red colouring matter containing both the albuminous and the iron-containing residues of hæmoglobin. In the case of CO-hæmoglobin the compound deposited has presented the peculiar colour of CO-hæmoglobin.

General Conclusions.

The following are the conclusions to which I have been led by my experiments :—

1. The blood-colouring matter, oxy-hæmoglobin, as well as carbonic-oxide hæmoglobin and methæmoglobin, are decidedly diamagnetic bodies.

2. The iron-containing derivatives hæmatin and acethæmin are powerfully magnetic bodies. The differences in magnetic behaviour between the blood-colouring matter and acethæmin and hæmatin point to the profound transformation which occurs in the hæmoglobin molecule when it is decomposed in the presence of oxygen.

3. The preliminary study of the electrolysis of oxy-hæmoglobin and CO-hæmoglobin renders it probable that, in the blood-colouring matter, the iron-containing group, on which its physiological properties depend, is (or is contained in) an electro-negative radical: according to analogy, the iron in such a compound would possess diamagnetic and not magnetic properties.

In conclusion, I beg to acknowledge my indebtedness to Professor von Bunge, of Basel, to Professor Franz Hofmeister, of Strassburg, and to Dr. v. Ehrenberg, the technical director of the chemical factory of Messrs. Merck, of Darmstadt, for their great courtesy and kindness in placing at my disposal preparations of hæmoglobin prepared by themselves or under their direction. I have further to add that I reserve to myself the right of continuing without delay the researches of which the first results are contained in this paper.

"On the Resistance and Electromotive Forces of the Electric Arc."

By W. Duddell, Whitworth Scholar. Communicated by Professor W. E. Ayrton, F.R.S. Received and Read June 20, 1901.

(Abstract.)

The discrimination between resistances and electromotive forces in conductors, or apparatus, in which both of these quantities are functions of the current is considered, and it is pointed out that whether such an apparatus may be said to possess a resistance, or an E.M.F., or both, depends to a large extent on the nature of the definition of these quantities, and a definition of these quantities is adopted.

The essential stipulation is made that whatever means be used to measure the resistance and E.M.F.'s of the arc, the conditions of the arc must not be in any way changed by the test. It is considered that the main phenomena of the arc depend on the exact thermal conditions of its different parts, and on the distribution of the heated gaseous and other particles, so that it is necessary to maintain these constant during the test. This leads to the condition that not only must the testing current used be very small, but also that the test must be completed in an exceedingly short time after applying the same.

As illustrating how very short a time may be allowed to elapse, it was found that an appreciable change in the thermal conditions of an arc had taken place in 1/10,000 second after changing the arc current by as little as 3 per cent.

Historical.

A brief historical *résumé* is given showing that previous experimenters have not succeeded in measuring the true resistance and back E.M.F. of the arc, due to their not having realised the importance of completing the test before the conditions of the arc have had time to be altered by the testing current.

Those methods, similar to the Kohlrausch method of measuring the resistance of an electrolyte, in which an alternating testing current is superposed on the direct current, such as that employed by Messrs. Frith and Rodgers, who found that what they measured as the resistance of the arc had in some cases a negative value, are shown to have failed owing to the frequency of the alternating testing current not being high enough. This frequency should be, instead of a few hundred periods per second, as used by previous observers, many thousand periods per second, in order that the conditions of the arc may not vary, and the true resistance may be obtained.

Preliminary Experiments.

In the preliminary experiments the oscillatory discharge of a condenser was superposed on the main direct current through the arc, and was used as the testing current, the wave-forms of the superposed oscillatory P.D. and current being recorded by means of an oscillograph. If the arc behaved as a non-inductive resistance, the waves of P.D. and current should be similar curves, and in phase. This is found *not* to be the case with frequencies up to 5000 periods per second. The author concludes from these experiments that, each increase made in the frequency of the superposed alternating testing current has led to the arc conditions being less affected by it, and, in consequence, to the arc behaving more and more like an ordinary non-inductive resistance, and therefore that much higher frequencies are required to obtain the

true resistance. In fact, frequencies up to 120,000 periods per second were finally used. Owing to experimental difficulties in employing the above method with much higher frequencies, a fresh method was adopted.

Basis of Method adopted.

An apparatus A is considered which has resistance and E.M.F., but no self-induction, or capacity, and through which a steady current is flowing. There is mixed with the steady current an alternating testing current. It is shown that, if the apparatus A possess a true resistance, and if the frequency of the testing current be such that *the conditions of the apparatus are not in any way changed by it*, then the resistance of A will be a constant over the range of variation of the current, and equal to the impedance of A to the superposed alternating current.

A criterion that the apparatus A has a constant resistance is that the power factor of A with respect to the alternating testing current must be unity. It is concluded that in order to prove that the arc has a true resistance and to find its value it is necessary to show :—First that it is possible to find a value of the frequency of the testing current for which the power factor of the arc with respect to this current is unity; second, that the power factor remains unity and the impedance constant, even when the frequency is greatly increased above this value; thirdly, to determine the value of the impedance of the arc under these conditions, which will be its true resistance.

Method of Measuring the Impedance and Power Factor.

Owing to the high frequency of the testing current finally used, viz., 120,000 periods per second, it was difficult to devise a satisfactory method of measuring the impedance, and power factor; wattmeters and dynamometers could not be used, as at these high frequencies their windings behaved more like insulators than conductors, owing to their self-induction. The method finally adopted was the well-known three voltmeter method, for which three pieces of special apparatus were used—

(1) An alternator to produce the high frequency currents.

(2) A new measuring instrument called a "Thermo-galvanometer" to measure the three voltages.

(3) A standard resistance with which the impedance of the arc was compared, which had a time constant of only $2{\cdot}7 \times 10^{-7}$ second.

The High Frequency Alternator.

The alternator is of the inductor type; it was belt driven from two discs by means of a figure of 8 drive, each disc being separately belted to the source of power so as to balance, as far as possible, the pull on

the alternator spindle due to the driving belt. The speed of the alternator was 35,400 revolutions per minute, and the highest frequency 120,000 periods per second. To give an idea of how very high this frequency is, it is mentioned that if a frequency of 100 periods per second be represented by 10 inches, a very ordinary scale in plotting curves, then the squared paper that would be required to plot the curve between impedance and frequency for the solid arc, which extends over the range from 250 to 120,000 periods per second, would be 1,000 feet, or about 1/5th *mile* long.

It was found that the spindle alone of the alternator without the inductor could be driven at 60,000 revolutions per minute, or 1,000 revolutions per second.

A table of high frequency alternators shows that this alternator gives a frequency seven or eight times as high as the highest value previously attained.

The Thermo-galvanometer.

The principle of this new instrument consists in causing the current to be measured to flow through a very fine wire, the heat radiated by the wire being measured by a modified Boys' radio-micrometer. The instrument is practically non-inductive, and may be used equally well for direct or alternating currents. The actual instrument used has a resistance of about 18 ohms, and gives a deflection of 500 scale divisions at a scale distance of 2000 divisions (1 scale division = 1/40th inch) for a current of about 9×10^{-4} ampere.

Telephone and microphone currents can be easily measured with this instrument.

Results Obtained by Varying the Frequency.

This, the fundamental investigation of this communication, consists in varying the frequency of the superposed alternating testing current to see whether, at a sufficiently high frequency, the conditions of the arc remain constant. The criterion that the conditions of the arc remain unchanged has been shown to be that the power factor, as measured with the superposed alternating current, is unity. Under these circumstances the true resistance will be equal to the impedance. It is experimentally found by sufficiently increasing the frequency, that the power factor approximates asymptotically to + 1, and that for the highest frequencies used, it is + 1 to within the limits of experimental error, therefore at these frequencies the variations of the P.D. and current obey Ohm's law, and the impedance of the arc is equal to its true resistance.

With *solid* carbons the power factor at 250 periods per second is − 0·91, on increasing the frequency it decreases numerically until it vanishes at 1950 periods per second, with further increase of frequency

the power factor increases rapidly at first, then more slowly becoming asymptotic to + 1, and finally practically attains this value at 90,000 periods per second; above this frequency the power factor is within the limits of experimental error + 1 up to the highest frequency used, viz., 120,000 periods per second. The impedance of the *solid* arc increases with increase of frequency from 0·97 ohm at 250 periods per second to 3·8 ohm at 90,000 periods per second, above which it remains practically constant. *The true resistance of the above arc* 3 *mm. long between* 11 *mm. solid "Conradty Noris" carbons, and through which a current of* 9·91 *amperes is flowing, is found to be* 3·81 *ohms.*

The P.D. accounted for by ohmic drop is therefore 37·8 volts out of an observed P.D. arc of 49·8 volts, so that *there appears to be a real back E.M.F. opposing the flow of the current, in this arc of* 12 *volts.*

With *cored* carbons the power factor at 250 periods per second is + 0·67, and it increases until it is practically + 1 at 15,000 periods per second, and remains unity within the limits of experimental error up to the highest frequency tried of 50,000 periods per second, the impedance becoming practically constant as with solid carbons. *The true resistance of the above arc* 3 *mm. long between* 11 *mm. cored "Conradty Noris" carbons, and through which a current of* 10 *amperes is flowing, is found to be* 2·54 *ohms and the back E.M.F.* 16·9 *volts.*

The fact that the solid arc has, at low frequencies, a negative power factor, indicates that the arc is supplying power to the alternator: this is shown to be the case by means of a wattmeter. This is not, of course, at variance with the principle of conservation of energy, as the alternating energy given out by the arc is derived from the direct current energy supplied to it. This fact that the solid arc is capable of transforming, under suitable conditions, direct current into alternating current is the basis of the "Musical Arc" recently shown for the first time, at the Institution of Electrical Engineers.

Effect of Varying the Direct Current.

Having found that it is possible to measure the true resistance and back E.M.F. of the arc, the effect of changing the direct current, the arc having a constant length of 3 mm., is examined.

The resistance of both the *solid* and the *cored* arcs is found to increase with decrease of the current through the arc, apparently tending to become infinite for current O.

The back E.M.F. of the *solid* arc first decreases with increase of current and then increases again, having a minimum value of 11·3 volts at about 6 amperes. With *cored* carbons the back E.M.F. increases with increase of current from 12·2 volts at 1 ampere to 18·5 volts at 20·8 amperes. The high P.D.'s required to maintain small current arcs are shown to be due to the high resistance of these arcs.

The connection between the resistance r and the current A for the *cored* arc, length 3 mm. between 11 mm., "Conradty Noris" carbons, can be approximately expressed over the range 1·5 to 20 amperes by

$$(r + 0{\cdot}25)\,\mathrm{A} = 29.$$

For the *solid* arc, length 3 mm. between the same size and make of carbons, and over the range 1·5 to 11 amperes, the relation is

$$r = \frac{33{\cdot}5}{\mathrm{A}} + \frac{42}{\mathrm{A}^2}.$$

Effect of Varying the Arc Length.

The direct current through the arc being kept constant, the change in resistance and back E.M.F. due to change of arc length is examined. It is found that both for *solid* and for *cored* arcs increasing the length increases the resistance, the curves between resistance and length being very similar to those between P.D. arc and length. This latter curve is generally assumed to be a straight line for *solid* arcs, but such was not the case over the wide range of length, 1 to 30 mm., used for these experiments.

Effect of Varying the Nature of the Electrodes.

Both the resistance and the back E.M.F. are found to depend greatly on the composition of the electrodes; thus simply soaking a pair of solid carbons in potassium carbonate, reduced the resistance of the arc between them from 3·81 to 2·92 ohms, and increased its back E.M.F. from 12 volts to 15·6 volts, the arc length and direct current being kept constant: similar results were produced by introducing other impurities. The author is of the opinion that the resistance of an arc between *perfectly pure carbon* electrodes would be very high, so high that it might be impossible to maintain a true arc, and that traces of impurities are essential to provide the carriers of the electric charges in the vapour column.

Seat of the Back E.M.F.

In order to determine whether the back E.M.F. and resistance are localised at the electrodes, or are distributed along the vapour column, a search carbon was introduced into an arc 6 mm. long between *solid* "Conradty Noris" carbons, 11 mm. diameter, current 9·91 amperes. The impedance to the high frequency testing current, of that part of the arc between the search carbon and each of the main carbons, was measured for three different positions of the search carbon. From these tests it is deduced that the resistance of the above arc, as a whole, consists of three parts—a resistance at or near the contact of the positive electrode and the vapour column of about 1·61 ohms; the

resistance of the vapour column, about 2·5 ohms; and a resistance at or near the contact between the vapour column and the negative electrode of about 1·18 ohms.

The back E.M.F. consists of two parts located at or near the contact between the electrodes and the vapour column. That at the *positive* electrode, about 17 volts, *opposes* the flow of the direct current while that at the *negative* electrode, about 6 volts, *helps* the flow of the direct current, *i.e.*, is a *forward* E.M.F.

Conclusion.

The author considers that the new facts given in the paper assist in formulating a consistent explanation of the resistance and back E.M.F. of the arc. The values found for the resistance of the vapour column and for the contacts between it and the electrodes offer no serious difficulties. The greater part of the two E.M.F.'s are considered as being most probably due to thermo-electric forces, and experiments in support of this view are described, in which it was found possible to obtain a P.D. of 0·6 volt by unequally heating two *solid* carbon electrodes with a blow-pipe flame, the voltmeter indicating that the hotter carbon was positive to the cooler. By using *cored* carbons and adding potassium salts, this P.D. was increased to 1·5 *volts.* It is pointed out that the differences of temperature existing in the arc must be many times as great as those which it is possible to produce with the blow pipe, as the cooler electrode must be red hot, or else it does not seem to make contact with the surrounding flame.

On the Resistance of an Electrolyte.

In measuring the resistance of an electrolyte by the Kohlrausch method, it is often assumed that the errors due to polarisation are avoided if the frequency of the alternating or interrupted current used, is as high as a few hundred periods per second. To investigate the accuracy of this assumption the arc was replaced by a cell containing sulphuric acid, density 1·20 (temperature 20° C.), as the electrolyte, and its impedance and power factor tested exactly the same way as those of the arc. It is found with this cell that it was not until the frequency exceeded 10,000 periods per second that the electrolyte behaved as a non-inductive resistance, and the errors due to the polarisation were avoided. If the resistance of this cell were tested in the ordinary way at a frequency of 100 periods *per second*, the value obtained would be over *twice* its true resistance. It is concluded that unless other methods are adopted to eliminate the effects of polarisation, *it must not be assumed that the use of alternating currents of ordinary frequencies of a few hundred periods per second, eliminates the possibility of errors due to polarisation.*