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ALFRED N. GOLDSMITH, Ph.D.

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THE MEASUREMENT OF RADIOTELEGRAPHIC SIGNALS WITH THE OSCILLATING AUDION*

BY

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WASHINGTON, D. C.)

For the measurement of received signals at a great distance, no methods have been found possible except those involving the use of the telephone. Even tho galvanometer methods have been developed which are sufficiently sensitive, the disturbances due to atmospheric discharges are so troublesome that it is found impracticable to use them under many circumstances. For purposes of measurement the audibility of telephone current is defined as the ratio $\frac{i}{i_o}$ where i is the given current, and i_o is the least current of the given frequency audible in the telephone to the given observer.[1] This ratio is determined experimentally by shunting the telephones so that the sound in the telephones just remains audible. Then if t is the effective resistance of the telephones for the given frequency and telephone pulse form, and s is the value of the shunt, the audibility

$$A = \frac{i}{i_o} = \frac{t+s}{s}$$

The best method for making this measurement seems to be, when such an arrangement is possible, to have test letters sent which are heard by one observer in unshunted telephones and which are heard by the observer taking the audibility in shunted telephones. The shunt is gradually reduced until the observer fails to get the letters correctly. In this way, if the room be perfectly quiet and there are no atmospheric disturbances, errors of observation may be reduced to about ten per cent. Under ordinary station conditions the errors are seldom less than twenty

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*Received by the Editor, October 31, 1916.

[1] The uniformity of audibility readings made by different trained observers has been very much underestimated. Of the half dozen or more men who have been engaged in this kind of work in the laboratory only one, who was known to be a little deaf, obtained results in general differing from the others by more than twenty per cent.

per cent and sometimes reach fifty per cent or even more under very bad atmospheric conditions.[2]

This method of making telephone measurements in radio telegraphy, in the case of electrolytic and crystal contact detectors, has been studied by several workers.[3]

The extensive use of three electrode vacuum tubes for the reception of continuous oscillations has rendered a similar study of the shunt telephone method for these detectors desirable.

CALIBRATION OF THE AUDIBILITY BOX

The arrangement of apparatus is shown in Figure 1. Here *A* is a wave meter circuit excited either by means of an audion or buzzer, *B* is an intermediate circuit or artificial antenna, *C* is the receiving circuit corresponding to the usual receiving secondary. The current in circuit *B* was varied by changing the coupling *A B* while the range of audibility in the receiver *C* for each experiment was fixed by the coupling *B C*. The radio frequency current in *B* was measured relatively by means of a silicon detector and galvanometer. It was, of course, impos-

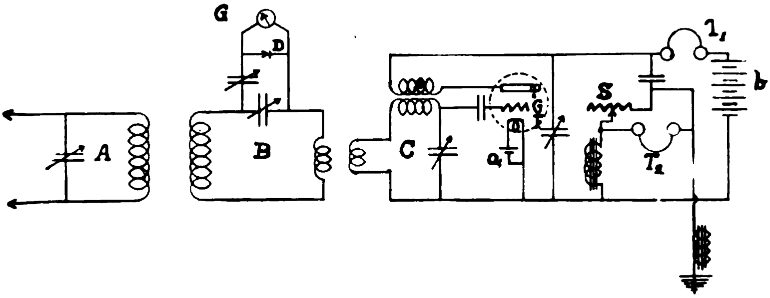

FIGURE 1

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[2] In general, in radio stations, the audibility readings tend to be too low on account of atmospheric disturbances, disturbing noises in the station. and lack of proper adjustment of the apparatus.

[3] F. Braun, "Jahrb. d. drahtl. Telegraphie," **8**, p. 203, 1914.

L. W. Austin, "Bulletin of the Bureau of Standards," **7**, p. 319, 1911, Reprint 159.

Klages and Demmler, ("Jahrb. d. drahtl. Tel.", **8**, p. 212, 1914), using a contact detector attempted to find a linear relation between sending current and telephone shunt value. In some reviews and references their lack of success has been quoted as an argument against the use of the shunted telephone method for quantitative measurements. Their own observations when recalculated using a probable value for their telephone resistance, show a fair linear relation between sending current squared and audibility as defined above.

sible to get readings on the galvanometer, covering the whole range of telephone audibilities from 1 to 5,000, especially since the silicon responds in proportion to the square of the high frequency current, while the audibilities of the oscillating audion are proportional to the first power.[4] The galvanometer could not be shunted during a series, as it was found to affect the sensitiveness of the detector.

The audibility shunt resistance used with the audion telephones was of a type already described.[5] Its range extended from 1 to 5,000 audibility in 34 steps controlled by a single movable contact arm. The box was calibrated to read directly in audibility when used with telephones having an effective resistance of 5,000 ohms at the given tone frequency. The telephones used had a direct current resistance of 2,040 ohms, and a current sensitiveness at 1,000 sparks per second, of 5×10^{-10} amperes.

In making the measurements, while keeping the coupling *B C* fixed, the coupling *A B* was varied and the corresponding audibilities and galvanometer readings noted. The coupling *B C* was then changed and the observations repeated for a new audibility range, care being taken that the coupling *B C* never became close enough to permit the local oscillations in the audion circuit to affect the detector in circuit *B*. In this way the ratio of the current in circuit *B* to the audibility readings was determined for various measurement ranges of the audibility box.

Table I shows the proportionality between audibility and received current over five ranges where the current is proportional to the square root of the detector galvanometer deflections in circuit *B*. The variations shown are well within the limits of experimental error.

TABLE I

Ranges of Audibility	$\frac{\text{Ratio of Current}}{\text{Ratio of Audibility}}$	Sets of Observations
1– 2	0.95	6
1– 10	0.93	6
10– 100	0.94	5
100–2000	1.05	7
250–5000	1.03	16

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[4] "Journ. Washington Acad.," **6**, p. 81, 1916.

[5] "Journ. of the Washington Acad.," **3**, p. 133, 1913.

Table II shows the detailed observations for a set taken between 3 and 80 audibility. From these results it may be concluded that, under the given experimental conditions, the shunted telephone method gives results which are correct within the limits of experimental error.

TABLE II

Audibility Ratio	Current Ratio	$\frac{\text{Current Ratio}}{\text{Audibility Ratio}}$
$\frac{12}{3}$	$\frac{5.24}{1.14}$	1.15
$\frac{20}{3}$	$\frac{7.78}{1.14}$	1.02
$\frac{50}{3}$	$\frac{19.24}{1.14}$	1.01
$\frac{80}{3}$	$\frac{28.8}{1.14}$	0.95
$\frac{20}{12}$	$\frac{7.78}{5.24}$	0.89
$\frac{50}{12}$	$\frac{19.24}{5.24}$	0.89
$\frac{80}{12}$	$\frac{28.8}{5.24}$	0.85
$\frac{50}{20}$	$\frac{19.24}{7.78}$	0.99
$\frac{80}{20}$	$\frac{28.8}{7.78}$	0.93
$\frac{80}{50}$	$\frac{28.8}{19.24}$	0.93

The above direct method of calibration is better than the usual one involving a determination of the impedance of the telephones. This is difficult to determine for the very small currents occurring in actual reception, and in addition it obviates the uncertainties due to changes in the total current pulse intensity when the shunt is closed.

ABSOLUTE SENSITIVENESS OF THE OSCILLATING AUDION

The relative audibility of the oscillating audion and the old type audion for buzzer signals has been determined many times, the average ratio being about 600. Similar comparisons have been made between the old audion and the free wire electrolytic, with the result that the mean sensitiveness of the old audion is found to be 1.7 times that of the electrolytic. The extreme deviations with different bulbs are 1.5 and 1.8. At the time of the Brant Rock tests[6] a rather careful determination was made of the number of watts in the receiving system required to give an audible signal for normal ears in the telephones then used with the electrolytic. This was determined to be 25×10^{-10} watts. With the improvement in telephones this has been reduced to about 12.25×10^{-10} watts. From all these data, it was estimated that the least power capable of producing a signal on the oscillating audion is 1.2×10^{-15} watts using 2,000 ohm telephones having a current sensitiveness of 5×10^{-10} amperes at 1,000 cycles. From this value a table[7] was calculated on the assumption that the oscillating audion produces a current variation in the telephone proportional to the square root of the received watts.[8]

In order to obtain a more certain knowledge of audion sensitiveness, a direct determination of the power in the receiving system corresponding to unit audibility in the oscillating audion has recently been made. The method used is practically that used in the Brant Rock experiments. The arrangement of apparatus, Figure 2, was with slight modifications that shown in Figure 1. The sending wave meter *A* was excited by an oscillating audion capable of giving out several watts, thus making it possible to use loose coupling between the circuits *A* and *B*. The detector in circuit *B* was removed, and a sensitive vacuum thermoelement of 28 ohms resistance was placed directly in the circuit. This thermoelement with the galvanometer used gave a deflection of 1 millimeter (0.04 inch) for 40.4×10^{-6} amperes in the *B* circuit. A double pole, double throw switch was introduced in the *C* circuit so that the receiving circuit proper could be connected to the audion or to a silicon detector and galvanometer. Using the silicon detector in the *C* circuit with the coupling *B C* adjusted so as to give the largest deflection on the silicon galvanometer, a comparison was made between the ther-

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[6] "Bulletin Bureau of Standards," 7, p. 315, Reprint 159, 1911.
[7] "Proc. I. R. E.," 4, p. 255, 1916.
[8] "Journ. Washington Acad.," 6, p. 81, 1916.

moelement deflections in circuit *B* and the detector deflections in *C*. By exterpolation it then became possible to use the detector galvanometer in *C* to measure the radio frequency currents in *B*, even when small enough to bring the response of the oscillating audion within the range of the audibility box when the audion was connected to the secondary receiving circuit *C*.

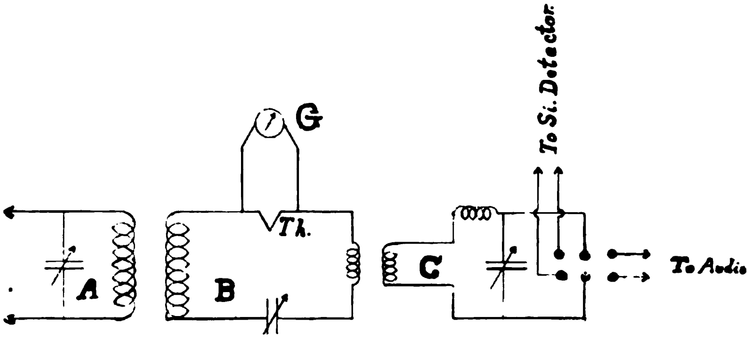

FIGURE 2

The sensibility of the audion depends very much on the adjustments of its circuits. It is therefore necessary to choose some definite method of making these adjustments. The following method, while not giving the greatest sensibility, seems to give the most easily reproducible readings: The antenna and closed circuit are first tuned for best signal at very loose coupling, adjusting the bridging condenser, grid condenser, and re-inforcing coupling, if one is used. Then the main coupling is gradually closed to the best point and the secondary retuned slightly for the note desired, leaving the antenna unchanged.[9]

The audibility observations were made by the test letter method already mentioned. Three wave lengths were used in the measurements: three thousand meters, six thousand meters and ten thousand meters. The inductance in the secondary *C* for three thousand meters was approximately twelve mh. At six thousand meters, observations were made with an inductance

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[9] In order to prevent false readings, if the signals are stronger than 100 audibility it is necessary to ground one side of the observing telephones thru a suitable choke (pair of 2,000 ohm telephones) to prevent the effects due to the capacity of the observer's body. To prevent the breaking down of the oscillations a high resistance (a hundred thousand ohms or more) may be placed across the grid condenser, or the grid may be grounded thru a condenser of a few ten-thousandths microfarad.

of twelve mh. and also with thirty-six mh. At ten thousand meters thirty-six mh. were used.

In Table III the complete data for a set of observations at three thousand meters are given. Here D is the detector galvanometer deflection, I is the current in circuit B, W is the watts in circuit B, A is the corresponding audibility on the audion, and W_o is $\frac{W}{A^2}$ or watts for unit audibility. The total resistance R of the table is the resistance of the B circuit plus the resistance due to coupling the C circuit with the silicon detector attached. This sum amounts to 1.7 of the resistance of the B circuit alone.

TABLE III

$\lambda = 3{,}000$ m. $R = 65$ ohms. $L_c = 12$ m h.
1 mm. deflection of Si detector galvanometer $= 6.2(10)^{-6}$ amp. in circuit B.

D mm.	$\sqrt{D}$	I $10^{-6}_{\text{amps.}}$	W 10^{-10}_{watts}	A	W_o 10^{-15}_{watts}
2.3	1.52	9.4	57.2	2,500	0.92
4.0	2.00	12.4	100.1	3,000	1.11
2.0	1.41	8.7	50.1	2,000	1.25
2.2	1.48	9.2	55.2	2,300	1.02
4.0	2.00	12.4	100.1	3,000	1.11
					1.09 Average

In Table IV the mean values of the power required for unit audibility for the given wave lengths are given.

TABLE IV

λ meters	L_c m h.	W_o 10^{-15}_{watts}
3,000	12	1.09
6,000	12	1.72
6,000	36	1.55
10,000	36	1.51
		1.45 Average

Since the watts are proportional to audibility squared, and audibility is by far the least accurate of the observed quantities, the accuracy of the value of watts for unit audibility is not very high. If we assume the error in the mean value of the audibilities to be 20 per cent., which is certainly great enough under the actual experimental conditions, the error in watts for unit audibility would be 40 per cent. We can then consider the probable minimum value of this quantity for our telephones and observers roughly as 1×10^{-15} watts, and the maximum value 2×10^{-15} watts. The value found by the comparison of the oscillating and non-oscillating audions, 1.2×10^{-15} watts, lies within these limits. The E.M.F. produced on the antenna by the incoming waves, and the received antenna current, which are from the theoretical standpoint the most important quantities derived from the observations in long distance work have the same error as the audibility readings.

SUMMARY: After considering procedure and accuracy in the measurement of audibility by the shunted telephone method, the author gives an arrangement for calibrating a usual audibility box when it is employed in conjunction with an oscillating audion. The method is found to be accurate to better than 20 per cent., exactly as with other detectors.

The absolute sensitiveness of the oscillating audion is found to be $1.2(10)^{-15}$ watts for a just audible signal. This is more than $(10)^6$ times the watt sensitiveness of the electrolytic detector and $6(10)^5$ times that of the normal audion on buzzer signals.

The details of the measurements and the necessary precautions are described in detail.

DISCUSSION

Edwin H. Armstrong: Dr. Austin's paper is naturally of great interest to me as I have often wondered just how sensitive the oscillating audion really was and how small an amount of energy was needed to give an audible response. To my knowledge, there has been no reliable determination of the absolute sensitiveness of this device, and for this reason it is very gratifying to have available the results of Dr. Austin's work along these lines. The method of calibration employed by Dr. Austin is somewhat involved and for this reason I would like to withhold comment on it until able to study it in detail.

There is one matter, however, on which I would like to comment and that is the standard of audibility which is now in general use. Primarily when we speak of the audibility of a signal in a telephone we have the concept of the energy necessary to produce that signal. We would naturally suppose that when a telephone is supplied with four times the energy necessary to give unit audibility that the audibility of that signal would be four. Certainly the amount of energy which has gone into the production of sound waves is four times that necessary for unit audibility. But by the present standard, since the telephone current is only twice the value of the current necessary for unit audibility, the audibility is only two. This leads to an absurdity in the case of the oscillating audion receiver. One of the great virtues of this receiver, or in fact of nearly all heterodyne receiving systems, is that the energy delivered to the telephones is directly proportional to the received energy. But according to the present definition of audibility it becomes necessary to say that the audibility is proportional to the square root of the received watts! I again like to call attention to the treatment of this audibility question by Mr. Lester Israel ("PROCEEDINGS OF THE INSTITUTE OF RADIO ENGINEERS," Volume 3, 1915, page 183), which covers the ground in complete detail.

It is very difficult to appreciate the great amount of work involved in preparing such a paper as the one presented by Dr. Austin unless one has been engaged along similar lines. The number of experiments and tests which must be made before work can be begun on the main object is surprising and will never appear from the relatively few pages of "PROCEEDINGS OF THE INSTITUTE OF RADIO ENGINEERS," in which the data are condensed. We are greatly indebted to Dr. Austin for the results of what must have been a long and tedious series of experiments.

Carl R. Englund: The audibility method of obtaining an estimate of the strength of radio signals is one of the same type as the "transmission" one used in measurements on wire telephone lines. Both are convenient and simple, since the actual procedure differs so little from commercial working of the apparatus, and are very practical in the sense of requiring minimum apparatus and operator skill. The second method, however, is normally a comparison one, the unknown line (loop) being compared with a known and variable line and the "transmission equivalent" is thus found, independent in great measure of the actual signal strength or detecting apparatus. There is in my mind no question that a similar transmission "coefficient" is the logical thing to measure in radio work, though impractical at present. The quotient $\frac{\text{watts radiated}}{I_s \times I_R}$ is as truly a circuit constant as the resistance of a piece of wire.

However, while a measurement of the above "coefficient" is not feasible, a comparison of the strength of the unknown signal with that of a known signal is possible and it seems to me very much preferable to the normal audibility method. It is true that Dr. Austin's data give proof that working results are possible, but the shunted telephone in these days of sensitive detectors and amplifiers is electrically too far away from the antenna, where the quantity to be measured is located, to allow anyone to feel safe without recalibrating the apparatus so often that a comparison method might as well have been adopted at once. To use such a method requires only a local generator with current indicator and a network for supplying to the antenna a known fraction of this current. Taking for granted the proposition that most of the measurements required in the future will be on sustained wave signals, the construction of a simple suitable generator is admittedly solved by the vacuum tube oscillator and the subdividing network offers no serious difficulty. I should, therefore, like to insist both on the desirability and practicability of the comparison method. It can be made accurate enough to meet most requirements without sacrificing manipulative simplicity or low cost.

May 26, 1917.

J. Mouradian: One or two points suggest themselves as worth while mentioning in connection with Dr. Austin's very interesting paper. In reference to the subject of percentage of error for observations made as to audibility, it has been the writer's experience that for any given individual the maximum error of a single observation, under the ideal conditions of freedom from room noises and other disturbances, will likely be as high as fifty per cent.; the average error of a series of observation varying, under the same conditions, from five to fifteen per cent. As between different individuals, the writer's experience has not been as encouraging as Dr. Austin's, the variation, as between individuals under the same ideal conditions of freedom from interfering noises, running as high as three hundred per cent. This figure was obtained for a group of five normal observers. Outside noises will seriously react upon the audibility for any given individual and to a different extent for different individuals. Under medium conditions of noise, such as obtains in the center of metropolitan areas, the audibility will vary, as an average for a number of observers, between three hundred and four hundred per cent. It is conceivable that under the conditions of observation which probably obtained at the United States Naval Radiotelegraphic laboratory in Washington, the audibility was not quite as seriously affected by outside or room noises.

In reference to the second part of the paper, the interesting set of measurements indicated on table III as to absolute sensitiveness of the oscillating audion appear to be indicative of the amplification power of the oscillating audion rather than of its sensitiveness. The values shown for the ratio of watts input to the audibilities squared (which is proportional to the watts output) will vary with the type of receiver used, and is consequently not a particularly good characteristic figure, in so far as the oscillating audion proper may be concerned. It may also be a question whether the ratios indicated on the last column of table III will not vary materially, if instead of working within the audibility range of 2,000 to 3,000, a different range of audibilities had been used.

May 30, 1917.

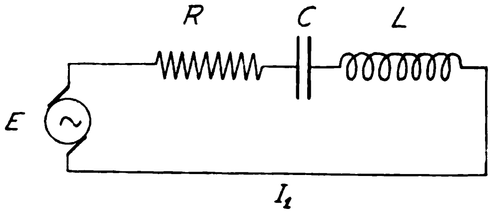
Edwin H. Armstrong (communicated): Upon considering in greater detail Dr. Austin's method of determination of the absolute sensitiveness of the oscillating audion receiver, it appears to me that a matter has been overlooked which will tend to give a greater sensitiveness than really exists, and for this reason the following analysis is submitted for consideration.

Briefly Dr. Austin's method is carried out in two steps. The first step consists in producing in an artificial antenna a current from a local source and measuring this current by means of a calibrated rectifier and galvanometer connected in a secondary circuit which is coupled to the antenna to the critical degree (i. e., that coupling which gives maximum current in the secondary). The second step consists in replacing the rectifier and galvanometer by an audion with the usual regenerative circuits, adjusting the same in accordance with a pre-determined method and measuring the audibility of the signal thus obtained. On the basis that the received power in the antenna is equal to the square of the antenna current multiplied by 1.7 times the effective resistance of the antenna circuit and the fact that the audibility of the telephone signal is proportional to the antenna current, the power in the antenna for unit audibility is calculated.

This calculation is based on the assumption that the power received in the antenna from the signaling source is the same whether the circuit coupled to the antenna contains a crystal rectifier or a regenerative tube. Because of a curious and valuable property of the regenerative circuit, the above assumption does not hold good, and the reason therefore will appear from the following simple treatment.

Assume first a simple antenna circuit such as shown in the figure of Case I and represent the electromotive force set up by an incoming signal by an alternator giving a potential E_1.

Case I



For resonance the current I_1, is given by

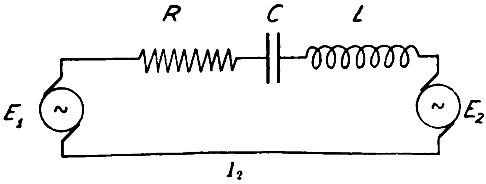
$$I_1 = \frac{E_1}{R}$$

and the power supplied to the circuit by the source E_1 is given by

$$P_1 = E_1 I_1 = I_1^2 R$$

Now consider that there is introduced in the circuit of case I, a second electromotive force E_2 of exactly the same frequency as E_1 and for the sake of simplicity, exactly in phase with E_1. This is the case of the regenerative circuit, whether in the stable or unstable state, and it may be represented by the figure of Case II. E_1 represents the signaling electromotive force and E_2 represents the final value in the steady state of the regenerative electromotive force.*

Case II



In general practice the electromotive force E_2 is introduced into the antenna thru the medium of the coupling coils and might therefore be shown across coil L instead of being shown conventially in series therewith.

The new current I_2 is now given by

$$I_2 = \frac{E_1 + E_2}{R}$$

and the total power P_2 in the circuit by

$$P_2 = (E_1 + E_2)\, I_2$$

The total amplification of the power in the antenna by the process of regeneration is given by the ratio of P_2 to P_1

$$A = \frac{P_2}{P_1} = \frac{(E_1 + E_2)\, I_2}{E_1 I_1} = \left(\frac{E_1 + E_2}{E_1}\right)^2$$

The power P_2 in the antenna is made up of two components; the power received from the signaling source which will be called P_2', and the power supplied by the regenerative action of the tube, which will be called P_2''.

$$P_2' = E_1 I_2$$

$$P_2'' = E_2 I_2$$

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* In receiving by the heterodyne method there would, of course, be a third electromotive force acting on the circuit. This applies whether the receiving is accomplished by a regenerative audion in the stable state with an external heterodyne or whether the regenerative circuit is adjusted to be in the unstable state and used as a self-heterodyne. This third electromotive force, however, is of a different frequency from the other two and need not be considered in matters affecting only the principle of regeneration.

Now it will be observed that *the power P_2' received from the signaling source when the local electromotive force E_2 is acting is not the same as the power P_1 received from the signaling source when the electromotive force E_2 is absent.* The power P_2' is the greater, and the greater by an amount depending on the relative magnitudes of E_2 and E_1.

$$\text{Hence}\quad \frac{P_2'}{P_1}=\frac{E_1 I_2}{E_1 I_1}=\frac{E_1+E_2}{E_1}$$

The *increase* in power drawn from the signaling source is proportional to

$$\frac{P_2'-P_1}{P_1}=\frac{E_1 I_2-E_1 I_1}{E_1 I_1}=\frac{E_2}{E_1}$$

The effect of the local or regenerative electromotive force E_2 is therefore to increase the power which is supplied to the system by the signaling source. A simple analogy is afforded by comparing the work done by a single cell battery when it is connected alone in a circuit, and again when it is connected in the same circuit with a second and similar cell in series. The total power delivered by the two is four times that of the single cell; each cell by reason of the presence of the other in the circuit does twice the work it would if placed in the circuit alone.*

It is obvious from the foregoing that when the crystal rectifier and galvanometer were replaced by a regenerative audion that the power in the antenna received from the signaling source was immediately increased by an amount approximately the ratio $\frac{E_2}{E_1}$. Hence the absolute sensitiveness as determined by Dr. Austin is too great by this ratio. As the ratio depends entirely on the adjustment, it is, of course, problematical what the error is, but from such measurements as I have made of the regenerative amplification occuring when the audion is in the oscillating state it would seem to be of the order of 1,000 per cent., altho it may readily be greater.

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* It is important at this point to consider the limitations of the foregoing analysis. It has been assumed thruout that the electromotive force E_1 stayed constant regardless of the amount of power drawn from the signaling source by the action of the electromotive force E_2. In the case of an artificial antenna, such as used by Dr. Austin in his calibration, the assumption is strictly correct, as the power in the antenna is certainly very small compared to the power available in the wave meter circuit. But in the case of reception on a real antenna the proposition is not so simple, as the power available in the incoming waves and the power actually received by the antenna approach each other more closely than in the case of the artificial antenna just considered. If it should so happen that the antenna constituted an overload for the energy available in the waves, then the value of E_1 will decrease and the foregoing considerations of the amount of amplification obtainable will not be quantitatively correct.

Many measurements have been made of the power of received signals with an oscillating audion receiver having this faulty calibration and close agreement has been obtained between these measured values and the values obtained by calculation with the Austin formula. [Notably the reception of signals at the U. S. Bureau of Standards from Nauen and Eilvese, "Journal of the Franklin Institute," November, 1916.] It is very probable that this close agreement has been obtained because the same type of error occurs in applying any of the standard formulas to predict the current in an antenna to which a regenerative receiver is attached. The error in the calculated current is numerically equal to the error made in the calibration of the receiving set (on the basis that E_1 remains constant) and of the proper sign to give compensation. For example take the Austin formula

$$I_R = \frac{377\, h_1 h_2 I_S}{\lambda\, d\, R}\, \varepsilon^{-\frac{0.0015\, d}{\sqrt{\lambda}}}$$

This formula was derived from experimental results obtained with crystal and electrolytic detectors. As long as the electromotive force produced in the antenna by the signaling waves is the only electromotive force of that frequency in the circuit the formula is applicable, but with the use of regeneration the current in the antenna becomes many times that given by the formula, the increase being given by the ratio E_1 which it is clear is the same as the error in the calibration of the receiver. The formula, E_1 for use with regenerative circuits, may be written

$$I_R = \frac{377\, h_1 h_2 I_S}{\lambda\, d\, R}\, \varepsilon^{-\frac{0.0015\, d}{\sqrt{\lambda}}} + \frac{E_2}{E_1}\, \frac{377\, h_1 h_2 I_S}{\lambda\, d\, R}\, \varepsilon^{-\frac{0\ 0015\, d}{\sqrt{\lambda}}}$$

$$I_R = \left(1 + \frac{E_2}{E_1}\right) \frac{377\, h_1 h_2 I_S}{\lambda\, d\, R}\, \varepsilon^{-\frac{0.0015\, d}{\sqrt{\lambda}}}$$

On account of the presence of the electromotive force E_2, it becomes necessary to use terms in their proper sense and the term "received current" should particularly be avoided, since its use will give rise to all sorts of difficulties. The electromotive force due to the incoming waves and that part of the power in the antenna which is actually drawn from the energy of these waves are the only quantities which can properly be termed "received." In terms of current and the effective resistance of the antenna the received power is given by

$$P_2' = I_2^2\, R\, \frac{1}{\left(1 + \frac{F_2}{E_1}\right)}$$

and the power supplied by regeneration by

$$P_2'' = I_2^2 R \frac{1}{\left(1+\frac{E_1}{E_2}\right)}$$

As a general proposition, in view of the difficulty of obtaining the value of the ratio of E_2, or of maintaining it constant by means of so delicate an adjustment as is necessary with the regenerative circuit it would appear preferable to make measurements of received power with a simple vacuum valve detector and an external heterodyne properly arranged to prevent regeneration. While the sensitiveness of this arrangement is not so great, it is a very constant quantity and it can be correctly calibrated by the method described in Dr. Austin's paper. In conclusion, I would like to state that such modifications as have been made of the Austin formula are quantitatively correct only as long as the electromotive force induced in the antenna by the signaling waves stays constant. Until data is available as to what extent regeneration on an efficient antenna can be carried without overloading the signaling waves quantitative relations are problematical.

ON THE POULSEN ARC AND ITS THEORY*

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CONTENTS

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INTRODUCTION

Many investigations have been made in order to elucidate the working of the Duddell-Poulsen arc. Besides the papers of Duddell† [1], [2], and Poulsen[3], [4], I shall mention only a few of the most important contributions. A long series of papers contributed by H. Th. Simon[5], [6], [7], and his school (H. Barkhausen[8], G. Lange[9], M. Reich[10], K. W. Wagner[11], and many others) have thrown much light upon the subject. A. Blondel[12] has made a very interesting oscillographic study of the Duddell arc. Of investigations of a more general character, but bearing on this subject, I may mention G. Granqvist's[13] papers on the influence of the heat conductivity of the electrodes on the behaviour of the arc, and the arc theories put forward by J. Stark[14], [15] J. J. Thomson,[16] and by C. D. Child.[16¹]

Thru the above mentioned papers and several others, some knowledge has been gained relative to the main features of the Poulsen arc—but this knowledge is far from being complete. The effect of the magnetic field, for instance, has not been explained so far in any satisfactory way, the current explanations being incomplete and very often misleading. A really satisfactory theory of the operation of the Poulsen arc does not exist at present, a satisfactory theory being one which will enable the calculation of the results, the necessary data being given.

It is, in most cases, impossible to state, even qualitatively,

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† The figures refer to the bibliography given at the end of the paper The notation used in this paper is also tabulated at the end of the paper.

by means of the present "theory," what will be the result of a change in one or more of the constants of the arc circuit or of the arc itself. That others are also feeling the insufficiency of the present theory appears from a paper by A. O. Liljeström[17] (of which see especially part 1).

While in spite of very extensive labor in this field, nothing truly satisfactory has been reached, such a state of affairs is mainly due to the great difficulties met with in analyzing oscillations of such high frequencies—that is, in obtaining reliable oscillograms of the potential difference and current. The investigations have, therefore, generally been limited to the Duddell arc at low frequencies, usually around 300 to 1000 cycles per second. An exception to this statement is found in some records made by means of the Braun tube. H. Hausrath[18] has described a method in which the rays of a Braun tube are made to describe some kind of a stationary Lissajous curve under the influence of the potential difference or current in the arc circuit, and in a secondary circuit in resonance for the high or radio frequency current and loosely coupled to the arc circuit. The shape of the Lissajous curve gives, then, the necessary information for drawing up the voltage and the current curves. Experience shows, however, that a loosely coupled secondary circuit may greatly affect an arc generator—causing, for example, considerable variations in the frequency. The explanation of these phenomena is indicated by P. O. Pedersen[21]. Furthermore, this method necessitates a comparatively long time of exposure—20 seconds or more—so that the Lissajous figure gives only a sort of average curve for several million cycles. Finally, the currents used are of such small value—the maximum being 3 amperes—that these investigations are of little value so far as the normal Poulsen arc is concerned. (See below.) Besides those mentioned, other circumstances have also contributed to the lack of success of the efforts to unravel the theory of the Poulsen arc. Nearly all of the above mentioned investigations have been carried out with comparatively small laboratory sets, using very small energy—the feeding current usually being only a few amperes. It is a fact, however, as will appear from the following, that in many respects simpler relations are found in the larger arc generators, carrying heavy currents, than in small ones. The operation of small and large arcs is rather different; and for this reason, many of the previous laboratory investigations are of little value for testing the theory of the Poulsen arc.

During some years I have had an opportunity to carry out several investigations in connection with the Poulsen arc, and in the present paper I shall report some of the results obtained. After a short description of the apparatus and arrangements used, the paper will be divided into two parts: **A** and **B**. The first—**A**—deals briefly with the theory of the Poulsen arc from an engineering point of view. In **B** I shall attempt to develop further the theory and comprehension of the arc; and particularly to explain the results obtained under **A** and the influence of the magnetic field. *On several points, I shall arrive at results differing considerably from those so far obtained.*

Most of the investigations were carried out in the Laboratory for Telegraphy and Telephony of The Royal Technical College in Copenhagen. I have had excellent assistance from engineers J. P. Christensen, H. Trap-Friis, and E. Jacobsen in carrying out the tests and experiments, from engineer Hugo Fortmeier while working out the paper and the drawings, from the mechanic at the laboratory, Folmer Nielsen in all the photographic work. I especially desire to thank Dr. Poulsen for the great interest he has taken in this investigation.

APPARATUS AND ARRANGEMENTS

Figure 1 shows a schematic diagram of the arc generator, while Figure 2 is a more explicit diagram of the arrangement used. Figure 3 is a photograph of the arc generator employed, sketches of the electrodes being shown in Figure 4. The anode is of copper, hollow, and water-cooled, while the active part of the cathode is formed of a carbon ring *d*, screwed on to a copper rod *a*, which is slipped into a brass tube *b*. *P* indicates one of the pole pieces of the electromagnet creating the magnetic field in which the arc is placed. The direction of the field is arranged so as to force the arc upward, and its intensity, *H*, is

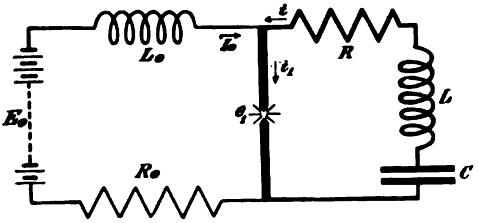

FIGURE 1—Duddell and Poulsen Arc

measured with a Grassot fluxmeter. The distance between the electrodes can be accurately regulated by rotating the hard rubber cylinder, visible in Figure 3, thus displacing the cathode. The starting of the arc is effected by pushing on the thinner hard rubber pin protruding thru this cylinder. The cathode is rotated slowly by means of the small electric motor also visible in Figure 3. The actual distance between the electrodes is much less than shown in Figure 4—being approximately one millimeter (0.04 inch).

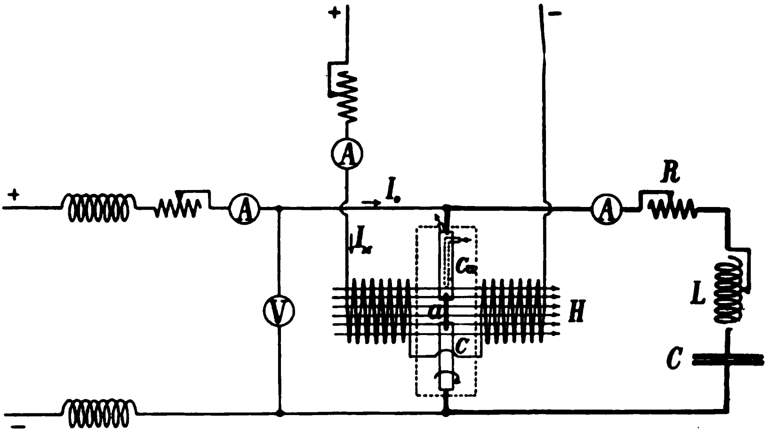

FIGURE 2—Complete Diagram for Arc Used in the Experiments

The capacity C in the arc circuit was composed of one or more oil condensers (containing castor oil), four of these being available and each one having a capacity of about 7,300 cm. (0.00811 microfarad). The inductance L was 70 turns of a copper helix of 5 mm. (0.2 inch) bare solid wire wound on a hard-rubber frame. The total inductance was 1.3×10^6 cm. (0.0013 henry). The resistance R in the arc circuit was made of carbon rods, its design being shown in Figure 5. The effective resistance of the arc circuit, with the carbon resistance short-circuited, was between 0.5 and 1.0 ohm; but as the work here considered is not intended to deal with efficiency determinations, R does only signify the value of the inserted carbon resistance when speaking about the experiments, altho it means the total effective resistance of the arc circuit in all theoretical calculations. The choke coils were made of stranded copper cable with a total inductance of 0.1 henry.

For power supply, there was used, according to circumstances, either 220 or 440 volts from the city supply, and for the magnetic field a local 110 volt storage battery was used. In most cases, the arc was burned in coal gas taken right from the city pipes; but in a few cases hydrogen was used, compressed in steel containers. Where the latter is the case, it is always pointed out in the description of the experiments.

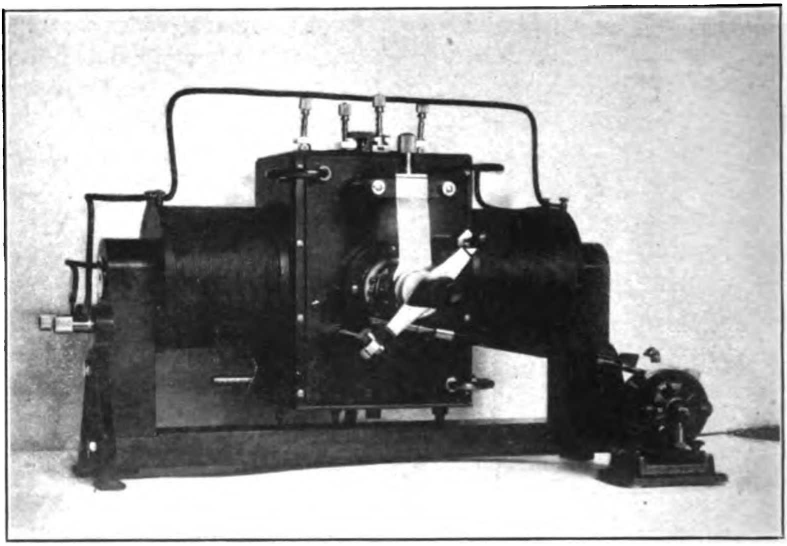

FIGURE 3—Photograph of the Arc Generator

For the greater portion of the experiments, one pole piece, P_2, and the corresponding coil, as shown in Figure 6, were removed and the hole in the arc chamber covered with a mica window, g_2, thru which a side view of the arc then could be photographed

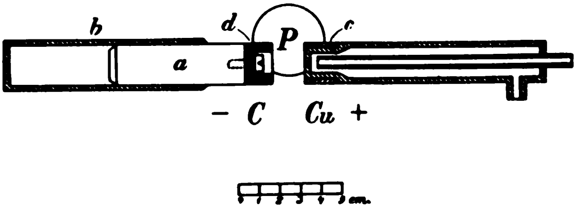

FIGURE 4—Cross Section of the Electrodes

by means of the lens, B_2, the shutter, L_2, and the photographic plate, FP_2. The lid of the chamber was provided with a projecting cylindrical portion with a mica window, g_1, on its top. Thru this window, by means of the lens, B_1, the metal mirror, Sp_1, and the shutter, L_1, either a stationary crater picture could be photographed on the plate, FP_1, or—when using the rapidly rotating metal mirror, Sp_2—the varying states of the crater and the arc could be photographed on the plate, FP_3, with the time as abscissa. The latter kind of pictures will in the following be called crater oscillograms. The rotary plane mirror was from a Gehrcke cathode glow oscillograph (see, for example, J. Zenneck, "Lehrbuch der drahtlosen Telegraphie," 2nd. edition, 1913, Figure 8, or Zenneck-Seelig, "Wireless Telegraphy," 1st. edition, 1915, Figure 8), and also the bibliography, numbers 25 and 6. This oscillograph was also employed when taking the oscillograms of the potential difference on the arc, as described later. The mirror could be rotated as rapidly as 200 revolutions per second.

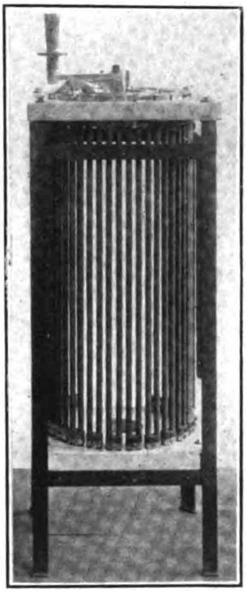

FIGURE 5—Carbon Rod Resistance

A

1. *a*. RATIO OF RADIO FREQUENCY CURRENT TO SUPPLY CURRENT

The only way to deal with the Poulsen arc, until a satisfactory theory has been evolved, obviously is to establish some empirical relations between the effective values of the different currents and voltages. The first question of interest is, then, how the ratio g between the effective value of the radio frequency current I and the feeding current I_0* is affected by the constants of the circuit, the design of the arc, the primary voltage, and other circumstances. K. Vollmer[22] is probably the only investigator who has published anything with regard to this question. Working on wave-lengths from 300 to 1,915 m., and with a supply current of from 1 to 7 amperes, he found $g = 0.77$. The characteristic of the arc circuit $\rho = \sqrt{\frac{L}{C}}$ was between 30 and 1,300 ohms. W. Duddell[1] found $g = 0.90$ when $I_0 = 5$ amperes, J. A. Fleming[23] $g = 0.63$ when $I_0 = 8$ amperes, L. W. Austin[24], found $g = 1$ when $I_0 = 4$ amperes with $\lambda = 3{,}600$ m. and $\rho = 4.5$

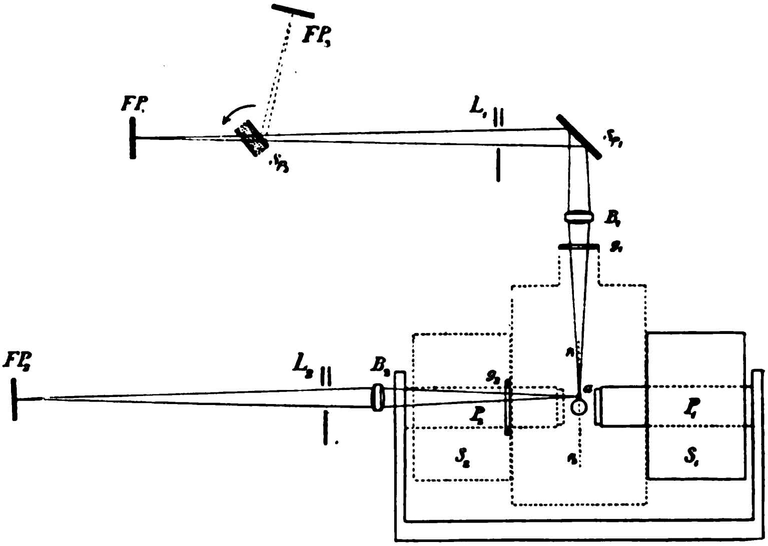

FIGURE 6—Sketch of the Photographic Arrangement

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* For the notation used in this paper, see "List of Symbols," page 315 at the end of the paper.

ohms, while Fassbender and Hupka[20] found $g=0.83$ when $I_o = 1.1$ amperes, $\lambda = 3{,}180$ m. and $\varrho = 567$ ohms.

For the normal Poulsen arc—by which I mean an arc that is working with at least 10-15 amperes d. c. with $\lambda = 1{,}000$ m. or more, and a value of ϱ not less than 50 ohms—*this ratio has the value*

$$g = \sqrt{\frac{1}{2}} = 0.707. \tag{1}$$

Under such conditions as are generally to be found in the larger arc stations, or when using similar laboratory arrangements, the formula (1) holds good with such accuracy that even with the best engineering design of ammeters for radio frequency current, no disagreement can be found. *Near the above mentioned limits, and after passing them, g will assume higher values.*

b. CALCULATION OF SUPPLY CURRENT OR VOLTAGE

Calling the effective resistance of the arc circuit R, the primary voltage V_o, and the efficiency factor of the arc γ, we have

$$\gamma I_o V_o = I^2 R = \frac{1}{2} I_o^2 R$$

or

$$2\gamma V_o = I_o R \tag{2}$$

The value of γ is not constant but will, in practice, be known approximately, and the formulas (1) and (2) then provide a very simple method for dertermining the values of V_o and I_o necessary for producing a given radio frequency current I.

2. *a.* THE MOST ADVANTAGEOUS ADJUSTMENT OF THE ARC.

Another important consequence of formula (1) is this: *As the ratio g is constant, the arc must give maximum of efficiency when V_o is a minimum.* With the arc burning on a power supply of voltage V_o, and with a constant resistance in the d. c. circuit, the arc must consequently give a maximum efficiency when I_o (or I) is a maximum. *In order to obtain the maximum of I under given circumstances, a certain distance between the electrodes and a certain value of the magnetic field is required, and these values are greatly dependent on the constants of the circuits.* Arc generators are therefore built so as to allow adjustment of the distance between the electrodes, and with a variable magnetic field. The arc is not active until pulled out to a certain critical length—for shorter arc-lengths, it works as an ordinary d. c. arc. Having reached the active length, however, the arc can be shortened a little without losing its activity (see V. Poulsen[4*], page 966).

The arc then gives maximum current I with as short a distance as possible between the electrodes; i. e., the critical distance or a little less. By increasing the distance, I will decrease and finally the arc is extinguished. Similar conditions exist with regard to the magnetic field. *The arc works most efficiently with a field just strong enough to keep it steady;* but this question will be taken up later in this paper.

b. The Conversion of the Arc from the Inactive to the Active State

It appears from the preceding that the arc generator either is active and supplies a radio frequency current equal to or larger than $\sqrt{\frac{1}{2}}I_o$, or does not operate at all (that is, is inactive) The r. f. current does not start as a small fraction of the value of I_o and then gradually increase as the conditions improve. It is therefore easily understood that even comparatively small changes in the condition of the arc can be the deciding factors as to its ability to operate as a radio frequency generator, since such small changes may just carry it past the critical point. This explains why it can be of such vital importance that the arc should burn in hydrogen instead of air, even tho the difference between these two gases in most other respect is only of a quantitative nature.

B

3. Arc Theory Based on Barkhausen's Simple Characteristic

The present view with regard to the working of the arc generator has been crystallized in the theory of Barkhausen[8a], based on his idealized simple characteristic shown in Figure 7, and only this theory has such a concrete form that the problem can be dealt with mathematically. Most modern literature dealing with the arc theory is therefore also based on Barkhausen's simple characteristic (see, for example, pages 260–293 in the excellent book by Zenneck, mentioned above). *For the sake of brevity in the following discussion, we shall call this view the B-theory.*

A question of immediate interest is, therefore, whether the value of the ratio g found above is in accord with the consequences of the B-theory or not. Before investigating this question we will, however, draw some mathematical consequences of the B-theory, using the symbols indicated on Figures 7 to 9, the meanings of which are further explained under "List of Symbols" at the end of this paper. Figures 8 and 9 show the current thru the arc and in the r. f. circuit and the voltage across the arc and the condenser, the calculations being based on the characteristic shown in Figure 7. In Figure 8, $R=0$ while in Figure 9, $R>0$.

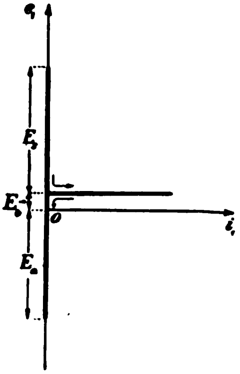


FIGURE 7—Barkhausen's Simple Characteristics

In the following, it is assumed that the choke coils in the supply cables are so great that the supply current I_o is constant, and this is correct practically.

For the sake of clearness, we will first take the ideal case with no resistance in the arc circuit.

a. $R=0$

While the arc is burning, the current in the radio frequency circuit is (see Figure 8)

$$i=I_m \sin(\omega_o t-\phi),$$

where

$$\omega_o=\frac{1}{\sqrt{LC}}.$$

While the arc is extinguished is $i=-I_o$. The time is reckoned from the moment i_1 begins, i. e., the instant the arc is struck. For $t=0$, we have, then

$$-I_o=i=-I_m \sin\phi,$$

consequently

$$\sin\phi=\frac{I_o}{I_m}. \tag{3}$$

The potential difference across the condenser e is determined by

$$e=e_1+L\frac{d\,i}{d\,t}, \tag{4}$$

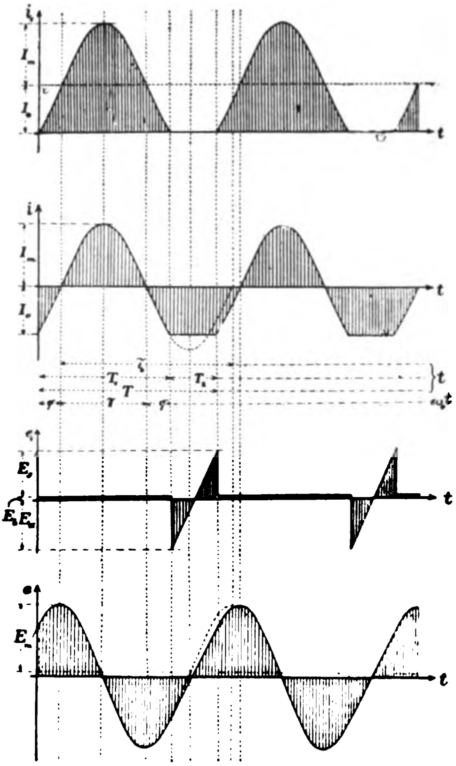


Figure 8—Current and Voltage Curves Corresponding to Barkhausen's Simple Characteristic $R=0$

where e_1 is the voltage of the arc. Equation (4) assumes two different forms according to whether the arc is burning or extinguished. These forms are respectively

$$e=E_c+\omega_0 L\, I_m \cos\left(\omega_0 t-\phi\right), \tag{5a}$$

when the arc is burning, and

$$e=e_1, \tag{5b}$$

when the arc is extinguished.

For $t=0$, we have further

$$e=e_1=E_s+E_c,$$

therefore, in consequence of (5a),

$$E_s=\omega_0 L\, I_m \cos\phi=\varrho\, I_m \cos\phi=\varrho\sqrt{I_m^2-I_o^2}, \tag{6}$$

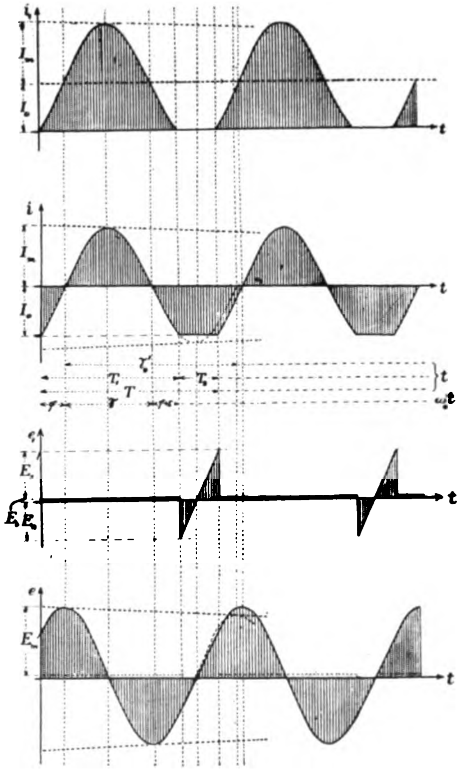


Figure 9—Current and Voltage Curves Corresponding to Barkhausen's Simple Characteristic $R>0$

or

$$\frac{I_m^2}{I_o^2}=1+\left(\frac{E_s}{\varrho\, I_o}\right)^2=1+k^2, \tag{7}$$

where

$$k=\frac{E_s}{\varrho\, I_o} \text{ and } \tan\phi=\frac{1}{k}. \tag{8}$$

The period T can be divided into two parts: the burning period T_1 and the extinguished period T_2. Calling the natural period of the radio frequency circuit $\tau_o = \frac{2\pi}{\omega_o}$, we have (see Figure 8)

$$T_1 = \frac{1}{2}\tau_o + \frac{2\phi}{2\pi}\tau_o,$$

and
$$I_o T_2 = C\,(E_s + E_c - E_a) = 2\,C\,E_s,$$

or
$$T_2 = 2\,C \cdot \frac{E_s}{I_o} = 2\,\omega_o L C \frac{I_m}{I_o} = \frac{\tau_o}{\pi} \cdot cot\,\phi. \tag{9}$$

The ratio f_o between the actual period $T = T_1 + T_2$ and the natural period τ_o is consequently

$$f_o = \frac{T}{\tau_o} = \frac{1}{2} + \frac{1}{\pi}(\phi + cot\,\phi) = \frac{1}{2} + \frac{1}{\pi}\left(tan^{-1}\frac{1}{k} + k\right). \tag{10}$$

We have

$$tan^{-1}\frac{1}{k} = \frac{\pi}{2} - k + \frac{1}{3}k^3 - \frac{1}{5}k^5 + \cdots$$

which, inserted in (10), gives

$$f_o = 1 + \frac{k^3}{3\pi} - \frac{k^5}{5\pi} + \cdots \tag{11}$$

Figure 10 shows the value of f_o as a function of k. It appears that only for values of k larger than 0.2 do we find f_o deviating noticeably from the value 1.

The ratio g_o between the effective value I of the current in the r. f. circuit and the d. c. I_o is determined by:

$$g_o^2 = \frac{\frac{1}{\omega_o} \cdot \int_o^{\pi} I_m^2 \cdot sin^2(\omega_o t) \cdot d(\omega_o t) + \frac{2}{\omega_o} \cdot \int_o^{\phi} I_m^2\, sin^2(\omega_o t) \cdot d(\omega_o t) + T_2 I_o^2}{\tau_o f_o I_o^2}$$

$$= \frac{I_m^2\left(\frac{\pi}{2} + \phi - \frac{1}{2} sin\,2\phi\right) + 2 I_o^2 cot\phi}{2\pi f_o I_o^2} = \frac{(1+k^2)\left(\frac{\pi}{2} + \phi\right) + k}{2\pi f_o}$$

$$= \frac{1}{2}\left(1 + k^2 - \frac{k^3}{\frac{\pi}{2} + tan^{-1}\frac{1}{k} + k}\right). \tag{12}$$

Figure 11 shows how g_o is dependent on k.

For small values of k, (12) becomes

$$g_o = \sqrt{\frac{1}{2}(1+k^2)} = \left(1 + \frac{1}{2}k^2\right)\sqrt{\frac{1}{2}}, \tag{13}$$

or, if we can cancel $\frac{1}{2}k^2$ as small compared to 1,

$$g_o = \sqrt{\frac{1}{2}} = 0.707.$$

For small values of k, the value of g_o is very nearly equal to this limit.

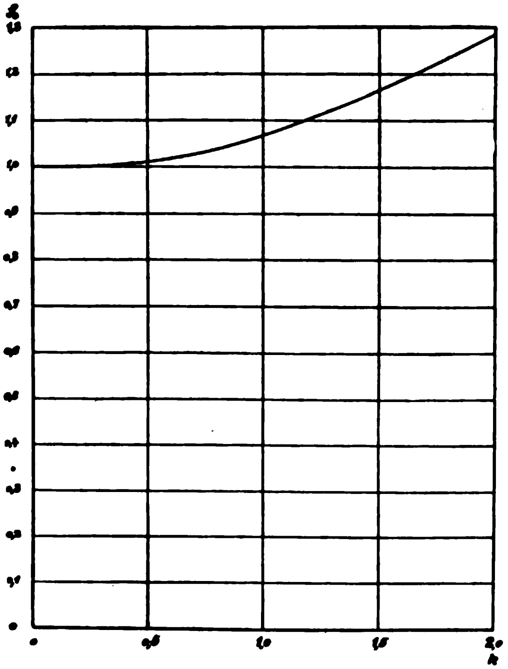


Figure 10—Ratio of the Period of the R. F. Current to the Natural Period of the R. F. Circuit. (With the parameter k as abscissa)

By inserting the value of k taken from (8) in (12), g_o is obtained as a function of $\frac{I_o}{I_m}$, and this function is shown in Figure 12.

We find without difficulty that $g_o = \sqrt{\frac{1}{2}}$ for $\frac{I_o}{I_m} = 1$, and that the tangent to the curve in this point makes an angle ψ with the axis where $\tan \psi = -\sqrt{\frac{1}{2}}$.

For values of $\frac{I_o}{I_m}$ not differing considerably from 1, we have with a good degree of approximation (see Figure 12)

$$g_o = \left(2 - \frac{I_o}{I_m}\right) \sqrt{\frac{1}{2}}. \tag{14}$$

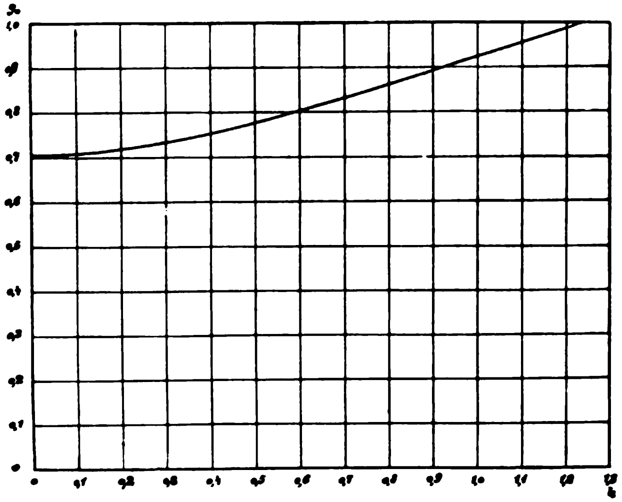


FIGURE 11—Ratio of the Effective Value of R. F. Current to the Supply Current. (With the parameter k as abscissa)

b. $R > 0$.

While the arc is burning, the current i in the r. f. circuit can be written

$$i = I_m \cdot \varepsilon^{-\kappa t} \cdot \sin\left(\omega_o' t - \phi\right) \tag{15}$$

When the arc is extinguished, $i = -I_o$.

For $t = 0$, both cases give the same value of i, namely, $i = -I_o$. Consequently we have

$$\sin\phi = \frac{I_o}{I_m} = \frac{1}{\sqrt{1 + k^2}}. \tag{16}$$

While the arc is burning, the potential difference across the condenser is determined by:

$$e = E_b + R\,i + E_m \cdot \varepsilon^{-\kappa t} \cos\left(\omega_o' t - \phi - \chi\right). \tag{17}$$

As i is the discharge current of the condenser, we must have

$$-i = C \cdot \frac{de}{dt},$$

consequently

$$I_m \sin(\omega_o' t-\phi) = CE_m\left[\kappa \cos(\omega_o' t-\phi-\chi)+\omega_o' \sin(\omega_o' t-\phi-\chi)\right]. \\ -R\frac{di}{dt} \qquad (18)$$

From this we obtain the following approximate formula:

$$E_m = \varrho I_m \text{ and } \tan\chi = \frac{\kappa}{\omega_o} = \frac{R}{2\varrho}. \qquad (19)$$

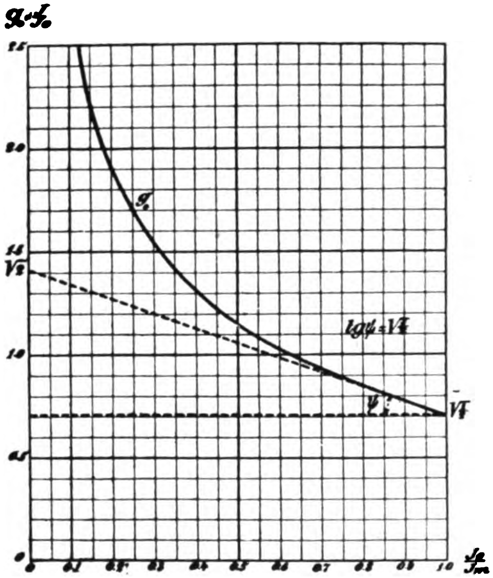


FIGURE 12—Ratio of the Effective Value of R. F. Current to the Supply Current. (With the Ratio $\frac{I_o}{I_m}$ as abscissa)

As the arc is supposed to strike or ignite just as $t=0$, the following equation must be satisfied:

$$E_s = I_o R + E_m \cdot \cos(\phi+\chi). \qquad (20)$$

Herein

$$\cos(\phi+\chi) = \frac{k}{\sqrt{1+k^2}} - \frac{1}{\sqrt{1+k^2}} \cdot \frac{\kappa}{\omega_o}, \qquad (21)$$

and, inserting this in (20), we obtain

$$E_s = k\,\omega_o L I_o + \frac{1}{2} R I_o.$$

or
$$k=\frac{o}{\omega_0 L}\left(\frac{E_s}{\varrho I_o}-\frac{R}{2\varrho}\right)=\frac{E_s}{\varrho I_o}-\frac{R}{2\varrho} \tag{22}$$

In most cases, (22) may be written
$$k=\frac{E_s}{\varrho I_o}. \tag{23}$$

Determination of the Period.

The time during which the arc is burning is, as above stated, T_1, that during which it is extinguished, T_2, and the complete period T is therefore $T=T_1+T_2$.

For the determination of T_2, we have
$$I_o T_2=C\,(E_s+E_b-E_a)=LC\left[\left(\frac{d\,i}{d\,t}\right)_{t=0}-\left(\frac{d\,i}{d\,t}\right)_{t=T_1}\right]. \tag{24}$$

Here we have
$$L\frac{d\,i}{d\,t}=I_m L\,[\omega_o'\cos(\omega_o t-\phi)-\kappa\sin(\omega_o' t-\phi)]\,\varepsilon^{-\kappa t}, \tag{25}$$

and therefore
$$E_s=L\left(\frac{d\,i}{d\,t}\right)_{t=0}=I_m L\,(\omega_o'\cos\phi+\kappa\sin\phi),$$

and
$$E_a-E_c=L\left(\frac{d\,i}{d\,t}\right)_{t=T_1}=I_m L\,[\omega_o'\cos(\omega_o' T_1-\phi)-\kappa\sin(\omega'_o T_1-\phi)]\,\varepsilon^{-\kappa T_1}$$

The moment of extinction T_1 is determined by
$$-I_o=I_m\varepsilon^{-\kappa T_1}\sin(\omega_o' T_1-\phi),$$
or
$$\sin\phi+\varepsilon^{-\kappa T_1}\sin(\omega_o' T_1-\phi)=0. \tag{26}$$

From the expression for E_s and E_a-E_b we obtain when using (26)
$$E_s-(E_a-E_b)=\omega_o' L\,I_m\,[\cos\phi-\varepsilon^{-\kappa T_1}\cos(\omega_o' T_1-\phi)]. \tag{27}$$

We have very approximately $\omega_o'=\omega_o$, and we will always use this approximation in the following discussion. The last equation then reduces to
$$T_2=\frac{1}{\omega_o\sin\phi}\cdot[\cos\phi-\varepsilon^{-\kappa T_1}\cos(\omega_o T_1-\phi)].$$

The ratio f between the period T of the radio frequency current and the natural period τ_o of the r. f. circuit is consequently determined by:
$$f=\frac{T}{\tau_o}=\frac{T_1+T_2}{\tau_o}=\frac{1}{2\pi}\left(\omega_o T_1+\cot\phi-\frac{\cos(\omega_o T_1-\phi)}{\sin\phi}\cdot\varepsilon^{-\kappa T_1}\right). \tag{28}$$

The period T is hereby determined as a function of T_1, and therefore this last quantity must be determined, which is done by solving the transcendental equation (26). In order to obtain an idea of the necessary accuracy with which this equation must be solved, we will calculate the differential quotient of T with regard to T_1, that is

$$\frac{dT}{dT_1}=1+\frac{1}{\omega_0 \sin\phi}\cdot\left[\kappa\cos(\omega_0 T_1-\phi)+\omega_0\sin(\omega_0 T_1-\phi)\right].\varepsilon^{-\kappa T_1} \quad (29)$$

which, by using (26), can be written as

$$\frac{dT}{dT_1}=\frac{\kappa}{\omega_0}\cdot\frac{\cos(\omega_0 T_1-\phi)}{\sin\phi}\cdot\varepsilon^{-\kappa T_1} \quad (30)$$

where the last factor is less than 1, so that

$$\frac{dT}{dT_1}<\frac{\kappa}{\omega_0}=\frac{\delta}{2\pi}. \quad (31)$$

Accordingly no very minute determination of T_1 is necessary.

For $\kappa=0$, equation (26) is satisfied by $\omega_0 T_1=\pi+2\phi$, and we therefore put

$$\omega_0 T_1=\pi+2\phi+\beta, \quad (32)$$

in consequence of which (26) can be written as

$$\cos\beta+\sin\beta\cdot\cot\phi=\varepsilon^{\frac{\kappa}{\omega_0}(\pi+2\phi+\beta)} \quad (33)$$

Generally β will be small, and if so (33) takes the form

$$\beta=(\pi+2\phi)\cdot\frac{\kappa}{\omega_0}\cdot\tan\phi, \quad (34)$$

where the square and higher powers of β and $\frac{\kappa}{\omega_0}$ have been neglected. In the derivation of (34) it is further assumed that $\frac{\kappa}{\omega_0}\tan\phi\ll 1$. As $\tan\phi$ can assume large values, this term must be specially examined. We have

$$\frac{\kappa}{\omega_0}\cdot\tan\phi=\frac{1}{k}\frac{R}{2\varrho}.$$

We will find later that the B-theory can be employed only when $k>\sqrt{6\frac{R}{\varrho}}$, and inserting this value in the above equation we obtain

$$\frac{\kappa}{\omega_0}\cdot\tan\phi<\frac{1}{2}\sqrt{\frac{R}{6\varrho}}=\frac{1}{6}\sqrt{\frac{\delta}{2}}. \quad (35)$$

The value of β as determined by (34) gives, therefore, in general a sufficiently close determination of T_1.

In consequence of (28), we have

$$\omega_o T = \omega_o T_1 + \omega_o T_2 = \omega_o T_1 + \cot\phi + \frac{\cos(\phi+\beta)}{\sin\phi} \cdot \varepsilon^{-\kappa T_1} \tag{36}$$

Using (32) and (34), we obtain from (36) the following approximate formula for T:

$$\omega_o T = \pi + 2\phi + 2\cot\phi - (\pi + 2\phi)\frac{\kappa}{\omega_o} \cdot \cot\phi,$$

and correspondingly

$$f = \frac{T}{\tau_o} = \frac{1}{2} + \frac{\phi}{\pi} + \frac{1}{\pi}\cot\phi - \left(\frac{1}{2} + \frac{\phi}{\pi}\right)\frac{\kappa}{\omega_o}\cot\phi, \tag{37}$$

or approximately

$$f = f_o - k\frac{R}{2\rho}, \tag{38}$$

so that f in practice differs only slightly from f_o which is shown in Figure 10.

For the value of $g = \frac{I}{I_o}$ we find, after some calculations, the following approximate formula:

$$g^2 = \frac{\frac{1}{\sin\phi}\left(\frac{\pi}{2} + \phi - \frac{1}{2}\sin 2\phi + (\pi + 2\phi)\frac{\kappa}{\omega_o}\tan\phi\right) + 2\cot\phi\left(1 - \frac{\kappa}{2\,\omega_o}(\pi + 2\phi)\frac{1}{\cos^2\phi}\right)}{\pi + 2\phi + 2\cot\phi - \frac{\kappa}{\omega_o}(\pi + 2\phi) \cdot \cot\phi}$$

$$= \frac{\frac{\pi}{2} + \phi + \frac{1}{2}\sin 2\phi}{2\pi f \sin^2\phi} = \frac{(1 + k^2)\left(\frac{\pi}{2} + \phi\right) + \frac{1}{k}}{2\pi f} \tag{39}$$

This equation is quite analogous to (12), so that g can be determined with sufficient accuracy from the curve shown in Figure 11. It appears that the numerator of (39) is exactly the same function of $\sin\phi = \frac{I_o}{I_m}$ as for $R = 0$. According to (38), f is very nearly equal to f_o, and consequently the following approximate formula, analogous to (14), holds good for g:

$$g = \left(2 - \frac{I_o}{I_m}\right)\sqrt{\frac{1}{2}}. \tag{40}$$

c. THE PARAMETER k.

In the preceding, we have introduced a parameter k, and assumed this parameter to be small—at least smaller than 1. If the constants of the arc-circuit are given, the B-theory itself does, however, put a limit to the value of k. This is easily seen thus: The condition for using Barkhausen's simple characteristic—or, put otherwise—a condition for producing oscillations of the second type is, according to the B-theory, that the arc current drops to zero, i. e., that the first minimum value of the arc current, $I_{1,min}$ is $\leqq 0$. With sufficiently close approximation, we can put

$$I_{1,min} = I_o + I_m \cdot \varepsilon^{-\kappa t} sin\,(\omega_o t - \phi), \tag{41}$$

where $\omega_o t$ is given the value $\phi + \frac{3}{2}\pi$, which, inserted in (41) gives

$$I_{1,min} = I_o - I_o \sqrt{1 + k^2} \cdot \varepsilon^{-\frac{R}{2\varrho}\left(\frac{3}{2}\pi + \phi\right)} \tag{41$_1$}$$

Having that $I_{1,\,min} \leqq 0$, we get

$$1 + k^2 \geqq \varepsilon^{\frac{R}{\varrho}\left(\frac{3}{2}\pi + \phi\right)} \tag{42}$$

The exponent in this expression always being small, we may write (42) as

$$k = \geqq \sqrt{\left(\frac{3}{2}\pi + \phi\right)\frac{R}{\varrho}}. \tag{42$_1$}$$

A condition for the use of the simple characteristic is therefore that, with sufficient accuracy for this purpose

$$k \geqq \sqrt{6\frac{R}{\varrho}} \tag{43}$$

In consequence whereof, the ignition potential difference must satisfy the following relation:

$$E_s \geqq I_o\left(\sqrt{6\varrho R} + \frac{1}{2}R\right). \tag{44}$$

The relations derived from the B-theory in this part of the paper have all been of a merely formal nature. In the following part, we shall examine whether the relations obtained agree with experimental results as far as the Poulsen arc is concerned.

4. COMPARISON OF THE CONSEQUENCES OF THE B-THEORY WITH EXPERIMENTAL RESULTS

We found previously that the parameter k, according to (43) must be larger than $\sqrt{6\frac{R}{\varrho}}$. If, for example, we put $R=5$ ohms and $\varrho=60$ ohms, we obtain $k>0.71$, which according to Figure 11, corresponds to $g>0.83$; while g for the Poulsen arc actually is very nearly equal to 0.71. To this experimentally obtained value of g correspond, in consequence of the B-theory, very small values of k, at any rate not greater than 0.15, since g for larger values of k, according to that theory, diverges rapidly from the value $\sqrt{\frac{1}{2}}$. *As, however, the application of the B-theory determines a minimum value of k which is much larger, that theory is not in harmony with the experimental results.*

The B-theory requires further that the "striking" or ignition voltage of the arc is at least equal to the value of E_s as determined by (44); but on measuring the maximum voltage across the arc by means of a micrometer spark gap—in series with a small condenser so as to avoid short circuiting—much smaller values are found. Thus for $I_0=20$ amperes, $R=3$ ohms, and $\varrho=400$ ohms, to which, according to (44), corresponds an $E_s=1{,}730$ volts, a spark gap as small as 0.01 mm. (0.0004 inch) was needed in order to obtain regular sparking. The gap was exposed to ultra-violet light from an arc. Consequently the maximum voltage is nearly the same as the critical voltage, that is, about 380 volts. The normal voltage for striking the arc is, therefore, far below the value found above, namely 1,730 volts, a fact also verified later on. This applies to the normal Poulsen arc with a normal distance between the electrodes which is nearly equal to the minimum critical distance (see section 2a). If the distance is increased as much as possible, the spark length increases up to 0.14 mm. (0.0057 inch) under the said conditions. This corresponds to a striking voltage of about 1,100 volts, which is considerably nearer the requirements of the B-theory, and later on we will see that the conditions existing when excessive arc lengths are used are in accordance with the B-theory.

5 *a*. REASONS WHY THE B-THEORY IS NOT APPLICABLE TO THE POULSEN ARC

The foregoing discussion shows that the B-theory does not apply to the normal Poulsen arc. On the other hand, there can be no doubt that the two most pronounced features of the characteristic shown in Figure 7—the comparatively high ignition voltage and the low voltage while the arc is burning—are essentially in agreement with the actual conditions. But there is a third feature of the arc phenomenon, which is missing in Barkhausen's simple characteristic, namely: the comparatively high voltage across the arc during the extinction. The simple characteristic of Barkhausen presupposes that the arc is extinguished on the lower voltage which exists while the arc is burning; but it is well known that this is not the case. The voltage during the extinction is often considerably higher (see, for example, A. Blondel[12]). When Barkhausen omits any reference to the extinction voltage, his motive is, no doubt, to simplify his characteristic. On the other hand, such an ideal characteristic is of value only if the results derived by means of it are in fair agreement with the actual conditions. *For the normal Poulsen arc, we have shown this not to be the case; and it will appear from the following that the reason why is that the extinction voltage is of very great importance in connection with the action of the normal arc generator.* It will also be shown that the Barkhausen characteristic, under certain circumstances, represents the actual conditions with a good degree of approximation; but these circumstances, tho often present during laboratory experiments, are never to be found in the normal Poulsen arc.

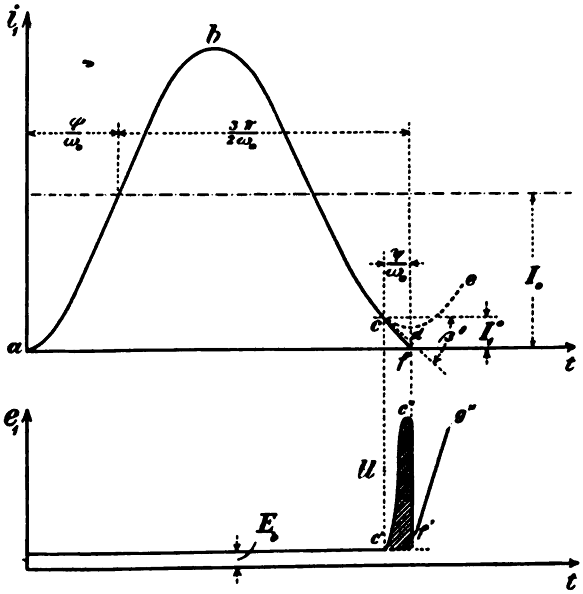
b. EXTINCTION OF THE ARC

We will now examine the conditions in the arc during extinction. In Figure 13, the curve *abcde* represents the current thru the arc, assuming this to be struck at *a*, and thereafter burning on the constant voltage E_b. The equation for this current curve is then

$$i_1 = I_o + I_m \varepsilon^{-\kappa t} \sin(\omega_o t - \phi). \qquad (45)$$

In this case, where the arc current does not fall quite to zero, according to the B-theory, the current curve would continue past the point *d* as a damped harmonic oscillation gradually dying out, the arc current becoming fairly constant until the magnetic field extinguishes the arc again and a new oscillating discharge takes place.

The conditions are, however, somewhat different in reality. When the arc current has decreased to a certain low value I_1^o—in Figure 13 assumed to be at the point *c*—the voltage across the arc will commence to increase noticeably. The consequence of this is a more rapid dropping of the current than the curve *cd* indicates, and the more the current decreases, the more the voltage rises in consequence and the steeper in turn becomes the drop of the current curve. If the arc current decreases at all to the value I_1^o, whereby the voltage at extinction commences to influence it strongly, the result will generally be that the arc is extinguished. We will now deduce the conditions for a drop in the arc current to a value of $I_1^o = aI_o$ or less, where $a \ll 1$. The condition for this is



k·Q1

Figure 13—Conditions for the Extinction of the Arc

$$1-\sqrt{1+k^2}\cdot \varepsilon^{-\frac{R}{2\rho}\left(\frac{3}{2}\pi+\phi\right)} \leq a,$$

or

$$(1-a)^2 \cdot \varepsilon^{\frac{R}{\rho}\left(\frac{3}{2}\pi+\phi\right)} \leq 1+k^2. \qquad (46)$$

For the normal Poulsen arc a will always be a comparatively small quantity, and as usual $R \ll \rho$. From (46) we can, therefore, derive the following approximate formula:

$$\frac{R}{\rho}\left(\frac{3}{2}\pi+\phi\right) \leq 2a+k^2. \qquad (47)$$

Here ϕ is a little less than $\frac{\pi}{2}$, while k^2 generally is considerably less than $2a$. Equation (47) can, therefore, be replaced with sufficient accuracy for the present purpose by

$$3\frac{R}{\varrho} \leqq a \quad \text{or} \quad I_1^o \geqq 3 I_o \frac{R}{\varrho} \tag{48}$$

According to (48) the extinction voltage must necessarily commence exerting its influence when the arc current has decreased to a value larger than—or at least equal to—$3 I_o \frac{R}{\varrho}$. *Only when this is the case will the arc extinguish once for every period, and only then will regular and continuous radio frequency oscillations be obtained.*

c. INTEGRAL VALUE OF EXTINCTION VOLTAGE. DETERMINATION OF ITS MINIMUM VALUE

It is even more important to examine what integral value the extinction voltage must at least assume in order to blow out the arc, when by the integral value is meant $U = \int (e_1 - E_b) dt$, where the integral is extended over the entire time it takes to blow out the arc. We do, however, meet here the difficulty that the law according to which the extinction voltage varies is unknown; and, as the experimental determination of it is very difficult, we cannot consider it on this occasion. Since, however, the main object is to reach a qualitative understanding of the phenomena, we will proceed so that we determine the smallest value which U can assume under the given circumstances. For this purpose we commence by determining the angle β which the tangent forms with the axis of abscissas at the point c. Using the symbols as in Figure 13 and with $\omega_o t = \frac{3}{2}\pi + \phi - \psi$, we have

$$\tan \beta = -\left(\frac{d i_1}{d t}\right)_{\omega_o t = \frac{3}{2}\pi + \phi - \psi} =$$

$$-\omega_o I_o \sqrt{1+k^2}\left(\sin \psi - \frac{R}{2\varrho}\cos \psi\right) \varepsilon^{-\frac{R}{2\varrho}\left(\frac{3}{2}\pi + \phi - \psi\right)} \tag{49}$$

At the point c the value of the arc current is

$$I_1^o = I_o\left(1 - \sqrt{1+k^2}\cos \psi\, \varepsilon^{-\frac{R}{2\varrho}\left(\frac{3}{2}\pi + \phi - \psi\right)}\right). \tag{50}$$

At this point c (Figure 14), where the arc current has the value I_1^o, the current decreases with the velocity

$$\frac{d i_1}{d t} = \tan \beta \cdot$$

Between the voltage across the arc and the condenser voltage we have, according to (4), the following relation

$$e_1 = e - L\frac{d\,i_1}{d\,t}, \tag{51}$$

where we do not consider the voltage drop caused by the resistance of the radio frequency circuit, as this is unimportant.

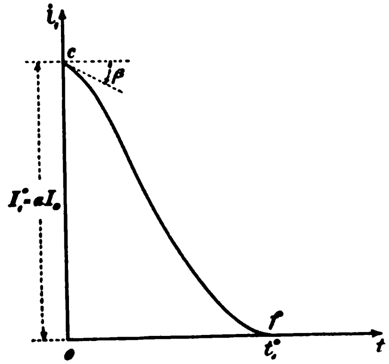


FIGURE 14—Current Curve during the Extinction of the Arc

As the blowing out of the arc commences just at the point c, we have (Figure 14)

$$(e_1)_{t=0} = E_b = (e)_{t=0} - L\,tan\,\beta. \tag{52}$$

We assume now, for the sake of simplicity, that $\alpha = \frac{I_1^\circ}{I_o}$ is so small a quantity that we can, with sufficient accuracy, consider the current charging the condenser to be constant and equal to I_o, during the entire time taken to extinguish the arc. With the normal Poulsen arc, this is practically the case. The voltage across the condenser while the arc extinguishes is then determined by

$$e = (e)_{t=0} + \frac{I_o}{C}t, \tag{53}$$

and consequently we have

$$e_1 - E_b = \frac{I_o}{C}t - L\left(\frac{d\,i_1}{d\,t} - tan\,\beta\right), \tag{54}$$

and

$$U = \int_o^{t_1^\circ}\left(e_1 - E_b\right)d\,t = \frac{1}{2}\frac{I_o}{C}t_1^{\circ 2} + L\,t_1^\circ\,tan\,\beta + L\,I_1^\circ. \tag{55}$$

where t_1^o is the time taken to extinguish the arc. From (54) it is seen that U is dependent only on the conditions when the extinction begins, the time this lasts, and finally the constants of the radio frequency circuit; while independent of the degree of progress of the extinction.

U will have the least possible value for

$$t_1^o = -\frac{1}{\omega_o^2 I_o} \cdot \tan\beta, \tag{56}$$

and

$$U_{min} = L I_1^o - \frac{1}{2} \frac{L}{\omega_o^2 I_o} \tan^2\beta. \tag{57}$$

If, inserting herein the values of $\tan\beta$ and I_1^o, given in (49) and (50), and also assuming—which is the case in practice—that 1) $k^2 \ll 1$, 2) ψ is so small a quantity that, with sufficient accuracy, we can put $\sin\psi = \psi$ and $\cos\psi = 1 - \frac{\psi^2}{2}$, 3) $\psi \gg \frac{R}{2\rho}$, we obtain this simple approximate formula for U_{min}:

$$U_{min} = \frac{1}{\omega_o} I_o R \left(\frac{3}{4}\pi + \frac{\phi}{2}\right), \tag{58}$$

or, as ϕ is slightly less than $\frac{\pi}{2}$, we obtain, with sufficient accuracy,

$$U_{min} = \frac{3}{\omega_o} I_o R. \tag{59}$$

At the same time, we obtain for t_1^o the approximate value

$$t_1^o = \frac{\psi}{\omega_o}. \tag{60}$$

The least average rise in voltage P during the extinction is therefore determined by

$$P = \frac{U_{min}}{t_1^o} = \frac{3}{\psi} \cdot I_o R. \tag{61}$$

6. OUTLINE OF THE WORKING PRINCIPLES OF THE POULSEN ARC

We shall now deal with the conditions at the moment the arc is struck; but first we must examine briefly the influence of the magnetic field on the arc phenomena and give a general outline of the working principles of the Poulsen arc.

The magnetic field drives the arc outward, the velocity increasing with increase of the intensity of the field. Not only the arc itself, but also its bases (or craters) are travelling outward along the electrodes; but we will later find occasion to treat this question thoroly. This travelling—or blowing out—of the arc contributes largely to a rapid de-ionisation thereof. With a comparatively weak magnetic field, we obtain the case sketched in Figure 15, part *a*, where the arc is not being fully extinguished. Owing to the quick rise in the potential difference across the condenser, the voltage across the arc also rises comparatively rapidly, thereby causing the current thru the arc to increase again before it has been quite extinguished. In this case, oscillations of the 1st type are obtained; but they are quite similar to those of the 2nd type. As we will see later, this condition is rather instable.

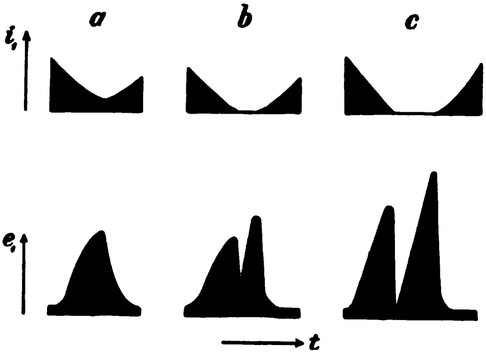


FIGURE 15—Sketch Representing the Influence of Magnetic Fields of Different Intensities on the Extinction and Re-Starting of the Arc

With a somewhat stronger field, we will obtain the case sketched in Figure 15, part *b*, where the arc is being completely extinguished, but comparatively slowly, so that the voltage across the arc at the moment of extinction only drops comparatively slightly below the maximum value of the extinction voltage. While the arc is out, the arc voltage rises with the same rapidity as the voltage across the condenser, and when the voltage has reached a certain value, the arc is lit again. *By choosing small distances between the electrodes*—and such are, as we shall see later, always used in practice—*the maximum ignition (or striking) voltage needs not be much higher than the maximum extinction voltage. The de-ionisation is, of course, more pronounced at the moment of lighting (or striking) than at* *the moment of extinction; but the lighting on the other hand is accomplished at a shorter arc length than the extinction, since the first takes place between the edges of the electrodes while the latter occurs some distance back on the electrodes, the arc being driven from the first to the second position by the magnetic field.*

With the field further increased we obtain the case shown in Figure 15, part *c*, where the arc is blown out so rapidly that the arc voltage at the moment of extinction drops very considerably, perhaps becoming reversed. It rises again, with the same rapidity as does the voltage across the condenser, until the ignition (or striking) voltage is reached. As the period of extinction in this case lasts a little longer, the ignition voltage must be somewhat higher than the extinction voltage; tho not very much more if the distance between the electrodes is short. The stronger magnetic field does, however, effect a very pronounced doubling of the voltage curve, thus producing two peaks of which the second one is slightly—but only slightly—higher than the first one.

The view here set forth does—as may be noticed—diverge considerably from the one we summed up above as the B-theory. This latter theory directs attention only to the ignition voltage and the conditions connected therewith. According to the B-theory, the efficiency of the arc generator is dependent mainly on a high ignition voltage, and an explanation of the means provided by Poulsen for increasing the efficiency of the Duddell arc is attempted from the point of view that these improvements tend to increase the ignition voltage. The extinction voltage is of no consequence at all in the B-theory.

According to the view set forth by the Author, and which we will briefly call the A-theory, the postulates are almost the reverse, the assumption herein being that the arc must be able to develop the necessary extinction voltage, while the ignition voltage must be as low as possible and exceed the former only by very little.

We have shown above that the consequences of the B-theory do not agree with practically obtained results so far as the Poulsen arc is concerned; and we will now undertake to ascertain whether the A-theory does agree with practice in this respect.

7. EXPERIMENTAL RESEARCHES ON THE A-THEORY

a. STUDY OF THE ARC VOLTAGE

The most direct method with which to investigate the correctness of the view here set forth is to take the voltage curve for the arc, while this acts as generator of continuous radio frequency currents. Considering the views set forth in the beginning of this paper, I have not thought it safe to employ the method indicated by Hausrath, in which a Braun tube is used. Presumably there remains available only the Gehrcke cathode-glow oscillograph[25]. This method has the advantage that a direct oscillographic reproduction of the form of the voltage curve is obtained—not a mean curve of several million periods as with the above named. A drawback is the low intensity of the light available at a high recording speed, and this is more severely felt just at present since the most sensitive photographic plates are not on the market. Another difficulty, when using the Gehrcke cathode glow tube is that even the maximum voltage across the arc in most cases is insufficient to light up the tube. This can be overcome, however, by "polarizing" the tube thru the application of a sufficiently high, constant, additional tension. The arrangement is shown in Figure 16 where G indicates the Gehrcke tube, FP the photographic plate; and HS the rotating mirror. In series with the arc and the tube is inserted a 500 volts battery, and in order to prevent any considerable amount of direct current from passing thru the tube—which would make it "sluggish"—there are also inserted two resistances made up of incandescent lamps a large resistance LB_1 and a smaller one LB_2. The voltage required to light the tube is about 600–700 volts, and since the voltage of the arc when it is burning is only approximately 50 volts or even less, the tube will light up only during the times when the voltage of the arc is considerably higher than when it is actually burning. In order to obtain the light flashes as pronounced as possible, a condenser C_1—of 25,000 cm. (0.028 μf.)—was shunted across the resistance LB_1.

In Figure 16a are shown reproductions of some of the oscillograms taken. Portions a, c, and d show the normal appearance of these oscillograms, which—as may be noticed—fully correspond to the voltage curve shown in Figure 15c and are altogether in good agreement with the A-theory. With a somewhat weaker magnetic field, oscillograms as shown in portion e are obtained, being of the same character as Figure 15, part a. *This oscillographic investigation has thus altogether verified the views here set forth.*

b. EXPLANATION OF THE EXPERIMENTAL VALUES OF g AND E_t

We shall now examine the above-mentioned points on which the B-theory failed, in order to ascertain whether the A-theory is more in agreement with the experimentally obtained results. We shall first estimate the value of the maximum voltages required by the A-theory. According to (61), the mean extinction voltage is determined by

$$P=\frac{3}{\psi}\cdot I_0 R.$$

We will assume here and in the following discussion that the angle ψ does not vary much in the various cases, a supposition which gains some support from the oscillograms. So far as the actual value of ψ is concerned, this cannot be determined with much accuracy from the material at hand, but by estimating we have fixed it at 0.6; and thus (61) reduces to

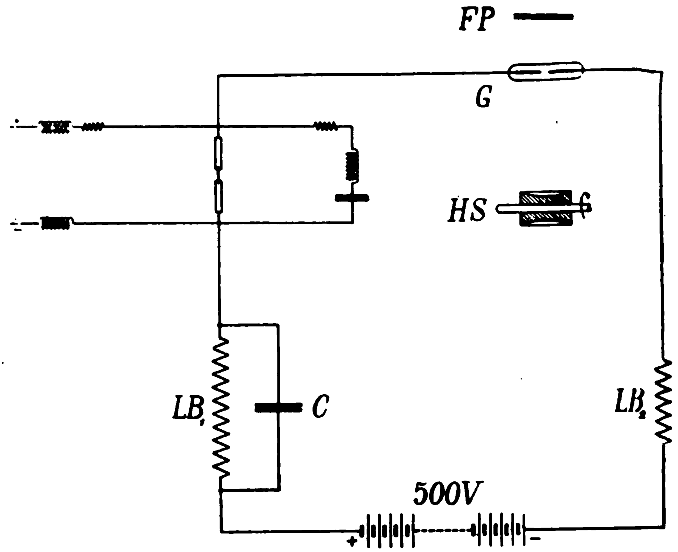


Figure 16—Diagram of the Gehrcke Cathode Glow Oscillograph

$$P=5\,I_0 R. \qquad (62)$$

For the example mentioned under heading 4, where $I_0=20$ amperes and $R=3$ ohms, P is therefore 300 volts. The maximum extinction voltage is, of course, somewhat higher than the mean, and the ignition voltage again somewhat higher than the extinction voltage; so that, according to the calculations, the maximum ignition voltage will probably be somewhat higher than the 380 volts as found in heading 4, but the disagreement is, at all events, far less than with the B-theory. If we further consider that the maximum voltages are only momentary, which—according to experiment—has the effect that the values of voltage indicated by the spark micrometer are too small, even if the gap is exposed to ultra-violet light, the results of these calculations are in as near agreement with the new

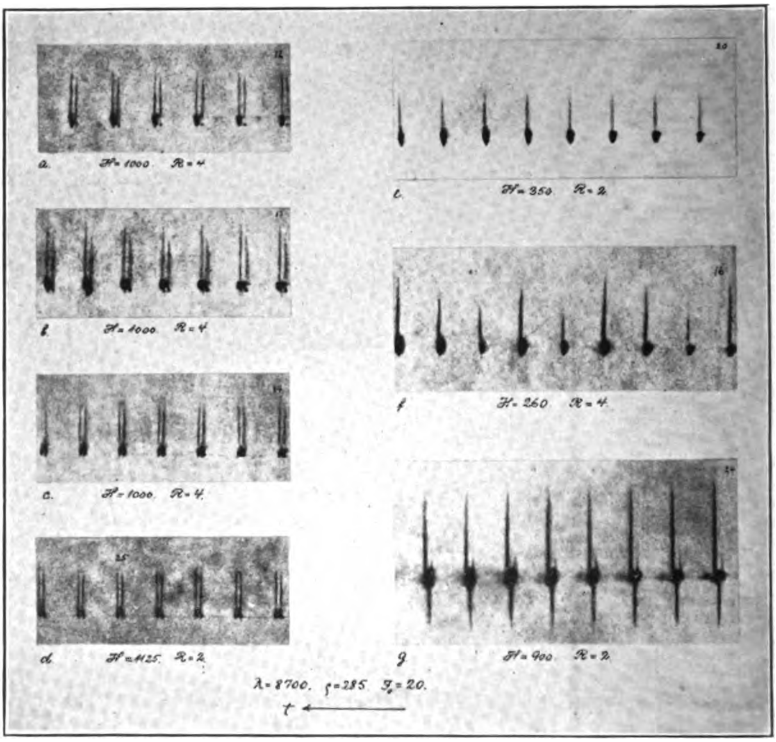


FIGURE 16a—Oscillograms of Arc Voltage Obtained with Gehrcke's Cathode Glow Oscillograph

theory as was to be expected. A determination of the maximum voltages of the arc based on the Gehrcke oscillograms did not lead to a definite result but indicated values around 300-500 volts. A full elucidation of this matter can not be expected until after a more thoro experimental and theoretical investigation of the conditions in connection with the extinction and the ignition of the arc. *But it may already be stated that the A-theory is, in the main, in accordance with the experimental results on this point.*

The next question concerns the value of g, which will be too high if determined by means of the B-theory, as this theory according to (43) demands a value of the parameter k larger than $\sqrt{6\frac{R}{\varrho}}$. This, again, is a consequence of the high ignition voltage required by the B-theory, as k and E_s are practically proportional. According to the A-theory, the ignition voltage is comparatively small, and even if the value of g according to the A-theory is not dependent on the value of k in the same manner as in the B-theory, it is, on the other hand, evident that the low ignition voltage requires a slow rise of the arc current immediately after the arc is ignited so that the current curve will be mainly a sine curve, which, at its beginning, intersects the axis at a very small angle. Accordingly, the value of g will be approximately $\sqrt{\frac{1}{2}}$. The exact, theoretical value of g can not be given at present; but it is perfectly certain to be around 0.71 as found experimentally. *The A-theory is thus in accordance with the experimental results on this point also, and provides a natural explanation of the experimentally obtained value of g.*

8. INFLUENCE OF THE DISTANCE BETWEEN THE ELECTRODES ON THE BEHAVIOUR OF THE ARC GENERATOR

As mentioned before, the distance between the electrodes in the normal Poulsen arc is comparatively small and does not differ much from the critical value. We shall now examine the result of an increase in the distance while maintaining a constant field intensity and constant supply current—the latter being done by reducing the series resistance. As the distance of separation of electrodes increases, the difference between the arc length at ignition and at extinction will become relatively less, and consequently the ignition voltage will become comparatively higher. Figure 16*a*, part *b*, shows the result of a small increase in the normal distance—about 50 per cent. By comparison with the parts *a* and *c*—both having normal distance and taken under identical conditions immediately before and after part *b*—it will be noticed that the ignition voltage already has assumed a somewhat higher value. This higher ignition voltage in turn requires a more rapid rise of current at ignition and also a steeper drop at the extinction. This latter condition results further in a reduction of the extinction voltage and a considerable drop of the arc voltage at the moment of extinction. The consequence of this is a negative arc voltage immediately after the extinction. A diagrammatic representation of these conditions is shown Figure 17, where part *a* gives the current and voltage curves for the normal Poulsen arc with the normal distance between the electrodes, while part *b* gives the same curves when the distance is larger than the normal. In case *b*, the extinction voltage is considerably smaller than in case *a*; and further *b* shows quite a considerable negative arc voltage immediately after the extinction. This negative voltage will assist the de-ionization of the arc space and consequently give an increased ignition voltage. If the distance between the electrodes be further increased, these conditions will become still more pronounced, as shown in Figure 17, part *e*. The conditions are here quite in accordance with the B-theory; and this is further verified by the oscillograms shown in parts *d* and *g* of Figure 16*a*, representing the voltage curve for the arc, and taken under conditions analogous to those mentioned; but while part *d* is with normal distance between the electrodes—about 1 mm. (0.04 inch)—part *g* is with an electrode distance of 4 mm. (0.16 inch)*. When increasing the distance, the d. c.

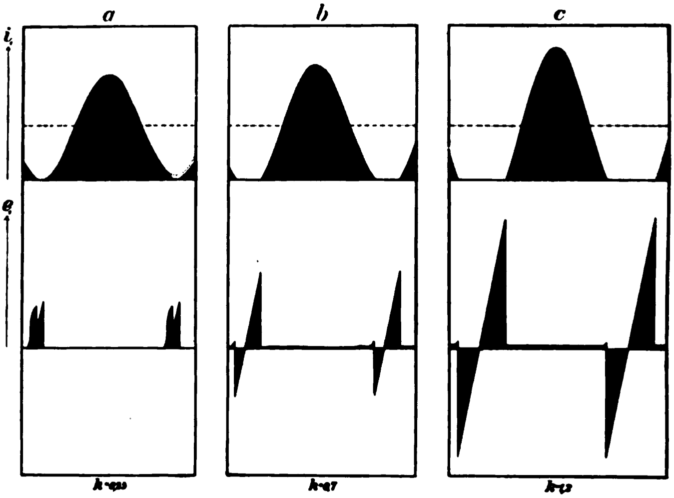


FIGURE 17—Sketch of Current and Voltage Curves for Different Distances between the Electrodes

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* A voltage oscillogram with normal distance between the electrodes was taken under conditions identical with those for part *g*, but the photographic contrast was insufficient for reproduction. It did, however, fully correspond in character to the parts *a*, *c*, and *d*.

voltage on the arc is simultaneously increased—in the above case from 85 to 160 volts. With equal supply current, the latter case will give slightly more radio frequency current than with the normal distance; but in spite of this, the efficiency factor is considerably smaller than for the normal arc. The smaller efficiency for the greater distance between the electrodes is mainly a consequence of the higher voltage demanded for keeping the arc lit. The greater distance is also objectionable in other ways as the arc then is apt to blow out. The greatly increased voltage variation from the moment of extinction to the moment of re-ignition causes a correspondingly prolonged time of "charging" and a correspondingly great "frequency sensibility" of the generator. Finally the higher voltages are inconvenient from an engineering point of view. *It can thus be fully explained why the shortest possible distance between the electrodes is used with the Poulsen arc and it is also easily understood why so many of the laboratory investigations, which more or less purposely have been carried out on the basis of the B-theory have shown results having very little relation to the conditions found in practice.*

If, on the other hand, the distance between the electrodes after having been normally adjusted is diminished, maintaining the various other conditions constant, then the re-ignition on the edge of the electrodes will take place more and more easily in proportion to the decrease in distance. A state is very soon reached where the arc instead of being extinguished will carry a considerable minimum current, and the conditions will then quickly develop into a state where the arc current is constant. This is fully in agreement with the conditions mentioned under heading 2, *a*, namely, that the arc requires a certain minimum length in order to be active.

9. INFLUENCE OF THE MAGNETIC FIELD ON THE ARC

a. PHOTOGRAPHS OF THE ARC

In order to get an understanding of the influence of the magnetic field, a series of experiments have been carried out, and numerous photographs of arcs and their craters have been taken by means of the arrangement shown Figure 6, which is explained previously. The pictures divide into 3 groups: 1. stationary crater pictures taken from above thru the mica window g_1, the lens B_1, and reflected from the mirror Sp_1 to the plate FP_1; 2. crater oscillograms, also taken from above, the light on the way to the plate FP_3 passing the rapidly rotating mirror Sp_2: 3. side views of the arc, taken thru the window g_2 and the lens B_2, on the plate FP_2. In all cases, shutters were used (L_1 and L_2), giving a time for exposure of about 0.01 second. Especially those photographs mentioned under groups 2. and 3. have contributed markedly to the explanation of the behaviour of the arc in a magnetic field under various conditions.

b. NORMAL CRATER OSCILLOGRAMS

When the arc generator is normally adjusted, i. e., when the distance between the electrodes is the most suitable, and the magnetic field has the most suitable value, at least approximately, oscillograms of the type shown in Figure 17*a*, parts *a–d*, and Figure 17*b*, part *a* are obtained. Figure 17*b*, part a_1 is a side view of the arc corresponding to part *a*—both taken simultaneously. When printing from the photographic negative, the negative crater has been exposed somewhat longer than the positive crater, since the density of the image of the negative crater is far greater than that of the positive one. (The term "crater" is here used for the bases of the arc on both electrodes, altho no actual crater exists, at least not on the positive electrode.) Figure 17*a*, parts *c* and *d* are differently exposed portions of the same plate, showing separately certain particular features. All necessary information concerning the oscillograms and the conditions under which they are taken is found from the title and the supplementary data given in the figures. Thus, small sketches show the location of the electrodes; arrows marked *t* indicates the direction of increasing time on the oscillograms; lines marked τ denote the length of the period, and scales show the dimensions at right angles to the time axis.

Figure 17*a*, part *a* corresponds to the most suitable magnetic field under the conditions in question ($\lambda = 8{,}700$ m., $R = 1$ ohm); not much is to be seen of the negative crater as it travels mainly along the vertical end surface of the carbon; the periodic character of the negative crater is clearly seen on the original plate, but the positive is by far the most pronounced. Part *b* corresponds to a shorter wave-length (4,300 m.) and a field a little too strong. Here the oscillogram of both craters is very distinct—especially that of the positive one. Furthermore, the oscillogram of the arc itself is seen between the two crater pictures. Parts *e* and *d* represent the conditions for a wavelength of 6,000 m., and a field considerably stronger than the most suitable one. Both of the craters and also the arc itself are here seen very clearly. In all of the three cases shown in Figure 17*a* the arc was burning in coal gas; whereas Figure 17*b*,

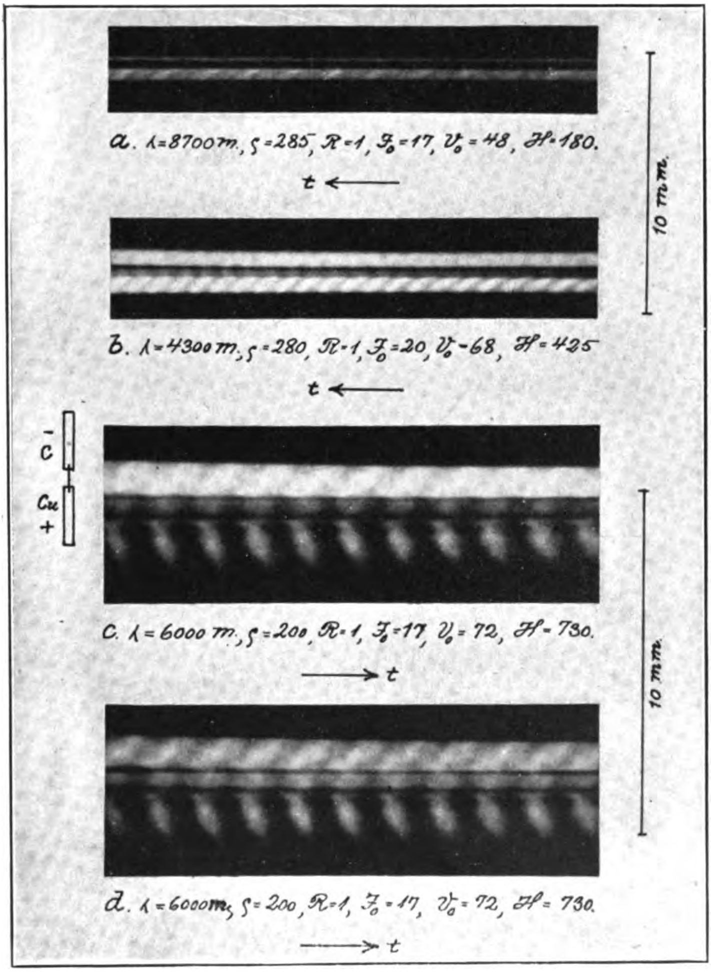

Figure 17a—Crater Oscillograms

part *a* shows the oscillogram of an arc in hydrogen. In hydrogen, only the violet core of the arc appears, while in coal gas this is surrounded by a greenish aureole.

It appears distinctly from the four oscillograms that the arc is struck once in every period on or near the edges of the electrodes and is then driven outward by the magnetic field, so that the craters in the course of the period move away from the edges.

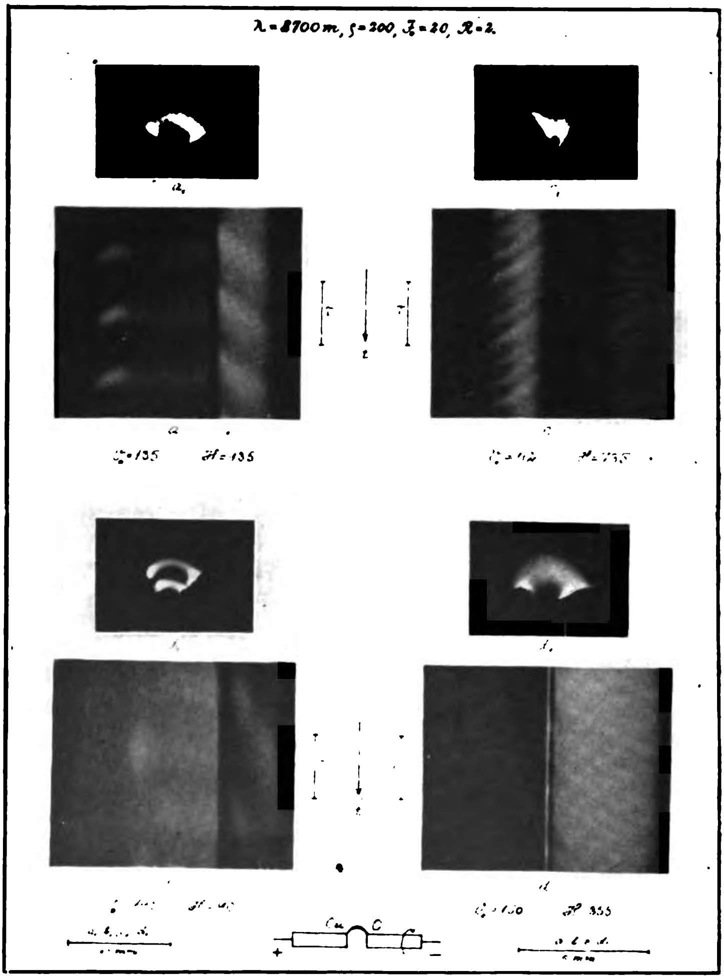

FIGURE 17b—Crater Oscillograms and Side Views. Parts a, a_1, c, c_1, d and d_1 in Hydrogen. Parts c and c_1 in Coal Gas

At the end of the period, the arc is extinguished in the outer position and re-ignites again at the edges. It is further seen that this process is repeated with much regularity.

For the purpose of a closer examination of these crater pictures, we will determine the theoretical form of the locus of the crater image during a period. We can, however, not expect any greater conformity between the theoretical and practical results, as the cathode will always be more or less eaten away, the surface thus losing its geometrically well-defined shape, and as our knowledge with regard to the movements of an arc in a magnetic field is very deficient. Nevertheless, the said investigation will still be of some interest.

For the calculations of the velocity of the arc in the magnetic field we will assume the following: 1. the current density is the same all over a cross section of the actual arc core and is constant equal to σ; 2. the cross section having the area A maintains an unaltered shape while travelling; 3. The distance x, which the arc has travelled is determined by the equation

$$A\,p\,\frac{d^2 x}{d\,t^2} = \frac{1}{10}\,A\,\sigma\,H, \tag{63}$$

where p is the density of the arc gases.

It is certain that these assumptions are only partly fulfilled. The arc will, when travelling, not only carry along the air volume contained in the arc core (fully or in part), but also some of the surrounding air. The resulting air stream will, on the other hand, accelerate the next following arc. Furthermore, the assumption that the arc carries along the larger portion of the air contained in the arc core is merely hypothetical, and not in harmony with the ideas applied—however, under essentially different conditions—by J. S. Townsend[26], R. S. Willows[27], and Wilson and Martyn[28]. The conditions can be very complicated, at least for discontinuous discharges; as appears, for instance, from the works by D. N. Mallik[29, 30]. All of these investigations are, however, almost exclusively concerned with the conditions under lower pressures and can therefore not be applied as the basis for an investigation of the matter in hand. However, many features favor the belief that our hypothesis is, in the main, correct. At all events, the equation (63) does form the simplest possible basis for our calculations, and as our immediate object is only to obtain a representation of the conditions which is correct in the main features, we shall postpone a closer investigation till later on and make equation (63) the basis of our calculations.

We shall further simplify the calculations by assuming the arc current to be constant during a part of the period and zero during the remainder of the period. That part during which the current is assumed to be constant we will estimate to be $\tau \sqrt{\frac{1}{2}}$.

By integration of the equation (63), we obtain the following equations provided x is measured from the point a, where the arc is lit (see Figure 18, part I), that the velocity of the arc at this point is zero, and that time is reckoned from the moment of ignition,

$$x = \frac{I_0 H}{20 A p} \cdot t^2 \text{ and } \frac{dx}{dt} = v = \frac{I_0 H}{10 A p} t, \qquad (64)$$

where v is the velocity of the arc.

The locus of the crater image will thus be a parabola having its vertex at the point of ignition and its axis at right angles to the time axis. The crater locus terminates at a distance h from the point of striking determined by

$$h = \frac{I_0 H}{20 A p} t^2 \doteq \frac{I_0 H}{20 A p} \frac{1}{2} \tau^2 = \frac{I_0 H \lambda^2}{36.10^{17} A p} = \frac{\sigma H \lambda^2}{36.10^{17} p}. \qquad (65)$$

We shall now examine whether the value of h determined by (65) agrees with those observed. In order to apply equation (65), we must know the values of σ and p. We have tried to determine σ by measuring the cross section of the violet arc core. This determination is not very reliable, but apparently the values for coal gas and hydrogen were the same. The value may probably be put as $\sigma = 2{,}000$ amperes per sq. cm. or 12,500 amperes per sq. inch. For the determination of p, the density of the arc, the arc-temperature, must be known. In both coal gas and hydrogen this is comparatively low. The temperature has not been exactly determined; but we have estimated the density to be $\frac{1}{4}$ of the density at 0° which corresponds to a temperature of about 1100°. At the moment of ignition the temperature is surely lower, later on probably higher. The density of hydrogen at $0° = 0.00009$ gm. per cc. and of coal gas $= 0.00045$ gm. per cc., and formula (65) then gives for hydrogen

$$h = \frac{2 H \lambda^2}{81.10^9}, \qquad (66_1)$$

and for coal gas

$$h = \frac{2 H \lambda^2}{405.10^9}. \qquad (66_2)$$

In the table below are given the calculated and the measured values of h for the four cases we have examined.

	h Calculated mm.	h Measured mm.	Remarks
Figure 17a, part a	0.66	0.37	Measured on the anode
Figure 17a, part b	0.38	0.45	Measured on the cathode
Figure 17a, part c	1.3	0.9	Measured on the cathode
Figure 17a, part a	1.3	1.2	Measured on the anode
Figure 17b, part c	2.7	2.0	Measured on the cathode

The measured values of *h* are, on the average, lower than those calculated; this is consistent with the fact that the arc itself is travelling a greater distance than the images of the craters which appears clearly from the side views shown. (See especially Figure 17*c*, parts *a* and *b*, and Figure 17*b*, part *b*.) When the entirely provisional character of the theory is considered, the theoretical and observed values of *h* must be admitted to agree fairly well.

From the preceding, it follows that the velocity of the arc and craters is smallest directly after the ignition, and consequently it is to be expected that the temperature of the negative crater is highest near the point of ignition. This view is confirmed by Figure 17*b*, part *a* and, tho not in so pronounced a fashion, by Figure 17*a*, parts *c* and *d*. This comparatively high temperature on the ignition point of course facilitates the reignition of the arc at this point. We have now, in the main, explained the behavior of the arc in a magnetic field under normal conditions, and we have found it in complete agreement with the outline of the A-theory given in Section 6. We shall next proceed to examine the conditions when the field is either too strong or too weak—which cases present some peculiar features of considerable interest.

c. MAGNETIC FIELD TOO STRONG

A couple of oscillograms taken with too powerful fields are shown in Figure 17*b*, parts *c* and *d*, with coal gas and hydrogen respectively. The locus described by the crater in this case does not consist of a single curve for each period but of several, mutually parallel and parabolic curves—three such curves in part *c* and two in part *d* for each period. As it is difficult to trace these crater curves on the photograph and still more so on the reproduction, we have drawn the diagrammatic Figure 18, part II, which gives a representation of the crater curves. We assume the arc to be lit at *a* where the velocity at first is small, but then rapidly increases owing to the strong magnetic field. The temperature of the negative crater is therefore, as mentioned above, comparatively high at *a* but drops quite rapidly as the crater travels outwards. The result of the rapidly

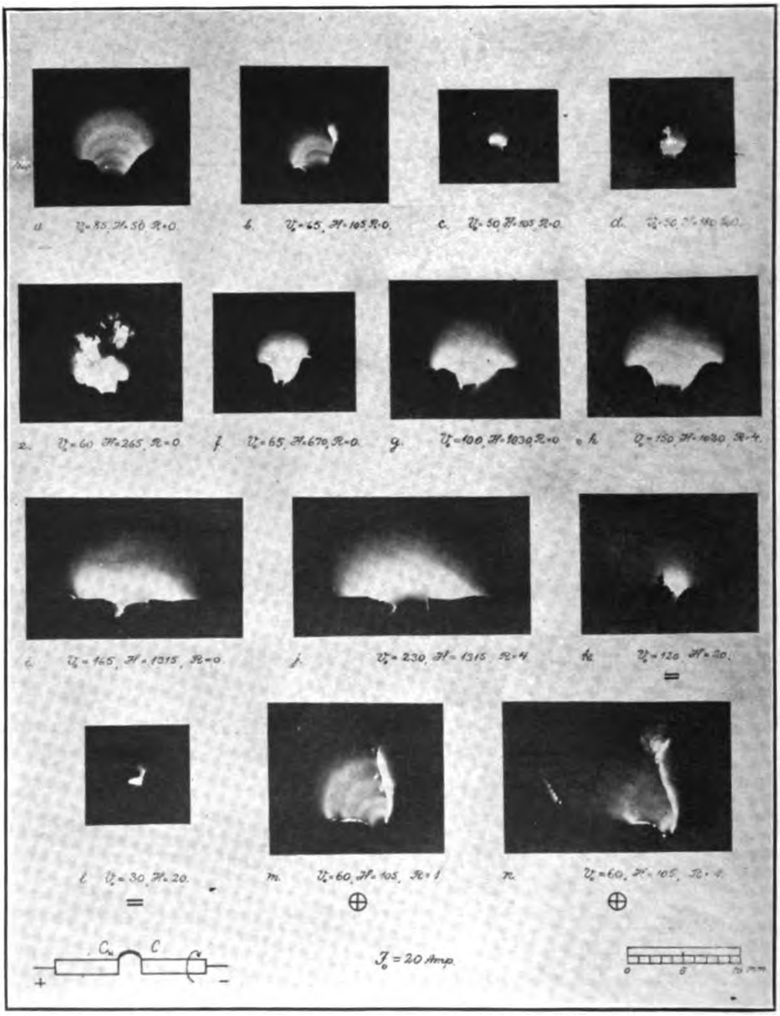

FIGURE 17c—Side Views of Arcs. For Parts *a* to *j* and *m*, *n*, $\lambda = 9000$ m. and $\rho = 200$ ohms. Parts *k* and *l* are d. c. Arcs. In Parts *m* and *n*, the Cathode Is Not Rotating

falling temperature is a rapidly increasing arc voltage, which causes a new arc to be struck at a_1 where the temperature still is comparatively high. The second arc increases at the cost of the first, which is extinguished at c. The second may eventually again be replaced by a third arc struck at a_2 and so on. *In too strong fields, there may thus exist simultaneously two or more concentric arcs between the electrodes.* Toward the end of the period, when the current is small, the crater temperature decreases and the arc voltage increases to the extinction voltage after which a new arc is struck at a'. The value of the extinction and ignition voltages are about normal as will appear from the oscillograms taken, these having quite the normal appearance even with field intensities considerably above the normal (see Figure 16*a*, part *d*). The intermediate peaks on the voltage curve corresponding to the re-ignition and partial extinction at a_1 and a_2 (Figure 18, part II) are not high enough for registration by the method applied when taking the voltage oscillograms. A full elucidation of these phenomena will therefore necessitate further investigation, but there can be no doubt that the explanation given is in the main correct. Too strong a field will, of course, necessitate an increase in the supply voltage V_o—as will also be mentioned later—and consequently reduce the efficiency. *Too strong a field is therefore disadvantageous both as regards economy and constancy.*

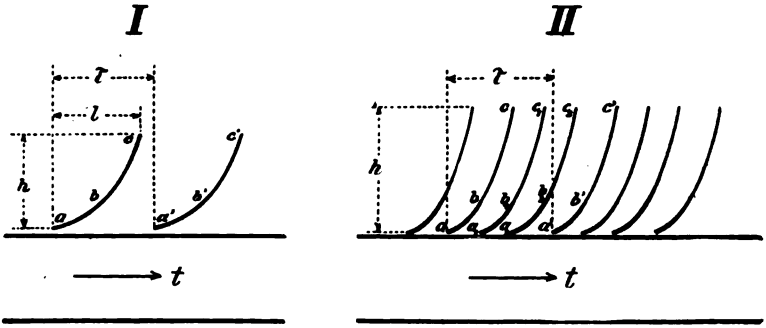

FIGURE 18—Theoretical Form of Crater Oscillograms

I. Normal magnetic field
II. Magnetic field too strong

d. MAGNETIC FIELD TOO WEAK

Too weak a magnetic field causes quite a different aspect of the arc phenomenon. The reasons are to be found in two circumstances, which are consequences of or concurrent with the magnetic field. To begin with, the arc is not completely extinguished, or, if so, only during an extremely short time. And secondly, the arc and craters travel only a very short way during a period. The combined result thereof is a marked tendency for *the arc to ignite again at—(or, if not completely extinguished, to continue from)—the point it has reached at the end of a period.* If the field is much too weak this is repeated several—and often many—times until the arc has attained such a length that the re-ignition takes place again most readily between the edges, whereupon the same succession of phenomena is started over again. These conditions are shown diagrammatically in Figure 19, where it is assumed that the arc ignites every third time on the edges. This ignition requires a considerable voltage, while the next extinction—and ignition—voltage will be comparatively small, and the next thereafter a little higher, as indicated in the figure. That the arc voltage really has this appearance is clear from Figure 16*a*, part *f*. Here the arc is struck at the edges alternately every second or third time.

The side views show a number of arcs corresponding to the various ignition points. The weaker the field is, compared with the normal field, the greater is the number of arcs (see Figure 17*c*, parts *a*, *b*, *m*, and *n*; Figure 19*a*, parts *a* and *b*; and Figure 17*b*, part b_1). *Of all these arcs only one exists at a time.*

That the above explanation is correct is very clearly verified in Figure 17*b*, part *b*, the arc in this case being distinctly seen to be ignited every second time on the edge, and thereafter some distance back on the electrode.

It is evident that *this behavior of the arc will result in an increase of the supply voltage as the potential difference required during the period of actual burning increases with increasing arc length.* The efficiency decreases, of course, when the field is too weak. At the same time, the constancy is affected. If, for instance, the arc regularly makes two "steps," two slightly varying periods are obtained. This affects the resonance possibilities of the oscillations and gives an irregular and flattened resonance curve. The conditions become still more complicated if the number of "steps" varies irregularly, and resonance curves with a "flat top" are then obtained.

In extremely weak fields, a new phenomenon appears, which we have endeavoured to illustrate in Figure 20. The arc in this case travels only a very short distance outward during each period, and continues this outward travel until the arc voltage becomes so high that a new arc is ignited at the electrode-edges. Since, however, the de-ionization in this case is comparatively small, *the outer arc will still exist after the new inner one has been started, and both will continue during a number of periods—the inner with increasing, the outer with decreasing current.* At the same time, the electrodynamic attraction between the two simultaneously existing arcs causes the inner one to travel with a speed greater than that corresponding to the intensity of the magnetic field and the outer with a less speed. As indicated in Figure 20, the mutual attraction may more than counterbalance the action of the magnetic field, the result being that the outer arc travels inward. Such a case is seen in Figure 20*a*, part *a*, which closely corresponds to Figure 20. The conditions can be even far more complicated, as is seen in Figure 20*a*, parts *b* and *c*, *showing that a number of arcs may exist simultaneously.* This phenomenon is due to the above-mentioned conditions in very weak fields and further to the fact that the arc voltage does not drop instantly after the ignition, but remains at the high ignition voltage during a definite tho short time; or it may even

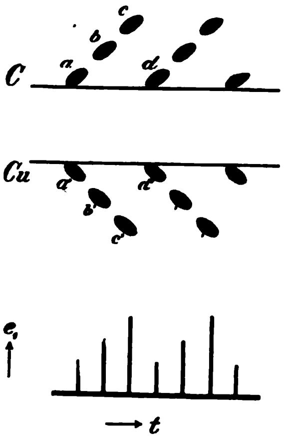

FIGURE 19—Sketch of Crater Oscillogram. Magnetic field too weak

be subject to a further rise. It is a matter of course that an arc generator works very irregularly in such very weak fields.

The rôle of the magnetic field in the Poulsen arc has formerly been much discussed. (Compare the bibliography numbers 32–35, 7*b*, and 7*e*, pages 64–66.)

FIGURE 19a—Side Views of Arcs in Weak Fields. Part A in Hydrogen. Part C in Coal Gas

e. MOST SUITABLE MAGNETIC FIELD

The preceding discussion shows that the arc should burn in the weakest field, H^o, in which it works normally, only igniting once a period, and always on the electrode edges. Both stronger and weaker fields require excessive supply voltage. H^o is thus the most suitable field intensity—the one giving the highest efficiency and the most constant behavior of the arc. In order to show the connection between V_o and H, we have taken some sets of measurements and plotted the results in Figure 21. As will be seen, V_o decreases regularly with H to a certain point (namely to the field intensity where the arc does not always strike on the edges), from which point, V_o again rises quite rapidly. The part of the curve corresponding to still smaller values of H is rather unstable, as the number of "steps," and therefore also the number of arcs seen in the side view, is changed by quite insignificant irregularities; but the greater the number of arcs seen in the side view, the higher is the value of V_o. Furthermore, the lower the value of H, the greater is generally the number of arcs simultaneously seen in a side view. A regular curve cannot be drawn, but those shown do, in the main, correspond to the measurements; and at the same time they indicate the probable theoretical shape.

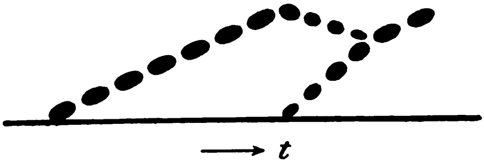

FIGURE 20—Sketch of Crater Oscillogram Magnetic Field Far Too Weak

It thus appears that the Poulsen arc gives the highest efficiency and works with the greatest regularity at a certain field intensity H^o. On the other hand the arc may work apparently quite regularly in magnetic fields the intensities of which are considerably greater or smaller than H^o. The arc may, for example, work apparently very regularly with 2 or 3 arcs to be seen in the side view. In this case, however, the alternate periods necessarily must have slightly different lengths, and as the number of steps may vary irregularly between 2 and 3, for example, the observed frequency will also vary in an irregular manner. *In investigations on the constancy of the Poulsen arc, it is absolutely necessary to ascertain that the arc is working with the most suitable field intensity* H^o, otherwise the results will be of but little value. This point has not, so far as I know, been duly considered in any of the investigations of this kind. K. Vollmer[22], for instance, in the paper describing his interesting and careful investigation of this question, with regard to the magnetic field only remarks that the investigation is made "on an arc with transverse field." (l. c., page 150.)

The constancy of the normal Poulsen arc is so great, that a further increase in constancy would not be of any great practical value. A closer investigation is therefore deferred.

f. APPEARANCE OF THE ARC IN MAGNETIC FIELDS OF DIFFERENT INTENSITIES

Figure 17*c* shows a series of side views taken under various conditions, especially for different values of *H*. An inspection of part *c* shows how small the arc is at field intensities near the

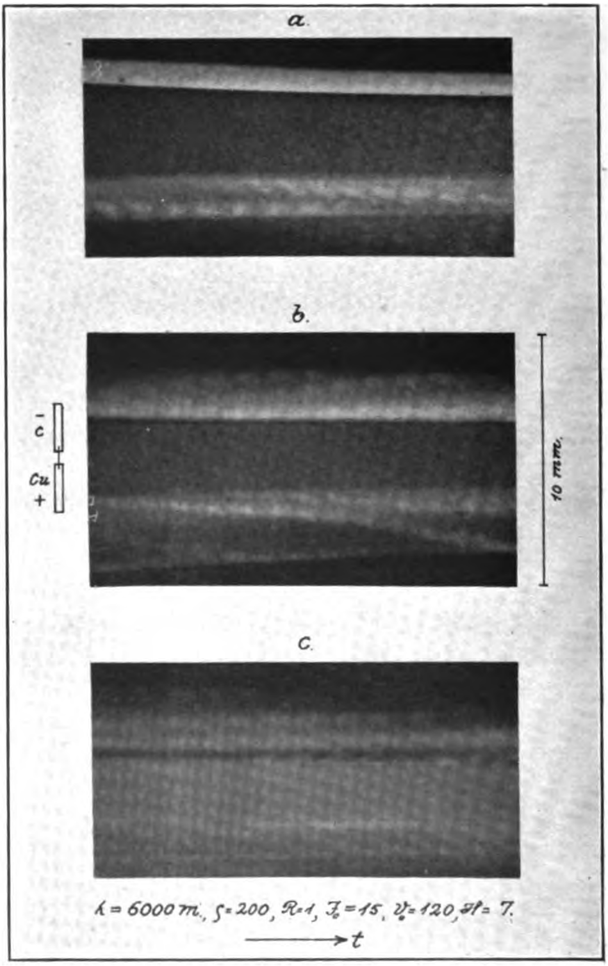

FIGURE 20a—Crater Oscillograms for Very Weak Magnetic Fields

most suitable one, H^o. On the other hand, part *i* shows how large the arc apparently is in strong fields.

A few peculiarities of arcs in coal gas may be merely mentioned. In *weak* fields a layer of *soft black* carbon is deposited on the walls of the arc chamber and tree-shaped masses of the same *soft black* carbon are deposited on the *anode*, just outside the crater as shown in part *e* of Figure 17*c*, and especially in part *b* of Figure 19*a*. In suitable weak fields, this deposition may be so rapid that the "anode-tree" may be seen to grow. At irregular interval, these anode-trees are thrown off by the arc itself. If, with these weak fields, the *cathode* is *not* rotating, no carbon deposit is formed on the anode but instead there is formed a horn-shaped deposit of black *hard* carbon on the cathode as shown in parts *m* and *n* of Figure 17*c*. This "cathode horn" is so strongly coherent that when it is broken off, the cathode carbon ring is generally also broken.

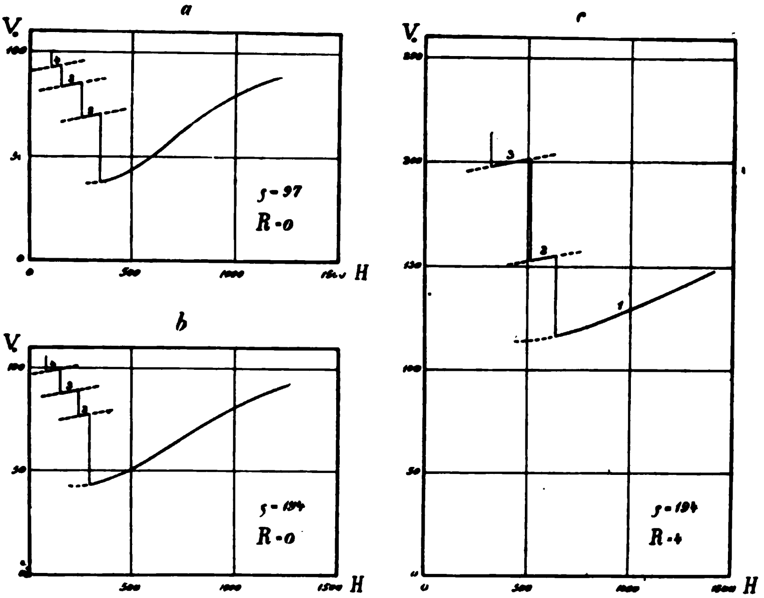

FIGURE 21—Relation Between Primary Voltage and Intensity of Magnetic Field for Constant Supply Current

In *stronger fields* very little carbon is deposited, and what little there is in this case as a *brown* rather hard powder. On the electrodes no appreciable deposit takes place in strong fields.

The explanation of these peculiarities is probably to be looked for in variations of the temperature of the arc caused by the magnetic field, but this question has not been further investigated.

10. FURTHER CONSEQUENCES OF THE A-THEORY

The above detailed investigation has given the main features of the influence of the magnetic field on the arc when used as a generator for sustained radio frequency currents. We shall now consider the consequences which, with the knowledge thus acquired, can be drawn from the A-theory with regard to the dependence of H^o upon the constants of the r. f. circuit and the strength of the supply current.

a. INFLUENCE OF THE WAVE LENGTH ON THE MOST SUITABLE INTENSITY OF THE MAGNETIC FIELD

We will begin by investigating how H^o depends on the wave length, the supply current, and all other conditions remaining constant.

According to (62), the average value P of the extinction voltage is proportional to $I_0 R$ but otherwise independent of the constants of the r. f. circuit. The voltage of the arc during extinction will, no doubt, increase simultaneously with the velocity of the arc. This velocity is, according to (64), proportional to the period or to the wave length. All other conditions being equal, we may therefore expect P to be dependent mainly on $H^o\lambda$, but not on H and λ separately. This being the case the most suitable intensity H^o and the wave length λ will satisfy the following relation:

$$H^o \lambda = \text{constant} \qquad (67)$$

A series of corresponding values of H^o and λ have been determined and the results plotted in Figure 22. It appears that the experimental values are fairly well represented by the curve shown having the equation

$$(H^o + 400)\,\lambda = 5000 \quad \text{(Gauss km).} \qquad (68)$$

The difference between (67) and (68) can be accounted for, at least partially, without difficulty. The buoyancy of the arc will, to some degree, act as an additional magnetic field. The electrodynamic forces on the arc will act in the same way.[29] Electrostatic forces will probably also act in the same way. As shown later, the value of H^o increases with increasing values of K; the experimental values of H^o are therefore relatively too great for small values of λ. All these disturbances acting cumulatively as they do, will probably suffice to explain the difference between (67) and (68). *The theoretically deduced relation between* H^o *and* λ *is therefore confirmed.*

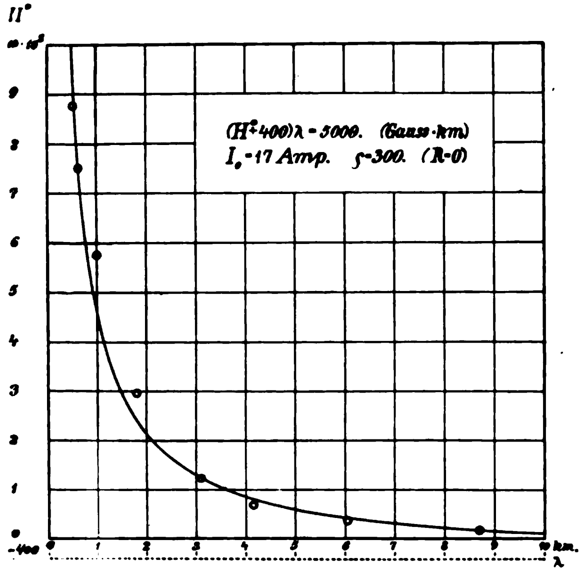

FIGURE 22—The Most Suitable Intensity of Magnetic Field as Dependent on Wave Length

b. INFLUENCE OF DENSITY OF GAS ON THE MOST SUITABLE INTENSITY OF THE MAGNETIC FIELD

The above remarks refer to the arc burning in coal gas. With the arc in hydrogen, the corresponding values of H^o are approximately 5 times smaller. This is in complete agreement with the results obtained in Section 9*c*. In this way, some well known peculiarities of the arc are easily explained. For example, working on short wave lengths, hydrogen has always been found preferable to coal gas; but at long wave lengths, sometimes hydrogen and sometimes coal gas or hydrogen more or less saturated with different hydrocarbons has been found to give the best results. The explanation is in the main simply this: *With too weak a field, it is preferable to use pure hydrogen, in too strong a field, a hydrogen compound having a greater density produces better results.*

c. H^o AS DEPENDENT ON R AND I_o

The next question is, how H^o depends on R, the supply current, and all other conditions being constant. According to the A-theory, the average extinction voltage P is proportional to R. (See, for example, equation (62).) We do not, however, know the exact relation between P and the velocity v of the arc at extinction; we only know that P increases with v. We are therefore unable to deduce any exact relation between H^o and R; we can only say, that H^o increases with R. The simplest supposition we can make is that P increases linearly with v. In this case H^o will also increase linearly with R. It appears from Figure 23, parts *a* and *b*, showing corresponding values of H^o and R, that H^o is really dependent linearly on R. Under the same conditions, H^o should be proportional to I_o, R and all other conditions being constant. This is confirmed by Figure 23, part *c*, in which are shown the values of H^o taken from Figure 23, parts *a* and *b*; the latter being reduced in the ratio of the corresponding currents, that is, in the ratio 1 to 2. The proportionality of H^o and I_o can, however, only be expected to be approximately true, since the cross section of the arc and the areas of the craters increase with increasing value of I_o. The greater these areas are, the greater in consequence must H^o be. We must therefore expect, that the (H^o, I_o)—curves will have their concavity toward the H^o—axis, a conclusion confirmed by Figure 24, showing corresponding values of I_o and H^o for different wave lengths.

11. CONCLUDING REMARKS

The theoretical deductions in Sections 9 and 10 were necessarily of a somewhat provisional nature. Their object was mainly to be an aid in the exploration of this difficult and at the same time important field. Notwithstanding this provisional nature of the A-theory, the experiments have, in the main, confirmed the conclusions drawn from that theory.

How far the A-theory is an advance over the B-theory is probably best ascertained by a consideration of the extent to which the two theories permit prediction of the influence of magnetic fields of different intensities. We have just seen that the A-theory has been quite successful with regard to this question. The B-theory, on the other hand, has not been able to throw much light on this point. The easiest way to prove this is to quote the last edition of Zenneck's excellent text book,

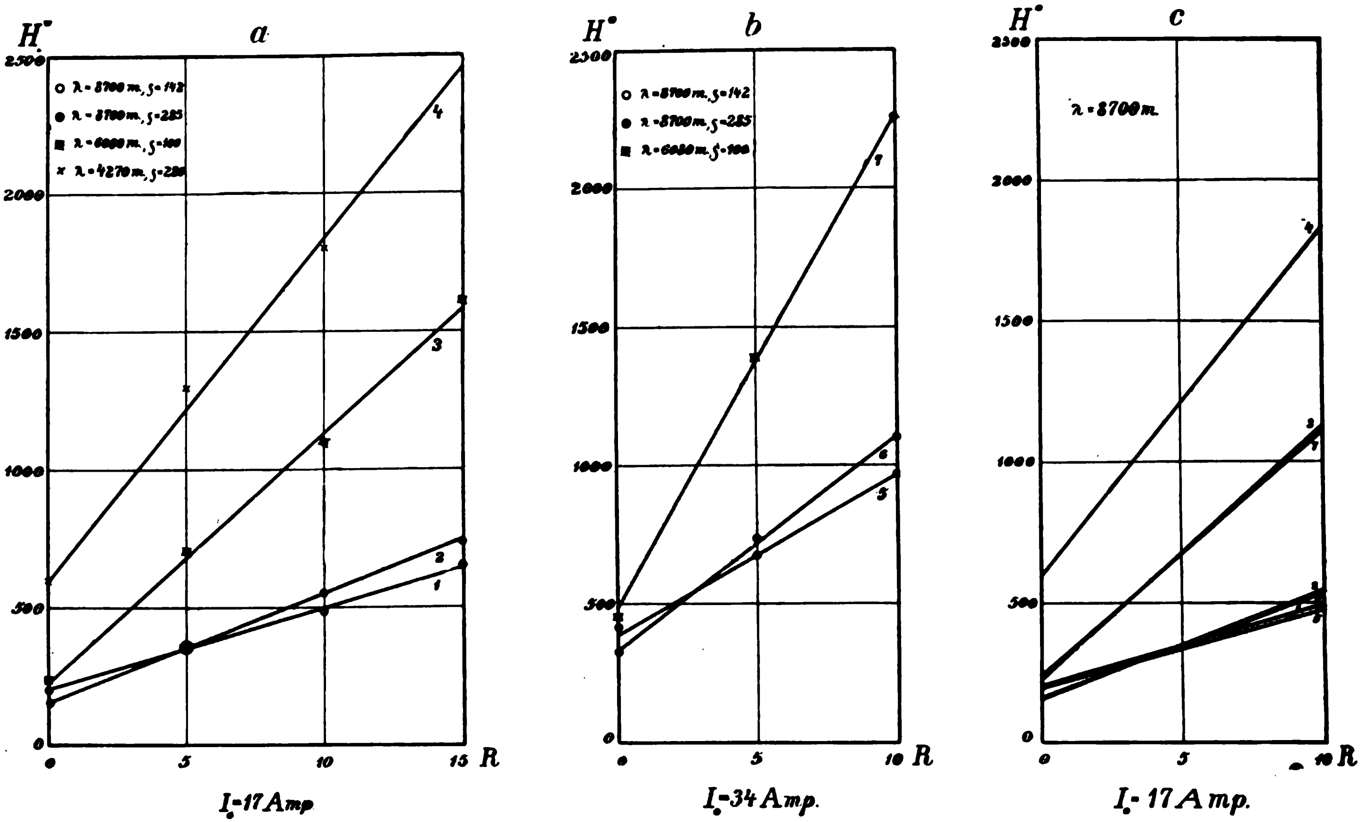

FIGURE 23—H° As Dependent On R and I_o

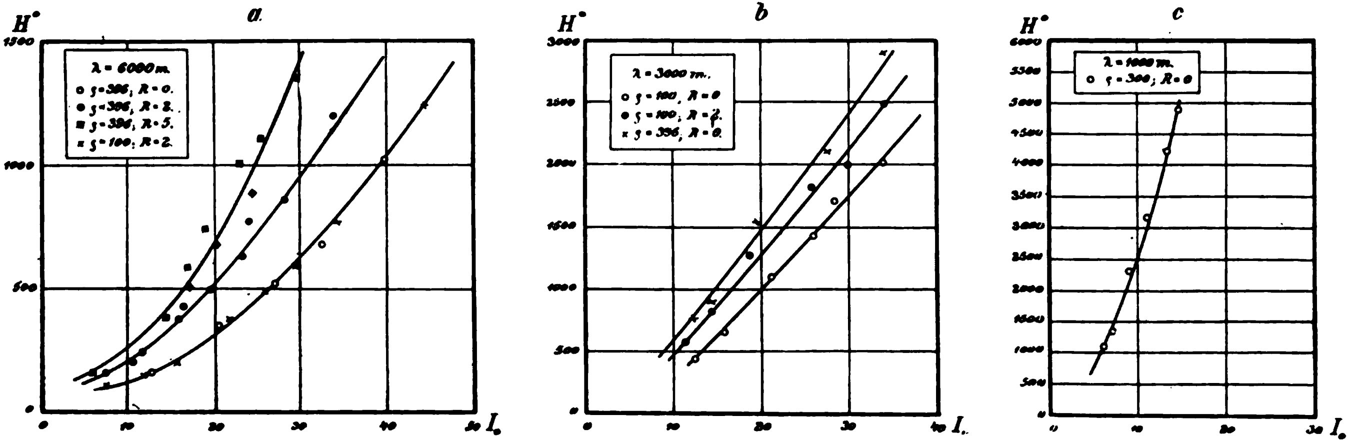

FIGURE 24—H° As Dependent On I_0 for Different Wave Lengths

"Es wurde . . . darauf hingewiesen, dass ein Quermagnetfeld, das die Energie der Schwingungen sehr günstig beeinflusst, sehr ungünstig für die Konstanz der Schwingungen ist . . . Es ist dies ebenso der Grund, weshalb man mit der Stärke des Quermagnetfeldes in allgemeinen nicht sehr hoch geht, obwohl es die Energie der Schwingungen erhöhen würde." (It . . . was already pointed out that a transverse magnetic field, which is very advantageous for the energy of the oscillations, is very disadvantageous for their regularity . . . This also explains why the strength of the transverse magnetic field is in general not made very great, sacrificing a further increase in the energy of the oscillations.) (Page 244.)

The existence, in every particular case, of a certain field intensity H^o giving maximum efficiency and greatest constancy is not mentioned; to say nothing about the dependence of H^o on wave length, gas density, supply current, and r. f. resistance.

That the B-theory does not suffice to give a satisfactory explanation of the influence of the magnetic field is a natural consequence of the fact that this theory considers only the ignition voltage which, in itself, is independent of the intensity of the magnetic field; this field only influences the conditions existing while the arc is burning (and this influence, which is mainly due to the velocity of the arc, is greatest at the end of the period—i. e., at the moment of extinction). *This is the reason why the A-theory, in which the main point is the extinction voltage, gives such a simple explanation of the influence of the magnetic field.*

SUMMARY: The paper deals with an experimental investigation of the Poulsen arc carried out by means of

1. **The ordinary electrical methods of testing**
2. **Gehrcke's oscillograph for taking oscillograms of arc voltage**
3. **Photographic side views of the arc**
4. **Photographs of the arc and craters viewed in a rotating mirror, i. e., crater oscillograms.**

The chief results of the investigation are:

The experimental values of ratio between radio frequency current and the direct current are satisfactorily explained on the basis of the A-theory. This is not the case for the theory based on Barkhausen's simple characteristic. (B-theory.)

The maximum voltage across the arc is very much smaller than required by the B-theory.

For the normal Poulsen arc, the extinction voltage is almost as high as the ignition voltage.

The most suitable intensity of the magnetic field H^0 is proportional to the density of the gas and to the frequency of the oscillations, approximately proportional to the feeding current and increases linearly with the r. f. resistance.

The behavior of the arc in fields of different intensities is investigated.

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LIST OF SYMBOLS

C = capacity in the r. f. circuit		(Farads)
L = inductance in the r. f. circuit		(Henrys)
$\rho = \sqrt{\frac{L}{C}}$ = characteristic of r. f. circuit		(Ohms)
R = effective resistance in r. f. circuit		(Ohms)
$\kappa = \frac{R}{2L}$ = damping coefficient of r. f. circuit		$\left(\frac{1}{\text{Sec.}}\right)$
$\omega_o = 2\pi n_o = \frac{1}{\sqrt{LC}}$ = angular velocity of r. f. circuit when $R=0$		$\left(\frac{\text{Radians}}{\text{Sec.}}\right)$
$\tau_o = 2\pi\sqrt{LC}$ = natural period of r. f. circuit when $R=0$		(Sec.)
$\omega_o' = 2\pi n_o' = \sqrt{\omega_o^2 - \kappa^2}$ = angular velocity of r. f. circuit when $R>0$		$\left(\frac{\text{Radians}}{\text{Sec.}}\right)$
$\tau_o' = \frac{1}{n_o'}$ = natural period of r. f. circuit when $R>0$		(Sec.)
$\delta' = \kappa\tau_o'$ = logarithmic decrement of r. f. circuit		(Numeric)
$\delta = \kappa\tau_o$ = approximate value of logarithmic decrement		(Numeric)
T = period of r. f. current		(Sec.)
ω = angular velocity of r. f. current		$\left(\frac{\text{Radians}}{\text{Sec.}}\right)$
λ = wave length of r. f. oscillation		(Meters)
I_o = supply current (constant)	(See Figure 8)	(Amps)
i_1 = instantaneous value of arc current		(Amps)
i = instantaneous value of condenser current		(Amps)
I = effective value of condenser current		(Amps)
I_m = maximum value of condenser current		(Amps)
$i_1 = I_o + i; \quad \frac{1}{\tau}\int_o^\tau i_1 \cdot dt = I_o$		
e_1 = instantaneous value of voltage across the arc	(See Figure 8)	(Volts)
V_o = d. c. voltage across the arc		(Volts)
$V_o = \frac{1}{\tau}\int_o^\tau e_1 \cdot dt$		
E_c = voltage across the arc when burning	(See Figure 7)	(Volts)
$E_s + E_c$ = ignition voltage		(Volts)
$-E_a$ = greatest numerical value of reversed terminal voltage		(Volts)
E_1^o = maximum value of voltage across the arc during extinction		(Volts)

= integral value of extinction voltage = $\int_{o}^{t_1^o}(e_1 - E_c)\,dt$ (Volts×Sec.)

= time of the extinction of the arc (see Figure 14) (Sec.)

$H = \frac{U}{t_1^o} =$ mean value of rise in arc voltage during extinction (Volts)

= Intensity of magnetic field (perpendicular to arc motion) (Gauss)

$H^o =$ most suitable intensity of magnetic field (Gauss)

$\sigma =$ current density in arc $\left(\frac{\text{Amps}}{\text{cm.}^2}\right)$

$p =$ density of arc gases $\left(\frac{\text{Grams}}{\text{cm.}^3}\right)$

$k = \frac{E_s}{\varrho I_o} - \frac{R}{2\varrho}$; approximate value $k = \frac{E_s}{\varrho I_o}$

$g_o = \frac{I}{I_o}, f_o = \frac{\tau}{\tau_o}$ when $R = 0$

$g = \frac{I}{I_o}, f = \frac{\tau}{\tau_o}$ when $R > 0$

$a \gg b$ means "a is much greater than b"

r.f. = radio (high) frequency (frequencies over 10,000 cycles per second)

DISCUSSION

Valdemar Poulsen (by letter): It is with great interest and pleasure that I have followed Professor Pedersen's investigations. Previously we had to find the most suitable magnetic field in the different cases in an empirical way. I myself have from the very first considered the influence of the magnetic field on the arc-generator as a very complicated one. I have therefore not put forth any theory with regard to this point. Not having been able to give any satisfactory explanation of the dependence of the most suitable field upon the different constants of the r. f. circuits, I have only discussed this point very sparingly in my papers.

I never found the explanations given by the Authors mentioned in Professor Pedersen's paper satisfactory. The experimental data at hand until now have been simply insufficient for the solution of this problem. Professor Pedersen has, in an admirable manner, procured the necessary experimental material, and he has at the same time given an explanation of the different phenomena in connections with the magnetic field, which, as far as I can see, is in every way satisfactory.

I wish to take this opportunity to renew my congratulation to my friend, Professor Pedersen, on this very important paper.

Copenhagen, February 2, 1917.

Leonard F. Fuller (by letter): Electrical machinery would be at a great disadvantage in commercial work if the load had to be suited to the machine available, rather than the machine being designed for the load. Likewise radio transmitters should be designed to fit the antenna available rather than by attempting to make the antenna fit the transmitter. This is quite proper, as in high power work especially, the antenna constants are always limited by considerations of cost.

I have read Professor Pedersen's paper with keen interest as it deals with the subject of arc theory with the idea of obtaining data useful in design work. The designer of arc transmitters, and especially of high power units, is constantly required to solve problems of which the following is a typical example:

Given:—Antenna $C = 0.015\ \mu$f.
Antenna $R = 1$ to 3 ohms, depending on wave length.
Wave length range $= 5{,}000$ to $20{,}000$ meters.

Required:—Design an arc converter capable of delivering 300 amperes in the above antenna, and determine the volts and amperes of the D. C. power supply.

In the design of the arc, the predetermination of the range of required flux densities in the magnetic air gap is the calculation of major importance as this affects both the copper and steel in the unit and will have a great effect, not only upon the cost of manufacture, but also on the general characteristics and performance of the converter. Determination of size of water jackets, electrodes, insulation, etc., are problems of mechanical design.

I am very glad to see Professor Pedersen's use of the term "normal Poulsen arc," and heartily agree with him that most previous laboratory investigations published are of little value in testing the theory of the Poulsen arc converter. In fact most publications dealing with arc theory and performance give results which are of little practical utility and are frequently dangerous for the designing engineer.

No arc is a normal Poulsen arc in which the ratio of direct current to radio frequency current varies appreciably from the $\sqrt{2}$. This ratio has been checked in units operating at full load, and at overload with inputs up to 500 kilowatts. In practical work, this frequently provides a very helpful means of checking the calibration of switchboard instruments.

Professor Pedersen's method of calculating the required direct current volts and amperes involves an assumption of arc efficiency. It is preferable for the arc designer to compute what the efficiency will be from the radio frequency circuit constants given him to make his designs. In these calculations he will at the same time predetermine the required direct current volts and amperes and thus leave nothing to guess-work or assumption. Of course such calculations cannot be made without the necessary design data and performance equations which connect the various variables involved.

One additional point may be added to Professor Pedersen's comments on the appearance of the arc in magnetic fields of different intensities. A normal arc working in a magnetic field of proper strength will frequently build up hard slate-colored tits on the anode from which the arc will burn. These tits are usually obtained only with a hydrocarbon atmosphere of illuminating gas rich in carbon, or when using gasoline or kerosene. If the ordinary grades of alcohol or the more volatile liquid hydrocarbons are used they will not ordinarily appear. Their rate of growth is dependent upon anode temperature and they do not appear except upon well cooled anodes. By proper adjustment of anode cooling water these tits can be used as an excellent protection to the anode tip proper and are a refinement in the initial adjustments of an arc which it is advisable to consider.

Pure hydrogen gas briefly mentioned by Professor Pedersen is a tempting proposition to the designing engineer, for its high molecular velocity so assists the magnetic field in "scavenging" or de-ionising the gap that, on short wave lengths especially, i. e., when the time allowed for de-ionisation is a minimum, it permits material reductions in the magnetic circuit, an expensive part of the arc. On large arcs operated on long wave lengths, but where heavy currents must be considered, the same arguments may be cited in its favor, and, in addition, there is the absence of soot deposit. This is often of assistance in the design of mechanical features of the unit.

The disadvantages of hydrogen are its explosive power and the inconvenience and cost of obtaining it. Even if produced electrolytically at the station, it necessitates distilled water and attention to the care of just that much more equipment. Obviously therefore the use of hydrogen is a means of helping the designer around certain technical difficulties and of reducing manufacturing cost at an increase in operating expenses.

Professor Pedersen's paper is of especial interest to me at this time as it deals fundamentally with the problem of predetermining arc performance. The Federal Telegraph Company has within the last year built three large arcs, the largest weighing 65 tons. I have had the pleasure of seeing the smallest of the three, a unit nominally rated at 200 K. W., operating on test up to 250 per cent. load with the direct current instruments and radiation ammeter all reading as calculated.

PALO ALTO, CALIFORNIA. March 7, 1917.