with constant current, the use of the amplifier has greatly diminished the region of silence on the bridge wire. If I_T is calculated as in the preceding table,[1] every telephone

TABLE II.

Comparison of several telephones with and without the amplifier.

Frequency: 1000 cycles. Plate battery voltage: 35. Current in bridge circuit: 0.33×10^{-3} amperes. $R = 10{,}000$.

Telephone.	Resistance of telephone.	Division of bridge wire for audibility current.		$I_T \times 10^9$.	
		Without amplifier.	With amplifier.	Without amplifier.	With amplifier.
1 Western electric CW834	2270	4.0	0.05	0.94	0.012
2 C. Brandes.................	1052	10.0	0.25	7.70	0.19
3 Unknown make............	154	35.0	0.4	31.60	0.35
4 Western electric tunable.....	106	100.0	1.0	91.00	0.91
5 Ordinary Bell..............	88	7.0	0.25	6.40	0.23
6 Unknown make............	63	60.0	0.5	55.00	0.46

tested with the amplifier shows an audibility current value of less than 1×10^{-9} amperes; in fact, very much less except in one instrument. The high resistance telephone of the Western Electric Co., developed especially for work in wireless telegraphy and telephony, is decidedly the most sensitive. On the whole, this type of test is quite unsatisfactory, but serves to determine the relative sensitivity of the telephones. The measurements show that with the insertion of the

[1] With this difference, that with the exception of No. 1, which was calculated by Equation 2, the direct current resistance was used for R_T, and the reactances were not taken into consideration. This will affect the results but little except in No. 2, in which the audibility current would be smaller, undoubtedly, if the impedance were used.

amplifier, even a relatively poor telephone becomes more sensitive than the very best telephone without it.

With the introduction into the circuit of an instrument as sensitive to all electro-magnetic disturbances in the vicinity as the amplifier is, naturally much care must be taken. If there are any appreciable inductive effects nearby, caused, for example, by electric furnaces fed by alternating current, a tone will be heard in the telephone whose pitch corresponds to the number of cycles of the a. c. supply, or the harmonics of this. The click of the relay attached to the thermostat, and any sparking in the generator of the high frequency current, will be heard. The latter, of course, would be eliminated entirely if the Vreeland oscillator were used as a source of current. However, using a Holtzer-Cabot generator, we have had but little trouble from the accidental sounds arising from this source. A good ground connection both to the bridge and to the amplifier is necessary, and the various cables leading to the bridge should be armored and this armor grounded. Our bridge, on account of the shop and power plant noises nearby, had been placed in a telephone booth. When the amplifier was placed in the booth, its proximity to the other parts of the bridge and to the operator was such that the null setting obtained could not be depended upon to give the true resistance. When it was placed outside the booth, and shielded,[1] this difficulty disappeared entirely, so that measurements of metallic resistances made with direct and alternating current have checked repeatedly to 1 part in 50 to 80 thousand. A condenser in parallel with the telephone is advantageous in damping out any harmonics. It is necessary further to adjust very carefully by the usual air condenser the capacity in the arm containing the Curtis coils, especially in the case of saturated solutions in small cells such as we are using. By proper adjustment of this capacity, however, and that in the telephone circuit, a minimum is obtained which is entirely devoid of either the higher notes or the fundamental.

The current[2] through the telephone, when used with an amplifier, consists (1) of the direct current maintained by the plate battery when no alternating voltage is applied to the grid; (2) of the alternating current which is present when such voltage is applied; (3) of a first harmonic; and (4) of a d. c. component due to the alternating input voltage. The only current of importance in amplification is the alternating output current, and this is a linear function of the voltage impressed upon the input circuit. The power amplification is independent of the input and the frequency. When the amplifier works into an impedance equal to

[1] Placing the amplifier in a grounded metal can proved to be a convenient and effective method of shielding.

[2] H. J. Van der Bijl, *Loc. cit.*

or greater than its own, the harmonic becomes negligibly small as compared to the main alternating current. The rapid increase in current through the telephone circuit as the sliding contact moves away from the null position on either side, and the consequent large increase in the sound from the telephone render the determination of the minimum setting very sharp, so that in work in which a minimum setting may be made readily with the ordinary arrangement, the introduction of the amplifier is a source of much satisfaction, owing to the very rapid decrease of sound to entire silence as the sliding contact passes over the balance point.

Our work necessitates measuring resistances of saturated solutions in a cell whose maximum external diameter is 13 mm., and whose electrodes may be separated by no more than 55 mm. Further, the restricted portion of the cell must be of large enough diameter to allow free circulation of the solution. If we allow 5 mm. for the diameter of this portion of the cell, the resistance for a saturated sodium chloride solution is about 100 ohms. The measurements should not differ among themselves by more than 0.003%. The small size of the electrodes necessitates considerable care to eliminate the effects of polarization. The possibility therefore, of greatly reducing the current, without decreasing the accuracy of determining the position of silence on the bridge wire, has been of great value to us. We are working, too, in a room in which the installation of a telephone booth has not sufficed entirely to remove distracting sounds. But the introduction of the amplifier has made the determination of the minimum an easy matter even under these adverse conditions.

The Electron Tube as a Source of Alternating Current.—By means of an arrangement[1] such as that shown in Fig. 4, the electron tube becomes a generator of high frequency current. The frequency is controlled by the condensers C and C′, one of which is of small capacity, and continuously variable over its range; the other, variable in steps of perhaps 0.005 microfarad. A generator of this gen-

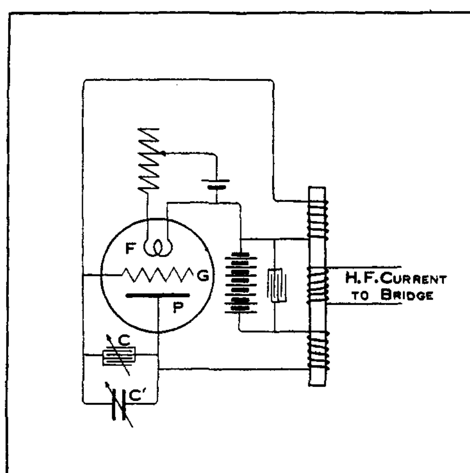

Fig. 4.—The electron tube as a generator of alternating current.

[1] This arrangement was brought to our attention by Dr. J. M. Miller, of the Radio Laboratory, Bureau of Standards.

eral type may be made to yield a current of from a few tenths of a milliampere or less to 25 amperes, and with a frequency varying from $^1/_2$ cycle per second to 50 million cycles per second.[1]

As a current generator for the preceding measurements, we used as oscillator a V.T. 1 tube, of the same type as used in the amplifier. The plate voltage was maintained by a 56-volt storage battery; the current for the filament was taken from the same source. The transformer was one which we happened to have; the resistance of the primary coils was 205 ohms, their inductance 25 henrys; the resistance of the secondary coils was 0.76 ohm, the inductance 0.064 henry. While the limits of frequency were not determined, a variation from a very few cycles per second to the limit of the ear for detection, was readily obtained by varying the capacities C and C′. For work at 1000 cycles, C and C′ could be omitted entirely, merely varying the current through the filament giving a sufficient range of frequency.

Table III contains data showing the current at a frequency of 1000 cycles in the external circuit when its total resistance was varied from 19000 to 550 ohms. The available power, although only a small fraction of a watt, would often prove sufficient for conductivity work. Of course, much more power could be obtained with a larger tube or higher plate voltage.

Table III.

Current obtainable from a V. T. 1 tube acting as generator, with varying external resistance.

Plate voltage: 56. C and C′: Set at 0.

Transformer:	Resistance ohms.	Inductance henrys.
Primary	204.8	25.4
Secondary	0.76	0.064

Total external resistance.	Vacuum thermocouple: microvolts.	Current milliamperes.	Power watts.
19200	41	0.33	0.0021
14200	72	0.44	0.0027
9200	154	0.64	0.0038
4850	547	1.26	0.0077
2700	1630	2.2	0.0131
1600	3110	3.1	0.0154
1000	5200	4.2	0.0176
800	6230	4.7	0.0177
700	6820	4.9	0.0168
600	7670	5.4	0.0175
550	8210	5.6	0.0173

The use of an electron tube as a source of alternating current in resistance measurements makes available a generator at once cheap and providing a wide range of frequency. Its main disadvantage lies in the fact that a first harmonic is present, which is particularly noticeable at

[1] W. C. White, *Gen. Elec. Rev.*, **1916**, 771 (September); **1917**, 635 (August).

low frequencies; at 1000 cycles or more, it is not noticeable enough to be troublesome.

Conductivity Measurements at Extreme Frequencies.—One other point of value in the application of the amplifier to conductivity measurements may be mentioned here. In wireless work, in which undamped oscillations of high frequency are used, the pitch of the resulting notes may be too high to be audible but the signals can be made audible in a telephone by beats. For instance, if two sources of oscillations, one of a frequency of 100,000 and the other of 101,000, act together on the same circuit, the note heard in the telephone will be that due to 1000 pulses per second. In wireless the one source of oscillations is the antenna, receiving them from the sending station; the other source is the electron tube itself, so adjusted to act as an oscillator. In this way, the tube acts simultaneously as a local source of oscillations, and as a receiver and amplifier of oscillations from the sending station. This is called the autodyne method. If, then, it would be advantageous for any reason to use higher frequencies than 5 or 10 thousand cycles in making conductance measurements, by an application of this method, the telephone could still be used for determining the point of balance in the bridge. We are planning to investigate this use of the audion tube.

Summary.

1. The use of an amplifier in conjunction with the telephone in the measurement of the resistance of solutions makes much simpler the determination of the balance position of the bridge. Any ordinary telephone becomes a more sensitive instrument with the amplifier than the best telephones without it. When a sensitive telephone is used, the current through the bridge may be reduced to a tenth of the value necessary without the amplifier, and the instrument still will have several times the sensitivity it has without the amplifier.

2. An electron tube may be used as a source of alternating current for conductance measurements. Its advantages are its cheapness and the wide range of frequencies which may be obtained with it. A first harmonic is present in the current, which is noticeable at low frequencies, but which is not troublesome at a frequency of 1000 cycles or more.

3. If, for any reason, it should be desired to use frequencies in conductance measurements beyond the limit of the human ear, a telephone could still be employed to indicate the bridge balance by the use of the autodyne method.

WASHINGTON, D. C.