DISCUSSION ON MAGNETIC PROPERTIES OF IRON AT FREQUENCIES UP TO 200,000 CYCLES." NEW YORK, NOVEMBER 10, 1911.

Harold Pender: I should like to call attention to the fact that the results of this paper are confirmed by some experiments which were performed at the Institute of Technology last year under my direction by F. B. Silsbee. The method used was entirely different. For the high frequency generator we used an arc giving a frequency something like 200,000 cycles per second. This frequency was impressed upon a primary winding on a small iron core made up of very fine iron wire, and the electromotive force induced in a secondary winding on the same core was measured. This secondary induced electromotive force was also calculated on the assumption that the true permeability is independent of the frequency. In making this calculation the proper allowance was made for the non-uniform distribution of the flux in the core, usually referred to as the magnetic skin effect. The measured and calculated electromotive forces were found to agree quite closely.

B. A. Behrend: This paper is interesting in bringing again to our attention the question of high frequencies, a question which 20 years ago was perpetually under controversy. The paper of this evening is extremely instructive, although I regret that the able author does not strongly bring out the fact that, as far as fundamental laws and principles are concerned, the problem confronting the physicist or the electrical engineer, whether frequencies of 10 cycles, 25 cycles, 60 cycles, 120 cycles, or 100,000 cycles are involved, remains exactly where it was before; in other words, the permeability of iron as such remains unchanged independent of the frequency. This fact has, I believe, been known for some time. The high frequency induces vitiating factors which make it appear as though the permeability of iron were different for different frequencies, which it is not.

There is another point in the paper on which I wish to comment and that is the point of efficiency of high frequency apparatus. The apparatus may have a high efficiency, as the author has stated, but the apparatus is useless in its present form for practical applications other than wireless telegraphy, because of its want of regulative properties; in other words, a transformer or a generator of high frequency, though its efficiency may be entirely satisfactory, is an inferior piece of apparatus, in fact, an impossible piece of apparatus for the operating conditions required by the use of current-consuming devices of low power factor.

The statement which I have made is of a certain measure of importance and of interest to those of us older men, who argued in former years strongly in favor of lower frequencies in order to be able to design satisfactorily transformers, generators, and motors. The higher efficiency of the high-frequency transformer may be a great desideratum, yet its lack of regulative properties,

owing to the high frequency, makes it an impracticable piece of apparatus for modern power plants.

Charles P. Steinmetz: The importance of this paper appears to me two-fold; first, in announcing the success of developing an alternator capable of generating at 200,000 cycles. It is very difficult, from the mere number, to realize what 200,000 cycles means. We were very proud when we succeeded in generating 10,000 cycles, one-twentieth of that frequency. We must realize that 200,000 cycles is 40 times as high a frequency as the highest frequency at which sound is audible; the pitch at which the ear fails is $1/40$ of this frequency. The most powerful research instrument we have, the oscillograph, fails at $1/40$ of this frequency, and even at 5,000 cycles it gives merely a single kick without shape or characteristic.

If we would send a current of 200,000 cycles into a line conductor, we would find that while the current flows into the conductor at one point, only 2,000 ft. away the current is still flowing in the opposite direction, is half a wave behind, and is zero 1,000 ft. away, at the center, and when the current stops at one point it is still maximum only 1,000 ft. away.

The second important feature of the paper is the information it gives us of the behavior of iron at these extremely high frequencies which are far beyond any machine frequency ever produced, but which are the frequencies of industrial importance in our wireless telegraph and telephone systems. The paper gives the quantitative values, showing that the permeability of iron at these frequencies is unchanged, and furthermore showing that with commercially practicable thickness of iron, while the eddy currents in the iron are formidable, still the effective permeability is 180 times that of air, that is, iron is still 180 times as good as air as the core for a 200,000 cycle transformer or reactive coil.

This may have an industrial value bearing in wireless apparatus. As you know, in wireless systems we transform the energy produced by the oscillating discharge from the voltage of the generator circuit to the much higher voltage impressed upon the antenna, by a transformer or auto-transformer, which is an air core apparatus. In these cases we deal not with alternating voltages, but with oscillating voltages; trains of waves which gradually, and usually quite rapidly, decrease in amplitude and then die out. The important problem, then, is to get the rate of dying out, the attenuation of the waves, as low as possible, to get as well sustained waves as possible, that is, to reduce the losses in transformation.

Iron has not been used in these transformers, not always because people did not believe iron would follow the frequency, but because the general impression is that the losses in the iron, even when as thin as commercially feasible, would be so formidable as to greatly increase the attenuation, increase the rapidity of dying out of the wireless wave.

As to the question of the magnetic action of the iron, the apparent permeability, I estimated theoretically, some years ago, the frequency at which the apparent permeability of iron, as affected by the eddy currents in the iron, would become inferior to air, that is, at what frequency the permeability would drop down to one, and I found this frequency to be of the magnitude of hundreds of millions of cycles, that is, up to a hundred million cycles iron still increases the magnetic flux, when using the thinnest feasible commercial sheet iron. But long before that, while the iron still increases the magnetic flux, it also increases the loss, and the increased loss, increased attenuation of the wave would make it useless.

Mr. Alexanderson's investigation gives for wireless frequencies, 200,000 cycles, definite numerical results of the apparent permeability, and shows this to be of the magnitude of 180. Thus iron is 180 times as good a conductor of magnetic flux as air, and in such transformers the losses in the iron are of the same magnitude as the $I^2 R$ loss. If we would redesign this iron core transformer tentatively designed by Alexanderson, to eliminate iron, using an air core, then the section of the air core to carry the same magnetic flux would have to be 180 times the size of the iron core used; that is to say, the length of the coil would have to be $\sqrt{180} = 13$ times as great; and to save half the loss, the core loss in the iron, we would have to increase the other half of the loss, the $I^2 R$ loss, 13 times.

So you see this investigation seems to show that by using an iron core of proper proportion, at wireless telegraph frequencies, we can materially improve the efficiency of the transformer or auto transformer, and so reduce the attenuation of the oscillating wave, and that is the problem of the power in wireless telegraphy.

Naturally, this design may be more or less, possibly materially modified, by the problem of the voltage that we have to generate, and the necessity of insulating for the voltage, which must be taken into consideration; but in general it seems from the conclusions of this paper that there should be a material advantage in wireless telegraphy in using iron core transformers, or auto transformers, instead of the air core apparatus used at the present time.

Reginald A. Fessenden (communicated after adjournment): For long it was supposed that iron lost its permeability at high frequencies, and was not able to respond quickly enough. This theory was a plausible one if Weber's theory that magnetization was due to currents circulating round the atoms, or if Kelvin and Maxwell's dictum that the electromagnetic rotation of light demonstrated conclusively that, to quote Maxwell, "some phenomenon of rotation is going on in a magnetic field", be accepted.

But about 1890 or earlier J. J. Thomson had shown that iron had a permeability of at least 200 for frequencies of 1,000,000 per second, by measuring the velocity of propagation of an electric wave along an iron wire. In March 1895 the writer

showed that the phenomena of magnetism could be explained both qualitatively and quantitatively by the theory that ionic charges, or electrons, circulated round the molecule with the velocity of light and that the maximum ferric induction so calculated agreed very closely with that found experimentally. Also, in March 1900 (*Phys. Rev.*) the writer showed that the mathematical work on which Kelvin and Maxwell based their conclusion was erroneous, in that the fundamental assumptions made virtually implied a theory of matter which was not justified, and that furthermore electromagnetic rotation could be mathematically deduced from the equations for an electric wave passing through an absorbing medium, without any assumptions as regards the nature of matter or of rotation, being a necessary consequence of the lag produced in the wave by the absorption and the presence of electrons.

Theory and J. J. Thomson's results were thus in agreement, but to what extent was unknown. Some experiments made with arc-produced high frequency currents in 1901 showed that the permeability of iron was of the same *order* as for low frequencies, but it might be a fifth as much or five times as much, for arc-produced high frequency currents are very unreliable, even when apparently continuous, having sometimes as much as 50 per cent of the waves missing, and also fluctuating so much in frequency as to make it absolutely impossible to get any accurate quantitative results. (*Lond. Electrician*, Feb. 15, 1907. Later confirmed by Fleming.)

Mr. Alexanderson's results form therefore the first definite and dependable knowledge in regard to this subject, and the paper is remarkable, both for its general interest and its scientific and practical importance. Workers with high frequency currents can now go ahead with confidence and use iron without fear. It will undoubtedly come into use as transformers, especially with the heterodyne system, where the electrostatic inductance between primary and secondary is of no importance and the shortening of the wave length along the wire winding does no harm, but may even in certain cases, be advantageous. I am able to confirm Mr. Alexanderson's statements as to the accuracy of the method used for measuring the power lost.

F. B. Silsbee (communicated after adjournment): In connection with Mr. Alexanderson's paper I would like to give a brief account of an investigation along similar lines which I carried on during the winter of 1910-11, at the Massachusetts Institute of Technology, under the direction of Professor Pender.

The object of the research was to decide whether or not iron can respond magnetically to a very rapidly alternating magnetomotive-force. Especial care was taken to arrange the conditions of the experiment so that they would be amenable to mathematical analysis, and all disturbing factors could be allowed for. The method used was quite different from Mr. Alexanderson's, as the specimens were magnetized by a primary winding, and the

flux" determined by measuring the voltage in a secondary winding. To allow for the magnetic " skin-effect " a careful mathematical analysis was made which took into account the effects of both eddy-currents and hysteresis. The assumptions it was necessary to make were: first, that the hysteresis loop, traversed by the iron during a complete cycle, was a simple symmetrical loop having the equation

$$\left(\frac{\mu H - B}{\nu B_0} \right)^2 + \left(\frac{H}{H_0} \right)^2 = 1 \quad (1)$$

where H = m.m.f. per cm. at any point.

B = corresponding flux density.

H_0 = max. value of H during the cycle.

B_0 = value of B corresponding to $H = H_0$.

$$\mu = \frac{B_0}{H_0}$$

$$\nu = \frac{B \text{ at } H=0}{B \text{ at } H=H_0}$$

and second, that μ and ν were constant and independent of H_0 . The iron used had been hardened in drawing so that the maximum permeability was only about 700. It was, however, very well suited for this investigation as μ was practically constant at 80 for values of H_0 between 0 and 3.5 c.g.s. units, ν also was practically constant over this range. From the above assumptions it can be proved that the secondary voltage is of the form

$$E_2 = -M_0 \omega I [B + \nu A + j(A - \nu B)] \quad (2)$$

where M_0 = mutual inductance between the two windings at low frequency.

ω = 2π times the frequency.

I = primary current.

j = $\sqrt{-1}$

A and B are functions of the radius of the core, the conductivity, permeability and hysteretic constant of the iron, and of the frequency; and are expressed as a rather complicated series.

The secondary voltage was measured by an alternating current modification of the potentiometer method, so commonly used in direct-current work. A variable inductance and resistance were connected in series with the primary winding, and the secondary winding was connected, in series with a suitable detector, so that its voltage was opposed to the IZ drop in the impedance. The inductance and resistance were both adjusted until there was no current in the detector, thus eliminating any demagnetizing action from the secondary coil. Then from the known values of the resistance and inductance,

and the primary current, as measured by a hot-wire ammeter, both the magnitude and phase relation of the secondary voltage could be computed.

The high-frequency current was obtained from a Poulsen arc formed between copper and carbon electrodes in an atmosphere of coal gas. The arc was supplied with 220 volts direct current and gave about two amperes at 350,000 cycles per second. The frequency was measured by the use of a resonating circuit, loosely coupled inductively to the primary circuit and containing inductance and capacity in series with a detector. The resonating circuit was adjusted for maximum current, and the frequency computed from its constants by the formula,

$$f = \frac{2 \pi}{\sqrt{L C}} \quad (3)$$

The detector used in this and also in measuring the voltage of the specimen was a thermo-couple heated by the passage of the high-frequency current, and connected to a low resistance D'Arsonval galvanometer.

Four specimens were used, made up of fine iron wire 0.009, 0.005, 0.004, 0.002 in. (0.228, 0.127, 0.101, 0.050 mm.) in diam. respectively. Each size of wire was wound into a ring of circular cross-section about 8 cm. in diameter, and having a total sectional area of iron of about 0.2 sq. cm. Great care was taken in insulating between adjacent wires. The material was passed through thick shellac, and thoroughly dried by a blast of hot air before being wound into the ring. The electrical resistance between the ends of the iron wire after winding was practically that computed from its length and resistivity, thus showing that there could be no short circuit between turns.

It will be seen from equation (2) that when the potentiometer circuit is balanced

$$L = M_0 (A - \nu B)$$

$$R = M_0 \omega (B + \nu A)$$

This was found to be the case in most of the measurements to within 3 or 4 per cent which was the limit of precision of the measurements. This shows that the true permeability μ is unaffected by frequency up to 350,000 cycles, at least over the range of H used. In some cases there were quite wide discrepancies but it is probable that they were due, at least in part, to the rise in temperature as suggested by Mr. Alexanderson. The observed values of the energy component were uniformly low, which suggested that possibly the hysteresis loss per cycle might be less at the higher frequencies, when the molecules are subjected to such rapid agitation. Such a decrease in hysteresis has been suggested by Ewing, Lodge and others. It would be interesting to know if Mr. Alexanderson has separated his core losses, so that this fact could be determined.