CALIBRATION OF AMMETERS AT RADIO FREQUENCIES.

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The phenomenal development within the last few years of appliances utilizing electric current at radio frequencies has rendered the problem of measurement of current and resistance at these high frequencies of great importance. The progress in methods of radio communication especially has given marked impetus to such a study. The measurement of resistance and of current can not easily be separated and since the two are mutually bound together, the calibration of an ammeter for particular frequencies is an important item.

While marked achievement has characterized the field of radio investigation in general, the method of calibrating ammeters for radio work has remained rather crude and inaccurate. The aim of the investigation which this paper describes has been to accurately calibrate ammeters over a wide range of radio frequencies, and, if possible, to devise a new scheme for such calibration. In the following discussion and data calibration curves have been worked out for commercial ammeters at frequencies of 1,000,000 (300 meters wave length), 10,000,000 (30 meters) and 60,000,000 (5 meters) cycles. More important than this is the application of a device involving basic principles of electron emission to the calibration of ammeters, and the successful checking of data worked out by the new method with the calibration curves obtained by the old method.

Theoretical Considerations.

Skin Effect. The ohmic resistance of a given conductor is a minimum for uniform cross-sectional distribution of current. In the case of alternating currents, particularly those of high frequency, not only is the impedance in general greater than the ohmic resistance, but the ohmic resistance itself is greater than in the case of direct currents. This is due to the non-uniform distribution of current over the cross-section, or the "skin effect". We may regard the situation in two ways:

(1) The inequality of current distribution may be accounted for on the basis of differences in inductance over the cross-section of a conductor. The counter electromotive force arising from self inductance is greater at the axis or central portions of a wire than at the outer portions. The value of the current will, on this account, reach a maximum in the outer portions before the maximum is reached near the axis. Now if the direction of current be reversed rapidly, the current may not have the time between reversals to reach a maximum in the

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central portions of the conductor. As a result the current density is greater near the surface.

(2) On the basis of the ether strain theory we may consider the current in a conductor established not by a process analogous to the push of a piston in a water pipe, but by an absorption of energy all along its surface from the surrounding dielectric. If the current be reversed in direction at a high frequency, energy may not have time to "soak in" to a very great depth.

Maxwell, Heaviside, and Lord Rayleigh have developed the principles of behavior of variable currents. The following factors must be considered, according to their development, in determining the nature of high frequency currents in a circuit:[1]

(1) Resistance of the circuit.
(2) Inductance of the circuit (considering the geometric form, the material and the nature of the surrounding insulator).
(3) Capacity of the circuit (considering geometric form and the dielectric constant of the medium).
(4) Dielectric conductance.
(5) Energy dissipation due to causes other than conductance (such as dielectric hysteresis).

Lord Rayleigh has shown[2] that if R is the true ohmic resistance (for steady currents) of a cylindrical straight wire of length l and magnetic permeability μ, that the resistance is increased to R′ for a simple harmonic alternating current of frequency η, where R′ is given by:

$$R' = R\left\{1 + \frac{1}{12}\frac{p^2 l^2 \mu^2}{R^2} - \frac{1}{180}\frac{p^4 l^4 \mu^4}{R^4} + \ldots\ldots\right\}$$

This formula shows that the effective resistance is increased as the frequency increases from zero to infinity. If the frequency is very low, the chief opposition to the current is ohmic resistance and the distribution of current over the cross-section will be uniform so as to make the opposition a minimum. If the frequency is very large, the chief opposition to current is inductance rather than ohmic resistance, and hence the distribution of current over the cross-section will be such as to make the inductance a minimum. This, of course, results in concentration of the current in outer layers of the conductor.

Computation of Resistance at Radio Frequencies. Lord Rayleigh's formula for the resistance of a straight cylindrical wire of non-magnetic material has been transformed by Fleming[3] into the expression:

$$R' = R\left\{1 + \frac{K^2}{48} - \frac{K^4}{2880} + \frac{K^6}{58647}\right\} \text{ where } K = \frac{\eta\pi^2 d^2}{\rho}$$

which is applicable if K is less than one. (η is frequency, d is diameter in centimeters and ρ is the direct current resistivity in C. G. S. units). If η and d are such as to make K greater than one, and especially if it becomes as much

[1] J. A. Fleming: "The Principles of Electric Wave Telegraphy."

[2] "On Self Induction and Resistance of Straight Conductors" (Phil. Magazine, May 1886, p. 382).

[3] J. A. Fleming: "Elementary Manual of Radiotelegraphy and Telephony" and "The Wireless Telegraphist's Pocket Book."

as five or six, Lord Rayleigh's formula[4] has to be modified. A. Russell's modification is:

$$R' = R\left\{\frac{\sqrt{K}}{2} + \frac{1}{4} + \frac{3}{32\sqrt{K}} - \frac{1}{16k\sqrt{K}}\right\}$$

which may generally be abbreviated into simply $R' = R\left\{\frac{\sqrt{K}}{2} + \frac{1}{4}\right\}$

From the above formulae one can compute the maximum diameter a wire could have in order that its high frequency and direct current resistance may be practically the same for any given frequency. Setting R′ equal to R in Russell's formula,

$$\frac{\sqrt{K}}{2} + \frac{1}{4} = 1, \text{ whence } \sqrt{k} = 1.5. \quad \text{That is } \sqrt{\frac{\eta\,\pi^2\,d^2}{\rho}} = 1.5.$$

If we solve the last equation above for d, we have:

$$d = .4774\sqrt{\frac{\rho}{\eta}}.$$

In Circular 74 of the Bureau of Standards the maximum diameters of wires which have a ratio of $\frac{R'}{R} = 1$ (to within one per cent) have been worked out for certain frequencies and materials. Some of these values, and extensions[5] computed from them are given below.

Material	Frequency	Diameter (cm)
Copper	1,000,000	.0112
	10,000,000	.00354
Platinum	1,000,000	.0354
	10,000,000	.0112
Manganin	1,000,000	.0564
	10,000,000	.0178
German Silver	1,000,000	.0614
	10,000,000	.0195
Tungsten	1,000,000	.026
	10,000,000	.0082

[4] Wein and Sommerfeld have deduced an expression for the ratio of high frequency resistance, R″, of a spiral of one layer of circularly cross-sectioned wire to R, the direct current resistance as: $\frac{R''}{R} = 2\sqrt{\pi}\,\frac{1}{2}\sqrt{K}.$

E. H. Barton (Proc. Phy. Soc. London, 1889 Vol. 16) has built up a series for the resistance in the case of damped oscillations.

[5] Diameters at η equals 10,000,000 are found by dividing the value at η equals 1,000,000 by $\sqrt{10}$. The value for tungsten is found by multiplying the value for platinum by:

$$\sqrt{\frac{\rho \text{ for tungsten}}{\rho \text{ for platinum}}}$$

Measurement of Current at Radio Frequency. It is pointed out in Circular 74 of the Bureau of Standards that the measurement of current is a cardinal operation in high frequency work (even to a much greater degree than at low frequency) since it is involved in measurement of resistance as well as in most of the measurements of other quantities. An ammeter for use at radio frequencies must, first of all, meet the requirement of simplicity. A large inductance or a large capacity would tend to make the current flow through the dielectric as well as through the conductor, in an amount varying with the frequency. In the case of a hot wire ammeter the deflection of the instrument depends upon the heating effect, which, in turn is proportional to $I^2 R$. Consequently if a deflection is always to correspond to the same current, it is necessary that R should not change with frequency. The permissible diameter of the wire at any frequency is then limited as indicated in the discussion above.

It is obvious that shunts can not be safely used in the construction of ammeters for use at radio frequencies, for the mutual inductance between the parallel branches will change the distribution of currents so that the effective resistance in the circuit will depend upon the frequency. This may be true even though the separate components in the shunted arrangement be made so small that each one's resistance, if used individually, is constant over the range of frequencies used. Indeed the writer has found that the ordinary law of shunt circuits does not hold at radio frequencies, but that it is possible to place two wires in parallel with the result that the effective resistance of the combination is greater than the resistance of one of them. One is confronted, in part, by the following array of very troublesome sources of error in radio frequency ammeters:

(1) There is erratic shifting of the zero reading.

(2) Electro-static coupling and charges on the dial and case of the instrument introduce errors.

(3) Within the range of radio frequencies commonly used there occur changes in current distribution with consequent changes of resistance.

(4) Leakage from the main circuit through the indicating device on the ammeter, and through the distributed capacity of the case, etc., may cause an error which is more or less problematic. Leakage in such instruments as the self-heated thermoelement type should be considerable, according to theory, and should cause an error in a direction opposite to that caused by increase of ohmic resistance.[6]

Perhaps the most annoying source of error, and one which it seems impossible to eliminate in the ordinary hot wire instrument is the zero shifting. In Circular 74 of the Bureau of Standards (p. 149) a rather elaborate method is given for the correction of a zero error. Such a procedure requires considerable time and is scarcely practicable for commercial work. It is certain, however, (see table I, p. 153) that unless

[6] Some experimental evidence in regard to the effect of capacity across the instrument terminals indicates that parallel resonance at particular frequencies may be the most important factor.

special precautions are taken, the zero shift will cause well constructed ammeters to vary among themselves and each one to vary with different trials by as much as ten per cent at one frequency.

CALIBRATION OF AMMETERS.

Calorimeter Method. The calorimeter arrangement employed by Fleming in measuring high frequency resistance can be used also in the calibration of ammeters. The apparatus involves only fundamental relationships, but is slow in action, and not extremely accurate, even at the best. The device as used in the investigation described in this paper consisted of two large glass tubes (4.3 cm. in diameter and 23 cm. long) sealed air tight with rubber stoppers at the ends and connected with a water manometer as shown in figure 1. It was found from experiment

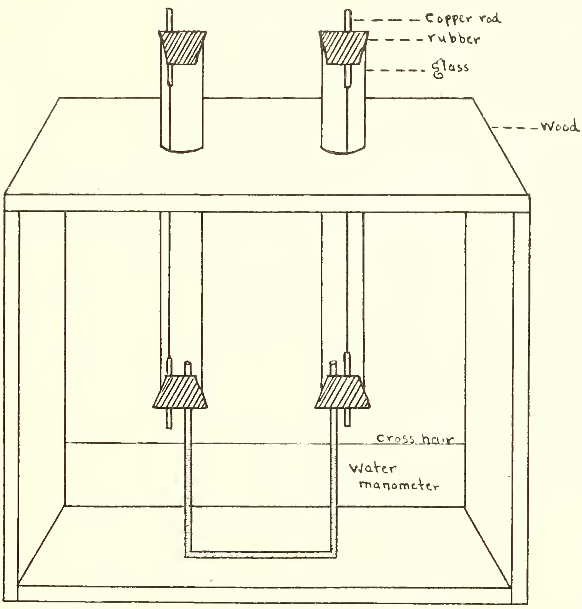

Fig. 1. Device used in the investigation for the calibration of ammeters.

that the volume of each tube should be very large in comparison with the volume of the manometer tube. Two resistance wires, R_1, and R_2 as nearly alike as possible are soldered at the ends to short pieces of heavy copper wire, and one resistance is placed in each tube with the heavy copper wires protruding at the ends for making electrical connection.

If an unknown high frequency current, i, be sent through R_2,[7] and the manometer balanced by direct current I_1, sent through R_1, then

[7] The two resistances in this particular apparatus were platium wires 16 cm long and of .00762 cm diameter. As may be seen from the table on page 147, this wire is small enough that its resistance at a frequency of 10,000,000 is within one per cent of its resistance for direct current.

(1) $I_1^2 R_1 = k\iota^2 R_2$, where K is some constant depending on the relative volumes and heat capacities of the two sides of the apparatus. Similarly if ι without change in magnitude be sent through R_1, and the balance restored with direct current I_2, through R_2,

(2) $\iota^2 R_1 = kI_2^2 R_2$ (if the wires have the same resistance for high frequency and direct current). Dividing equation (1) by equation (2) and solving for ι, $\iota = \sqrt{I_1 I_2}$,

The apparatus was carefully tested for leaks both before and after measurements were made. In addition two tests were made to determine the accuracy of the device by sending known direct currents through both resistance wires. With a current of .3 ampere, a change of current of .05 ampere changed the difference of levels in the manometer by 2 centimeters. By means of the cross hair one could easily read the levels to less than .5 millimeter, hence a change of current of .001 ampere could easily be detected. Of course the radio frequency current measured was, in general, not constant by any means, so the actual accuracy attained in practice was considerably less than .001 ampere at .3 ampere. The test with known direct currents indicated an average percentage of error of 1.25 over the scale range of .2 ampere to .4 ampere. This represents the inevitable percentage of error involved in the calibration apparatus. Any errors in an ammeter reading larger than one or two per cent, however, must be attributed to defects in the instrument under test at the particular frequency used.

The oscillator used for production of current at frequencies as high as 10,000,000 was of the Hartley shunt type shown in part A of figure 2. The heat apparatus and ammeters to be calibrated were connected in the tuned coupled circuit shown in part B figure 2.

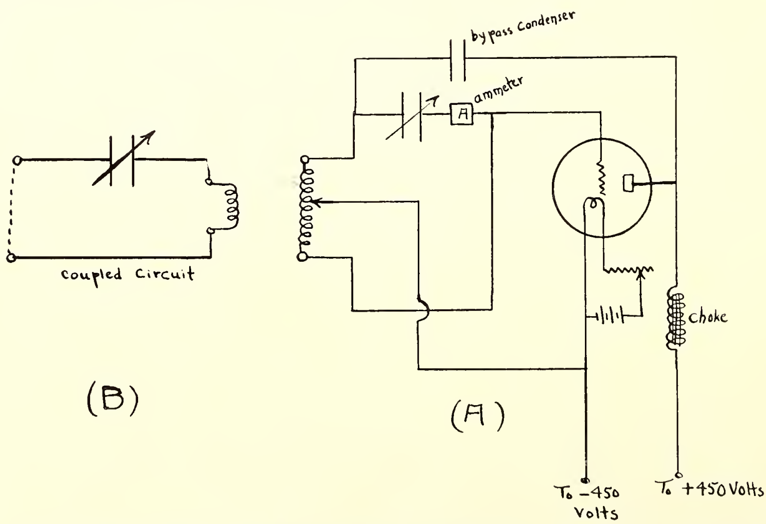

Fig. 2. The oscillator used for production of current is shown in A. The heat apparatus and ammeters to be calibrated were connected in the tuned circuit shown in B.

Calibration curves have been worked out at 1,000,000 and at 10,000,000 cycles for each of the following radio frequency ammeters:

Jewell (1 ampere, metal case) pattern 64; Jewell (.5 ampere) pattern 64; Weston (1.5 ampere) model 425; and Westinghouse (1 ampere) type PX-2.

Curves have also been worked out for Weston (100 milliamperes) model 425 at frequencies of 10,000,000 and 60,000,000. Some comparisons of the behavior of ammeters with metal and with bakelite cases (two Jewells model 425 and others listed above) have also been made. The instruments could be read accurately as follows: Jewell (1 ampere) at .3 ampere to within .01 ampere. Jewell (.5 ampere) at .3 ampere to within .005 ampere, Westinghouse (1 ampere) at .3 ampere to within .01 ampere and Weston (100 milliamperes) at 50 milliamperes to within 1 milliampere.

DATA AND RESULTS.

In order to determine how one radio frequency ammeter varied with successive readings at a particular frequency, and how different ammeters varied among themselves with successive readings at the same frequency, three ammeters (Weston, Jewell (1 amp) and Westinghouse) were connected in series and three sets of readings were made. After varying the current as indicated by the Weston instrument through the range of three-tenths ampere to one ampere and recording the corresponding readings of the other two instruments, the operation was repeated twice keeping the Weston readings constant and recording again corresponding readings (trials 2 and 3) of the other two ammeters. It may be seen from the data in table I and the curves in figure 3 that both the Jewell and Westinghouse ammeters varied individually and also with each other by as much as ten per cent. This in no way indicates a superiority in the Weston instrument, for on keeping either the Jewell or Westinghouse reading constant, the Weston ammeter was also found to vary individually with successive trials. It should be noted that the calibration curves are somewhat convergent toward the upper end of the scale.

TABLE I. Comparison of Ammeters in Series at 1,000,000 Cycles

Weston	Jewell (1 amp.)			Westinghouse		
	Trial 1	Trial 2	Trial 3	Trial 1	Trial 2	Trial 3
.3	.295	.27	.26	.33	.3	.3
.4	.39	.365	.375	.44	.41	.415
.5	.49	.465	.48	.54	.51	.52
.6	.6	.585	.58	.65	.635	.63
.7	.69	.68	.68	.74	.725	.725
.8	.78	.78	.78	.82	.82	.82
.9	.875	.875	....	.91	.91	....
1.0	.985	.985	....	1.0	1.0	....

The next few pages summarize data taken with several commercial ammeters by means of the heat method of calibration described on page 149. Several sets of readings were taken at each frequency used in the research work for purposes of checking on each ammeter, but only representative curves are described in this paper. In general the different ammeters behaved similarly so that the data on one ammeter

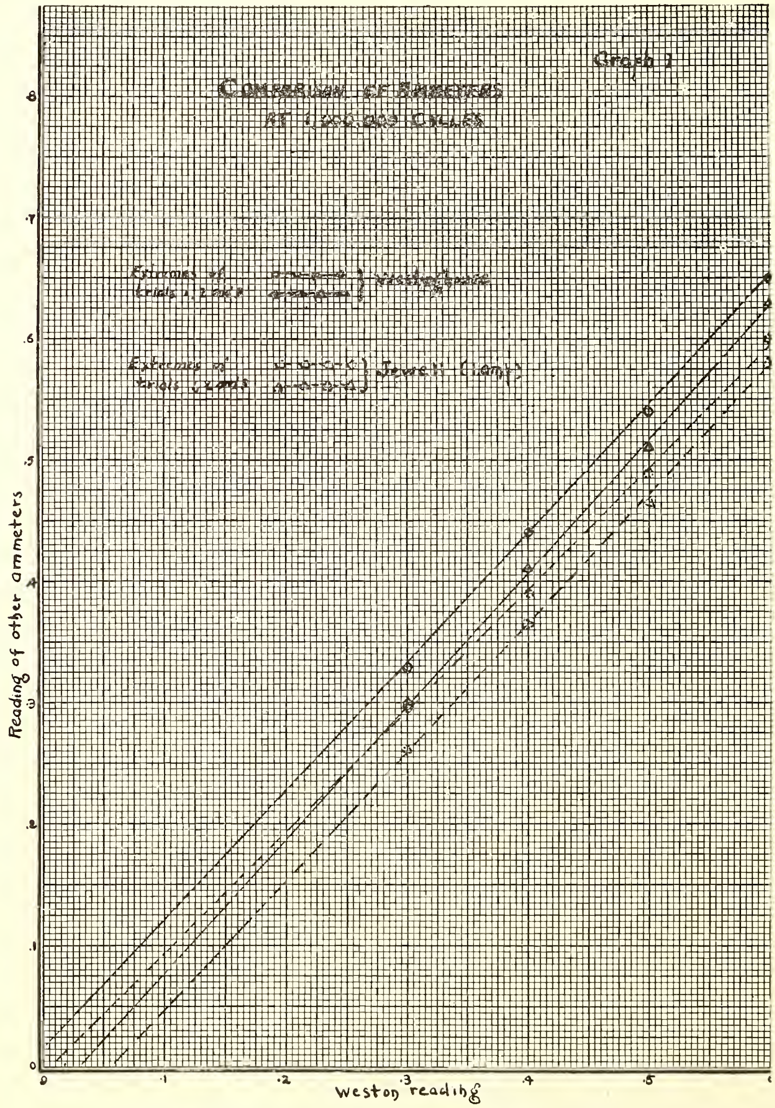

Fig. 3. Comparison of ammeters at 1,000,000 cycles.

approximately characterized the action of the others. It might be mentioned that the Jewell (.5 ampere ammeter) approached more closely to the line of zero error at all frequencies than any other instrument used. The behavior of the Westinghouse ammeter is indicated in the data of tables II and III and in figure 4.

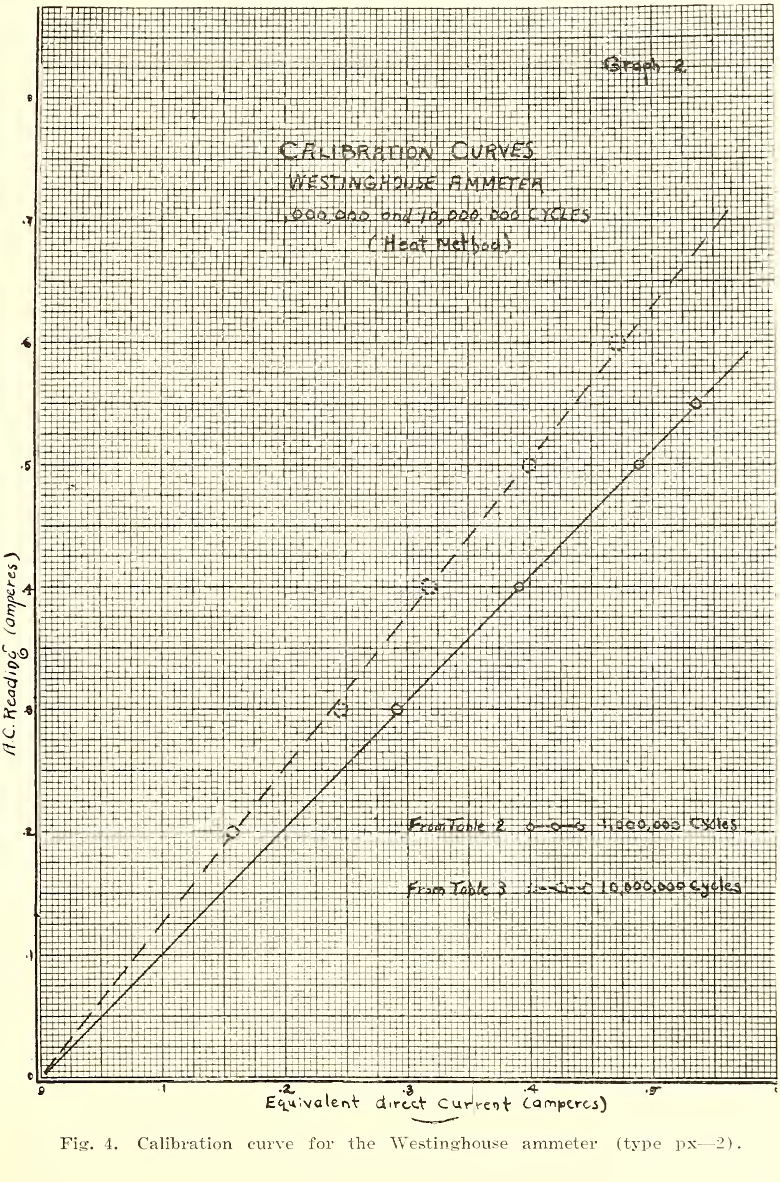

Fig. 4. Calibration curve for the Westinghouse ammeter (type px—2).

It would be expected that if the skin effect predominated in an ammeter, its reading should be too high. If one should plot its reading along the y axis and the equivalent direct current along the x axis, the resulting calibration curve would then lie above the line of zero error. Figure 4 indicates just this situation in the Westinghouse instrument. The calibration curve lies above the line of zero error and is steeper than the line of zero error. With this particular ammeter the skin effect is pronounced at a frequency of 10,000,000 cycles per second. For instance when the reading was six-tenths ampere at this frequency the actual current through the instrument was only .472 ampere which indicates an error of 27 per cent. If the skin effect is neutralized by factors which tend to make an ammeter reading too low on high frequency current, such as leakage through capacity shunts in the case and movement, then the calibration curve may fall below the line of zero error. With an increase of frequency the slope of the calibration curves of most of the ammeters was increased. Even though the reading of an instrument was low at 10,000,000 cycles, it was in general higher than at a frequency of 1,000,000 cycles. The results for all ammeters used are summarized in table IV.

TABLES II and III. Calibration of Westinghouse Ammeter

1,000,000 CYCLES (Heat Method) 10,000,000 CYCLES

Experimental			Computed	Experimental			Computed
A. C.	D.C. I_1	D.C. I_2	A. C.	A. C.	D.C. I_1	D.C. I_1	A. C^2
.3	.255	.34	.294	.2	.227	.11	.158
.4	.355	.435	.393	.3	.287	.21	.245
.5	.455	.53	.49	.4	.36	.28	.317
.55	.5	.57	.534	.5	.423	.38	.401
				.6	.485	.46	.472

TABLE IV. Summary of Ammeter Calibration

Instrument	Reading at 1,000,000	Reading at 10,000,000	Reading at 60,000,000
Westinghouse	Slightly high	Very high	
Jewell (1 amp)	Considerably low	Slightly low	
Jewell (.5 amp.)	No appreciable error	No appreciable error	
Weston (1.5 amp.)	Slightly low	Slightly low	
Weston (Milliammeter)		High on lower end of scale Low on upper end of scale	Considerably low

II. A NEW METHOD FOR CALIBRATING AMMETERS AT RADIO FREQUENCIES.

The calorimeter method is crude and inaccurate at the best. The following discussion concerns a new method, which, over a limited range is much more sensitive and at the same time much better adapted to rapid work. The device involves only the fundamental physics of electron emission and the action of a thermionic vacuum tube. In fact, an ammeter may be dispensed with and the calibration instruments described below used directly to measure radio frequency current.

Theoretical Considerations.

If direct current is sent through the filament of a vacuum tube, on closing the circuit the temperature of the filament begins to rise at a rate controlled by the net gain of calories per second and the material and dimensions of the filament. That is, the rate of increase of temperature is proportional to calories received minus calories lost, the quantity divided by the heat capacity of the filament. Now the number of calories received per second is proportional to I^2R, and since R changes with temperature the rate of heat production varies. At first, when the filament is cold, R is small and so the heat production will be relatively large. Also the rate of loss of calories will be small because the temperature of the filament is low. These factors combine to produce a large initial rate of temperature change. As the temperature increases R increases and I decreases, so that I^2R decreases. At the same time the rate of loss of calories will increase with rise of temperature with the consequence that rate of increase of temperature decreases. Now radiation is the chief source of loss of heat in a vacuum tube, and the rate of radiation, being proportional to a high power of the temperature, increases very rapidly. At some instant the calories lost will equal the calories received and the temperature will cease to change. If we should plot temperature against time we should have such a curve as shown in figure 5.

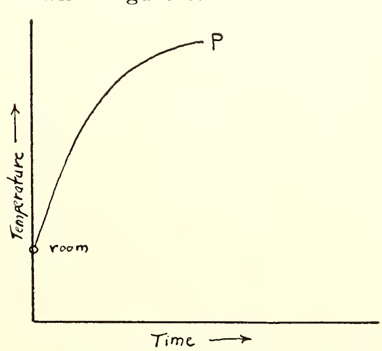

Fig. 5. Curve obtained, plotting temperature against time.

The exact curve would, of course, depend upon the current, heat capacity of the filament, etc. If when the temperature has reached the point P, the current is stopped, cooling will follow a symmetrical curve, (dotted) as shown in figure 6 because the same factors control the rate of decrease of temperature as well as the rate of increase. If we should intermittently open and close the circuit through the filament, the temperature would increase on the solid curve, and decrease on the dotted curve.

Between room temperature and A, the intersection of the curves, the rate of increase is greater than the rate decrease, but from A upward the rate of decrease is greater than the rate of increase. Hence A will be the mean value about which the temperature will vary for intermittent current. If the period of interruption of the filament current is small compared to the time required to reach the steady temperature when the uninterrupted current is turned on, the value of the temperature will not vary much on either side of A.

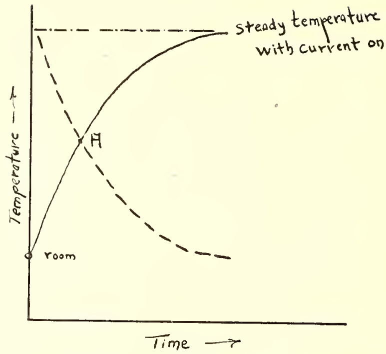

Fig. 6. Cooling follows a symmetrical curve (dotted) when current is stopped after the temperature has reached the point P.

Now if a simple harmonic alternating current be used instead of an intermittent direct current, the curves would be modified somewhat. Starting with a small current the temperature would rise more slowly than in the case of direct current. The curve would appear as in figure 7, which resembles a typical filament temperature-plate current characteristic curve for a vacuum tube. Again the temperature will have a mean value at A, the intersection of the curves, and if the period of the high frequency current is very short compared with the time required to raise the temperature from room value to its maximum value, B, then the value of the temperature will not vary much from A. From these considerations it seems safe to assume that with frequencies of several thousands the temperature of a vacuum tube filament due to an alternating current will be the same as the temperature of the filament produced by an equivalent direct current. With low frequencies the validity of the assumption would hold only for the mean value of the temperature.

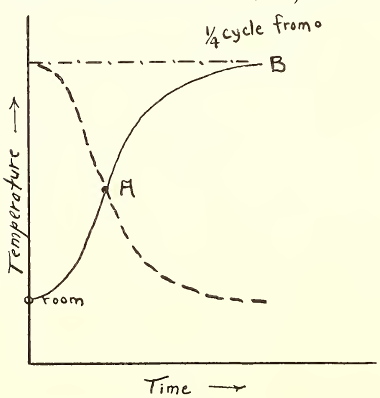

Fig. 7. Modification of curves if a simple harmonic alternating current is used instead of an intermittent direct current.

If the filament of a two electrode themionic vacuum tube be small enough that its resistance for direct current or 60 cycle alternating current is equal to its resistance for current at a given radio frequency, the latter current should produce the same average filament temperature that is produced by the equivalent direct current. As has been pointed out, the temperature will not even fluctuate about the mean value to any appreciable extent if the frequency of the alternating current is very high. Now the rate of electron emission of a hot filament

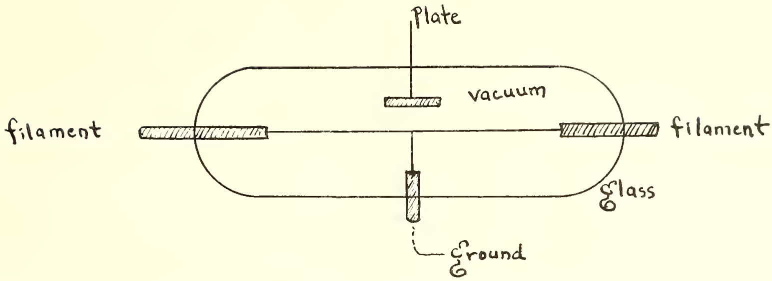

Fig. 8. Construction of tube used in experiments.

is a function of the temperature. Hence a radio frequency current through the filament which produces a given plate current is equal to the direct current which, if sent through the filament, will produce the same plate current, provided the potential gradient from filament to plate is the same in the two cases. In order to meet this condition the filament may be made non-inductive, the filament plate capacity may be made practically zero, and 60 cycle alternating current substituted for direct current. The reason for using 60 cycle current instead of direct current, is that with one leg of the filament grounded in the case of direct current it is either the positive or negative leg always, a situation which would not be duplicated with alternating current. A tube constructed as indicated in figure 8 would meet the requirements. The mid point of the filament may, if desired, be grounded as shown by the dotted line.

Since it is only necessary to get a measurable plate current, the plate may be made very small.

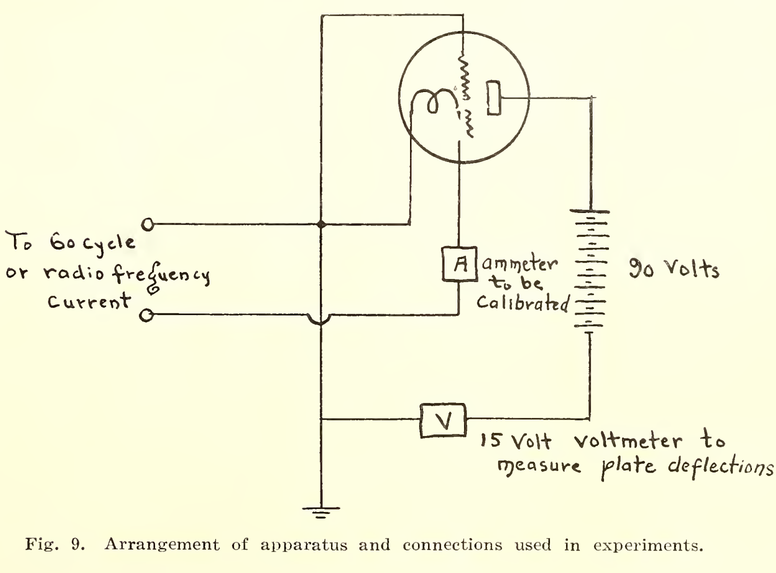

Fig. 9. Arrangement of apparatus and connections used in experiments.

A commercial amplifying tube for radio receiving sets does, of course, not quite meet the above requirements in that the plate is large, the filament is slightly inductive, and the presence of the grid offers possibilities for such undesirable occurrences as eddy currents and irregular modification of the potential gradient between the filament and plate.

DATA AND RESULTS.

The following measurements show how nearly the predicted results may be obtained even with an ordinary radio receiving tube. The arrangement of apparatus and connections used are shown in figure 9.

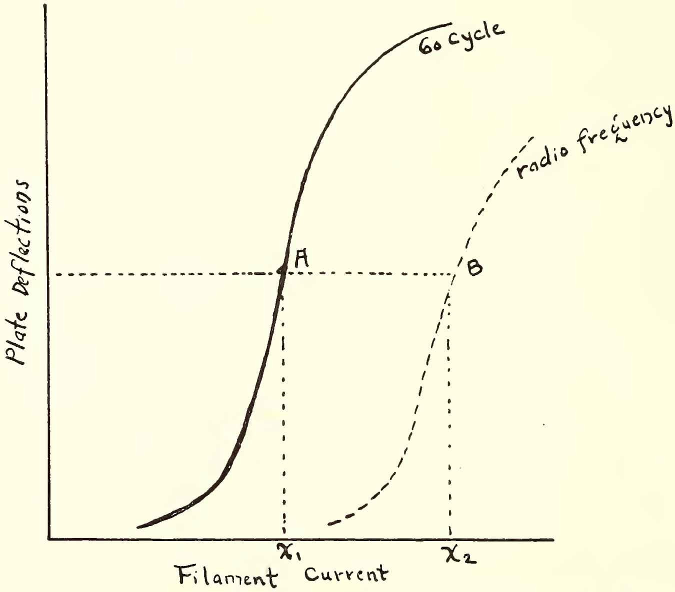

Fig. 10. By comparing the two characteristic curves obtained, the true value of the radio frequency current through the filament is determined.

In order to calibrate an ammeter by the vacuum tube method it is necessary to obtain the filament current-plate current characteristic curve of the vacuum tube used—by plotting filament current at 60 cycles against the plate current. The plate current, or deflections proportional to the plate current may be obtained by placing a voltmeter or a micro or milliammeter in the plate circuit of the tube as shown in figure 9. The filament current at 60 cycles must be accurately measured by some instrument which is calibrated for use at this low frequency. Usually the radio frequency ammeter to be calibrated may be used for this purpose. The characteristic curve should then be again obtained, this time substituting current of the desired high frequency through the filament instead of 60 cycle current. If the current through the filament and the plate deflections have been accurately measured in both cases, the same characteristic curve should result. If, however, the tube curves (one obtained with 60 cycle current through the filament and the other with radio frequency current through the filament) do not coincide, some error has been made in measurement.

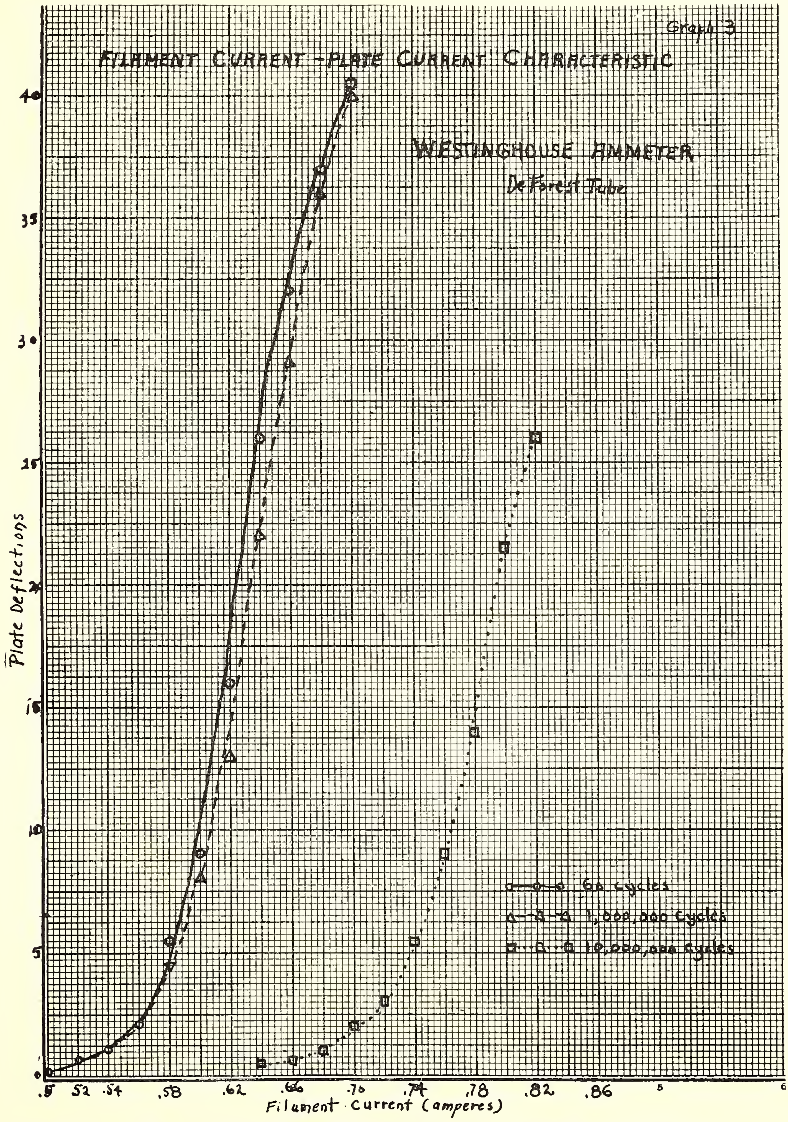

Fig. 11. Vacuum tube characteristic curve for the Westinghouse ammeter.

Now one can easily measure 60 cycle current and direct current in the plate circuit with accuracy, so any discrepancy between the curves may be traced to errors in measuring the radio frequency current through the filament. If the precautions already mentioned concerning the construction of the tube and the arrangement of the circuit in which it is used are taken, one can find the true value of the radio frequency current through the filament by comparing the two character-

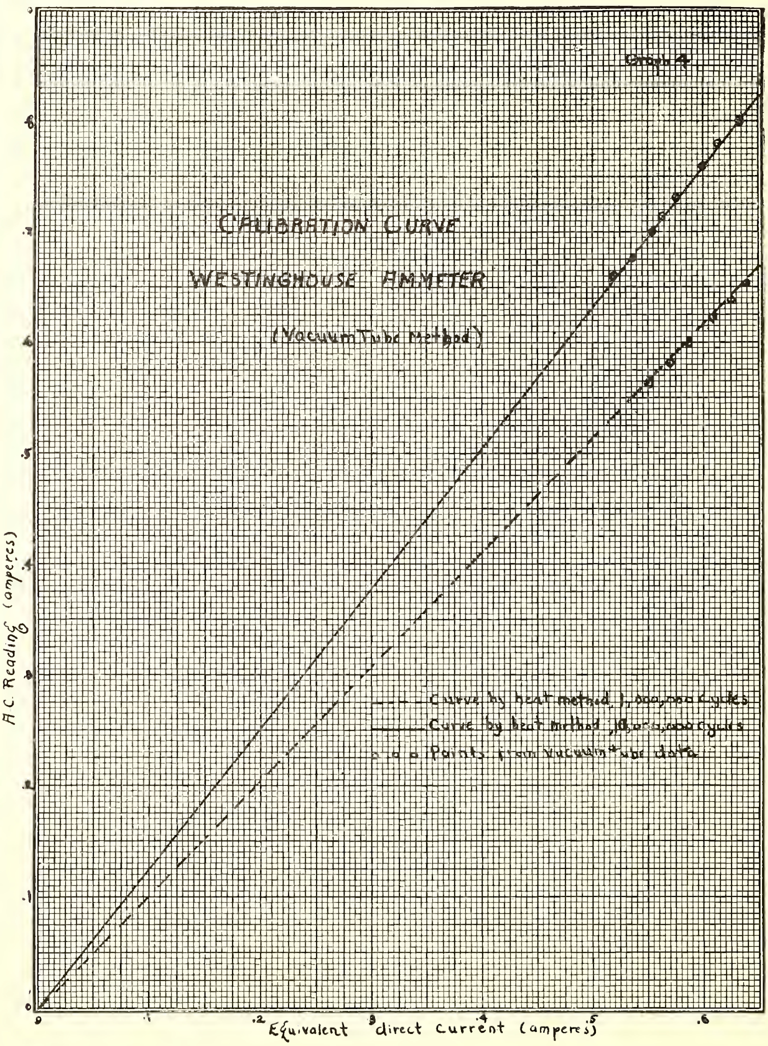

Fig. 12. Comparison of calibration curves as obtained by the heat method at 1,000,000 and 10,000,000 cycles, respectively.

istic curves. For example, let the solid line in figure 10 be the curve for accurately measured 60 cycle current through the filament, and let the dotted line be the curve obtained with radio frequency current through the filament. From the 60 cycle curve, x_1, is the true value of the filament current which produced the plate deflection at A. Then tracing across horizontally to the point B on the radio frequency curve at which the same plate deflection occurred, one sees that x_2 was the reading of the ammeter for the filament current which produced the plate deflection, B. That is x_2 is the reading of the instrument which corresponds to the true value of current x_1. Hence the calibration curve can easily be plotted from this data. Table V and figures 11 and 12 show the curves for the Westinghouse ammeter. In figure 12 the calibration curves already found by the heat method (fig. 4) are plotted and values from the characteristic curves of figure 11 are shown in circles. It will be seen that the curve obtained by the vacuum tube method practically coincides with the one obtained by the heat method.

TABLE V. Filament Current–Plate Current Characteristic
De Forest Tube

WESTINGHOUSE AMMETER

60 Cycles (May 11)		1,000,000 Cycles (May 20)		10,000,000 Cycles (May 11)	
Filament Current (Amperes)	Plate Deflections	Filament Current (Amperes)	Plate Deflections	Filament Current (Amperes)	Plate Deflections
.5	.2	.52	.2	.64	.5
.52	.7	.54	1.0	.66	.6
.54	1.0	.56	2.0	.68	1.0
.56	2.2	.58	4.0	.70	2.0
.58	5.5	.6	8.0	.72	3.0
.60	9.0	.62	13.0	.74	5.5
.62	16.0	.64	22.0	.76	9.0
.64	26.0	.66	29.0	.78	14.0
.66	32.0	.68	36.0	.80	21.5
.68	37.0	.7	40.0	.82	26.0
.70	40.5				

SUMMARY.

Some of the outstanding limitations of the ordinary radio frequency ammeter have been demonstrated. Not only is there considerable variation with frequency, but variations at any particular frequency, due chiefly to the zero shift, are not to be ignored. At extremely high frequencies the insertion of an ammeter in the circuit would so profoundly change the constants of the circuit that its use would be worthless.

The problem of measuring rather large radio frequency currents with great accuracy has not been completely solved. The distributed capacity of the commercial hot wire ammeter introduces factors of unsolved complexity.

An application of the special form of thermionic vacuum tube described in this paper offers solution to all these difficulties in a new form of radio frequency ammeter. The indications of such a device, depending on the fundamental property of electron emission of hot bodies, would be practically instantaneous in its action, and comparatively free from zero shifting. Since a given tube could, from the nature of its functions, cover only an extremely limited range of current, and since the change of plate current with a very small change of filament current can be made enormously large, the instrument would be "microscopic" in its accuracy. Tubes of tiny dimensions can be constructed with negligible inductance and capacity, offering opportunity for use in circuits of extremely high frequency, and offering possibility of combination in parallel for measuring large currents. Several tubes can be mounted in one set with a single galvanometer for recording the plate current, so that a large range of current magnitude may be taken care of. In conclusion, it seems that one may add the much needed ability to measure radio frequency current to the already long list of applications of the thermionic vacuum valve.[8]

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