

THE ELECTRIC CAPACITY OF SUSPENSIONS WITH SPECIAL REFERENCE TO BLOOD.*

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In recent papers (1-4) and in others which will follow, certain theoretical and experimental investigations on the capacity of disperse systems are described, a short summary of which is here given.

THEORY.

We define the specific electric capacity of a suspension as that capacity which, combined in parallel with a certain resistance, electrically balances 1 cm. cube of the suspension. This capacity is rather large for most biological systems, being a measure of that long recognized effect usually called the electrical polarization of the tissue. In general the capacity may be due to one or both of two different causes: (1), a polarization at the interphases of the suspension, and (2), the static capacity of the thin membranes which often are situated at the interphases, such for example, as the cell membranes for the case of biological cells and the adsorption films for the case of protected metallic colloids.

As will be shown in the present paper, the capacity of blood, which is of the order of a few hundred micromicrofarads per 1 cm. cube, is probably due to the second of the above causes. An interesting application of the measurement of the capacity for such a case consists in the calculation of the thickness of the membrane, on which the static capacity depends, a method which probably will be found useful also in investigations of certain non-biological disperse systems, such as protected graphite suspensions which contain well conducting particles surrounded by thin poorly conducting films. The fact that in any

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case the capacity of a disperse system is determined by the state of the interphases, makes it probable that it be an important characteristic of the colloidal properties of the system (5); especially for the case of a biological system.

A problem which immediately presents itself when investigating the capacity of suspensions, is the calculation of the capacity per sq. cm. of the interphase in terms of the capacity of the suspension, the volume concentration of the suspended phase, and the geometrical constants of the single suspended particle. For certain important cases this problem has been solved in the papers already referred to. In the present paper we shall only consider the case defined by the requirement that the capacity of the suspension is due either to a static capacity as the result of the existence of a poorly conducting interphasial membrane; or to a polarization, the resistance of which is small as compared to the impedance of its capacity. The frequency is furthermore supposed to be so low that the impedance of the interphasial capacity is high as compared with the interior resistance of the single particle.

For many cases the average particle of the suspension can be considered to be equivalent to a certain spheroid. We have considered such a suspension in a previous paper (3), in which the following formula was derived:

$$C = C_o \cdot \alpha \cdot q \left(1 - \frac{r_1}{r}\right) = C_{100} \left(1 - \frac{r_1}{r}\right) \quad (1)$$

or

$$C_o = \frac{C}{\alpha \cdot q \left(1 - \frac{r_1}{r}\right)} = \frac{C_{100}}{\alpha \cdot q}, \quad (2)$$

where C_o is the capacity per sq. cm. of spheroid surface; C , the specific capacity of the suspension; $2q$, the major axis of a spheroid; and r and r_1 , the specific resistances of the suspension and of the suspending liquid respectively. C_{100} is the specific capacity of the 100 per cent concentrated suspension.

α depends on the geometrical constants of a spheroid, but is independent of the volume concentration of the suspension. The value of α is given in the paper referred to above and it is tabulated in Table I.

The influence of the volume concentration is expressed solely through the factor $\left(1 - \frac{r_1}{r}\right)$. It may be noted that this part of the formula $\left[C = C_{100} \left(1 - \frac{r_1}{r}\right)\right]$, is of a very general character, being practically independent of the form of the single suspended particle.

TABLE I.

$\frac{b}{a}$	α	$\frac{a}{b}$	α
1	1.50	1	1.50
2	1.30	2	1.03
3	1.27	3	.94
4	1.28	4	.94
∞	1.65	∞	$.118 \cdot \frac{a}{b}$

Experimental Method.

This formula was tested by measurements of the capacity of suspensions of red corpuscles of varying volume concentration. The capacity is of the order of a few hundred micromicrofarads, in parallel to a resistance of a few hundred ohms per 1 cc. of normal blood. It was measured with a specially designed Wheatstone bridge¹ over a range of frequencies from 800 to $4\frac{1}{2}$ million cycles. The sensitivity of the bridge is such that a capacity in parallel to 100 ohms at the lowest frequency can be measured with an accuracy of a few micromicrofarads. Two arms of the bridge (Figs. 1 and 2) contain a Kohlrausch slide-wire which is always used near its middle point; the third arm contains a decade resistance box R_l (General Radio Company, $\frac{1}{10}$, 1, 10, and 100 ohms decades) with a condenser C_l in parallel, and the fourth arm contains the electrolytic cell with a variable condenser C_r (General Radio Company Standard Precision Condenser) in parallel. By means of a switch S the electrolytic cell can be replaced by a decade resistance box R_r similar to R_l . The coils in the resistance boxes are wound by the

¹This bridge was constructed with the assistance of Mr. I. E. Beasley of this laboratory.

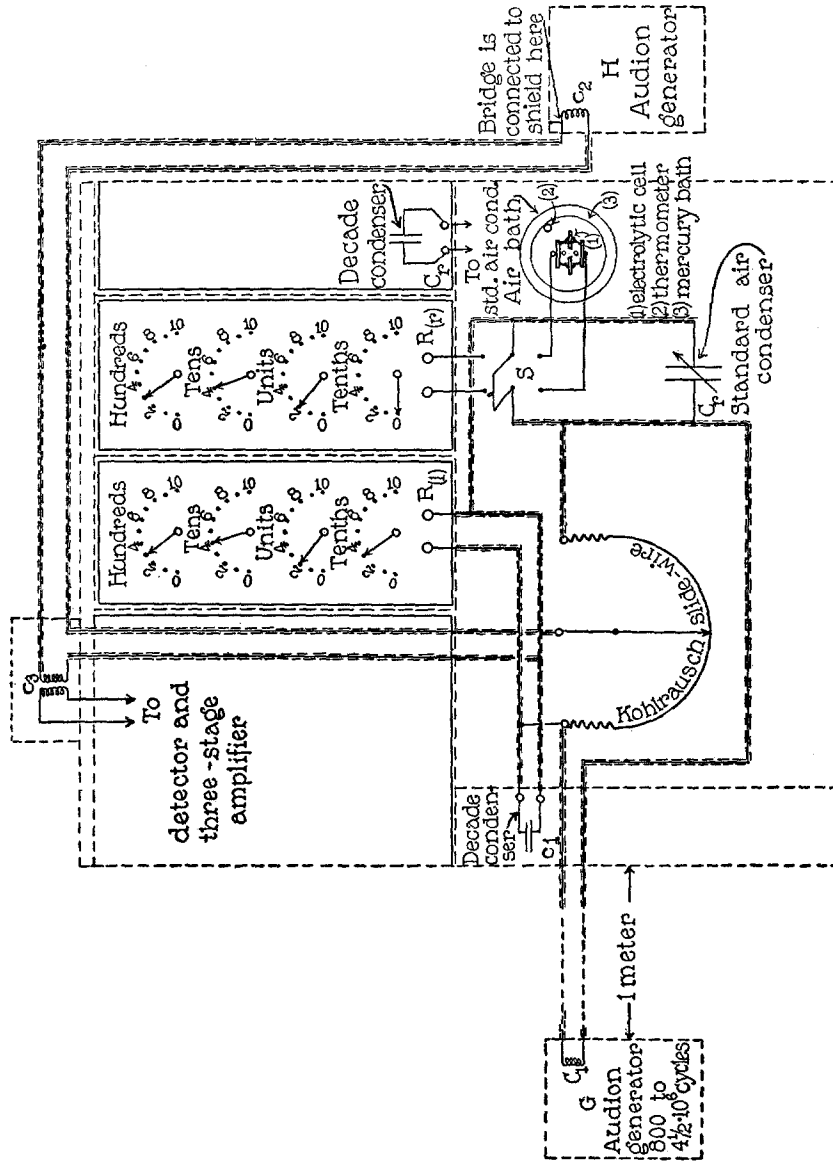


FIG. 1. Diagram of high frequency bridge for measuring electric resistance and capacity.

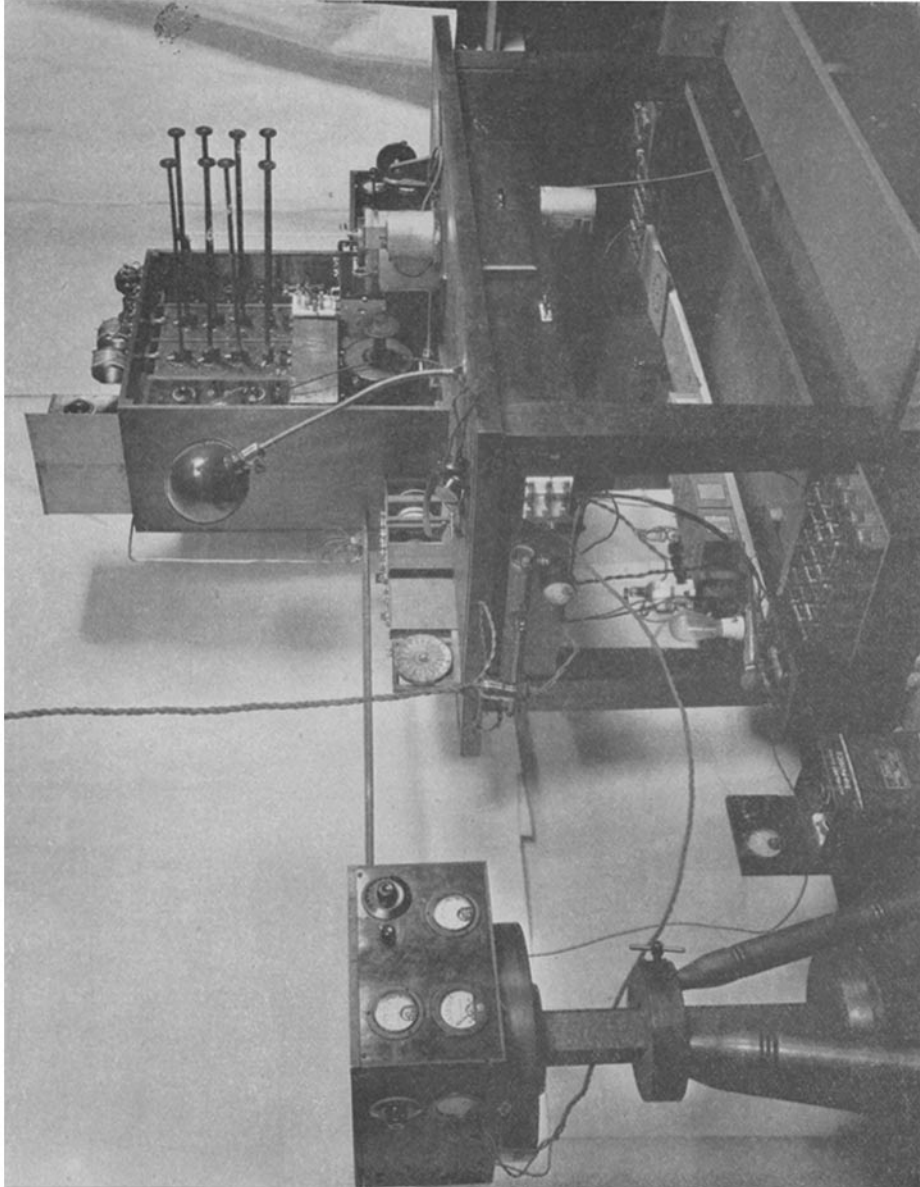


FIG. 2. Photograph of high frequency Wheatstone bridge for measuring electric resistance and capacity.

Ayrton-Perry method and their effective inductances are rather low. The current to the bridge is delivered by an audion oscillator G and the heterodyne method of detection is employed, the beat note being produced by the audion oscillator H ; three-stage amplification is employed. The bridge is connected to the generating and heterodyne oscillators and to the detector tube by the very loose inductive couplings c_1 , c_2 , and c_3 . All parts of the bridge are carefully shielded, the bridge being connected to the shield at c_2 . The oscillator is placed at a distance of about 1 meter from the bridge in order to reduce the direct coupling between them. The electrolytic cell has the form of an hour-glass with large platinized platinum electrodes sealed into the glass at the ends; it is designed to have the lowest possible amount of polarization at the electrodes. Effective stirring, which is essential, is accomplished by gently blowing through two glass tubes which are sealed to the top of the cell. (A picture of the cell is given in Fig. 2 of the following paper (7).)

A substitutional method is employed, in which the blood in the last analysis is compared with a diluted serum of the same specific resistance as the blood, the blood and the serum being placed consecutively in the same electrolytic cell. The abstract of the protocol given in Table II will explain the procedure. The cell is filled with the blood and a balance is first obtained with the cell in (switch S down); the settings of the left resistance box R_l' , of the standard condenser C_r' , and of the slide-wire are noted; a balance is thereafter obtained with the right resistance box R_r in (switch S up) and the settings R_r'' and C_r'' noted; if the setting of the slide-wire had to be changed in the last measurement, a change of $\frac{1}{10}$ ohm is made in R_r and the slide-wire and standard condenser are changed until equilibrium is again established. R_r'' is the resistance of the suspension, while $C_r'' - C_r'$ represents an uncorrected value for the capacity. This value is first corrected for the inductance of the coils used in the resistance box R_r , and for the difference between the inductances of the leads which connect the cell and R_r , respectively to the bridge; this correction for our case is $\frac{L}{R_r'^{1/2}}$ farad when this total inductance is L henry. A small correction is thereafter introduced

TABLE II.
Abstract of Protocol.
Blood (11.1 per cent).

No. of experiment.	IV ₁	IV ₂	IV ₃	Diluted serum.	
R'_1 (ohms).....	93.3	93.0	93.2	93.1	187.8
C'_1 (arbitrary units).....	6.47	6.43	6.61	8.08	8.18
Setting of slide-wire.....	-1	-7	-7	-1	
R''_1 (ohms).....	93.9	93.5	93.7	93.8	189.1
C''_1 (arbitrary units).....	10.05	10.10	10.26	10.72	9.27
Setting of slide-wire.....	-14½	-7	-2½	0	-1
Temperature.....	23.30°	23.12°	23.20°	22.40°	22.40°
$C''_1 - C'_1$ (arbitrary units).....	3.58	3.67	3.65	2.64	1.09
$C''_1 - C'_1$ (m.m.f.).....	217	223	222	160	66
Inductance of coils $\left\{ \begin{array}{l} L_{100} \\ L_{10} \\ L_1 \\ L_{.1} \end{array} \right.$			247.	141	2270
of resistance box. $\left\{ \begin{array}{l} L_{10} \\ L_1 \end{array} \right.$	8760	8760	8760	8760	7950
(10^{-10} henry.)	1970	1970	1970	1970	5120
	1960	1130	1650	1650	370
Difference of inductance of leads respectively to box and to cell.....	-900	-900	-900	-900	-900
Total inductance (10^{-10} henry).....	11,790	10,960	11,300	11,480	14,810
Equivalent capacity $\left[= \frac{\text{total inductance}}{R''_1} \cdot 10^3 \right]$	134	126	130	130	41.
m.m.f.....	123	129	118	132	40.
Capacity corrected for inductance.....	83	98	92	30	25
Capacity corrected for difference in slide-wire setting.....	101	98	97	29	26
Capacity corrected for static capacity of electrolytic cell.....	95	92	91	21	18
Capacity for cell filled with serum.....	21	21	21	21	
Capacity of blood.....	74	71	70	70	

for the static capacity of the electrolytic cell, which for low frequencies is $\frac{7.2}{\left(\frac{r}{r_1}\right)^c}$ micromicrofarads in which r and r_1 are specific resistances of suspension and intercellular liquid respectively and c is the constant of the electrolytic cell $\left(\frac{\text{resistance}}{\text{specific resistance}}\right)$.

The value thus corrected is still faulty on account of the difference in static couplings between the electrolytic cell and other parts of the bridge on one side, and on the other side between the resistance box R_r and other parts of the bridge. The corresponding correction, called the zero capacity, depends on the resistance; it is obtained by making a series of similar measurements with the cell filled with various dilutions of serum. The values of the zero capacity thus obtained are plotted against the resistances. The final value for the capacity of the blood is obtained by subtracting the zero capacity.

The procedure described above would not have given a correct elimination of a polarization at the electrodes of the electrolytic cell if such an effect had been present to any appreciable amount within the experimental range of frequencies. The frequency at which the polarization becomes appreciable is easily determined by measuring the serum at decreasing frequencies; the setting of the standard condenser remaining practically constant until the critical frequency is reached, when an abrupt change takes place.

A confirmation of the accuracy of the method described was obtained by making measurements on cream in which case the resulting capacity is zero. The fact that the value of the capacity of a corpuscle suspension is found to be independent of the form of the electrolytic cell and of the frequency serves as a further confirmation. (The capacity is found to be independent of the frequency between 3600 and 87,000 cycles per second; for higher frequencies the capacity decreases because of the fact that the impedance due to the static capacity of the corpuscle membrane becomes comparable with the impedance of the corpuscle interior.)

Measurements of Suspensions of Red Corpuscles.

In Tables III and IV is given a complete series of measurements with suspensions of the red corpuscles of a dog. This series is typical of several others, in which, besides the blood of a dog, the blood of rabbits has also been used. C_{100} (the capacity for a 100 per cent solution) is calculated by formula (1) and except perhaps for the very

TABLE III.

Capacity of Suspensions of Red Corpuscles in Own Serum.

Blood of dog.		Frequency: 87,000 cycles per sec.			Date, Mar. 24, 1925.
No. of experiment.	Volume concentration calculated from resistance.	Resistance (r) (ohms).	Capacity (C) m.m.f.	Capacity (C_{100}) for 100 per cent concentration (calculated).	Origin.
	<i>per cent</i>				
I	43.9	188.7	232	388	Original blood.
II	30.8	140.1	172	374	From original blood by dilution.
III	20.6	113.7	126	378	From 30.8 per cent suspension by dilution.
IV	11.1	94.0	72	371	From 20.6 per cent suspension by dilution.
V	10.6	93.4	74	391	From original blood by dilution.
VI	42.8	185.3	221	374	Original blood.
Average: 380 m.m.f. ± 2 per cent.					

Defibrinated blood of Dog 1 was diluted with own serum.

Resistance (r_1) of serum: 75.8 ohms. Temperature: 23.10°C. Constant of electrolytic cell: .98. Specific capacity for 100 per cent concentration: 372 m.m.f. Capacity per sq. cm. of membrane: $C_0 = .81$ m.f.

highest volume concentrations is constant within the experimental error, which is a few per cent.

The volume concentration is calculated from the resistance by a formula recently given (6) in which $\frac{a}{b}$ (ratio of thickness to diameter of corpuscle) is taken as equal to $\frac{1}{4}$.

The average value of C_{100} for the blood used in Table I is equal to 380 m.m.f., the constant of the electrolytic cell being .98. The corresponding specific capacity is obtained by multiplying the average value of C_{100} with the constant of the electrolytic cell and therefore is equal to $380 \cdot 98 = 372$ m.m.f. This value would be too small (with a factor of the order of $\left(\frac{r_1}{r_1 + r_2}\right)^2$) if the resistance of the

TABLE IV.

Capacity of Suspensions of Red Corpuscles in Own Serum.

Blood of dog.		Frequency: 87,000 cycles per sec.			Date, Mar. 23, 1925.
No. of experiment.	Volume concentration calculated from resistance.	Resistance (r) (ohms).	Capacity (C) m.m.f.	Capacity (C_{100}) for 100 per cent concentration (calculated).	Origin.
	<i>per cent</i>				
I	83.9	931.	374	411	Concentrated by centrifugation from original blood.
II	21.0	126.9	129	385	From 83.9 per cent suspension by dilution.
III	72.0	498.	343	411	From 83.9 per cent and 21. per cent suspensions.
IV	47.5	230.2	237	374	From 72.0 per cent suspension by dilution.
V	60.2	329.	286	385	From 83.9 per cent and 47.5 per cent suspensions.

Defibrinated blood of Dog 1 was concentrated by centrifugation, and the concentrated suspension was diluted with serum.

Resistance (r_1) of serum: 84.25 ohms. Temperature: 18.95°C. Constant of electrolytic cell: $c = .98$.

² Polarization by alternating current has been hitherto mainly investigated at metal electrodes. For small current densities it is equivalent to a capacity in series with a resistance. Only a few simple cases have been adequately investigated theoretically and experimentally and our knowledge of the subject is still very limited and is restricted mainly to the very low frequencies (under 1000 cycles). One important type of polarization is caused by the change in concentration at the electrode surface due to the electric current, of one or

corpuscle membrane (r_1) were appreciable compared with the resistance of the mass of the inter- and intracellular liquid (r_2) which is in series with the membrane (compare Fig. 1, diagrams (a) and (c) of the following paper (7)). A lower value for the resistance of the membrane may be derived from the maximum value of the resistance of the concentrated corpuscles of the blood of a dog which we can obtain by centrifuging the blood for a long time at the highest possible speed. It is about 60 times the value for the serum. According to observations of the resistance of blood at very high frequencies (7) the specific resistance of the interior of the corpuscle is about 3.5 times the specific resistance of the serum, so $\frac{r_1}{r_2}$ is at least equal to $\frac{60}{3.5} = 17$; consequently the factor by which C_0 may be too small, is of the order of $\left(\frac{18}{17}\right)^2 = 1.12$, which is negligible compared with what may be due to other sources of uncertainty.

In order to calculate C_0 , the capacity per sq. cm. of surface, we use

several substances on which the electrode potential depends, such as the cation for a metal in a solution of one of its salts and hydrogen gas for platinum in an acid. This concentration variation produces a change of the normal electrode potential, which is directed against the electric current and in effect is equivalent to the presence of a capacity at the electrode surface. The variation of this capacity with the frequency depends on the process by which the substances in question are removed from the geometrical surface of the electrode. In one important case, which has been discussed theoretically by Warburg (8), the removal is solely due to ordinary diffusion; here the maximum change of concentration during one cycle varies directly and therefore the polarization capacity varies inversely as the square root of the frequency. This case is realized experimentally with a few non-polarizable electrodes, such as mercury in a solution of mercuric sulfate in sulfuric acid or silver in an acid solution of silver nitrate (9). The capacity is here proportional to the concentration of cation and for a 1/1000 N solution and 1000 cycles is of the order of a few hundred microfarads. It may also be noted that according to investigations by Gildemeister (10) the polarization in frog skin follows Warburg's theory for frequencies between 400 and 90,000 cycles.

Metals in solutions which do not contain the metal ion or contain it in very low concentration usually have a low polarization capacity, which varies more slowly than with the inverse square root of the frequency, being independent of the frequency (11) in certain cases within the limited frequency ranges investigated. The capacity is of the order of 10 m.f. per sq. cm., being not very

$\frac{a}{b} = \frac{1}{4}$, which value was found to secure best agreement between the volume concentration of the blood of a dog as directly observed by Stewart and as calculated by a formula which has been recently derived (6). α (Table I) accordingly equals 1.28.

For the diameter of a corpuscle we use $2g = 7.2 \cdot 10^{-4}$ cm. Consequently by formula (2): $C_0 = \frac{372}{3.6 \cdot 10^{-4} \cdot 1.28 \cdot 10^{-6}}$ microfarad = .81 microfarad.

The experiments in Tables II and III were made with a frequency of 87,000 cycles per second; it is found, however, that the capacity is independent of the frequency, when this is lower than about 100,000 cycles per second. The lowest frequency which we have used has been 3600 cycles. The accuracy of the determinations over this range of frequencies is within a few m.m.f. For frequencies over 100,000 cycles per second the capacity begins to decrease. For frequencies up to $4\frac{1}{2}$ million cycles, however, as has been shown elsewhere (7), this decrease is solely—or very nearly so—due to the im-

different for different metals and solutions; it is usually very inconstant and unreproducible, as would be expected since the same is true for the potential. A theory of Krüger (12) explains polarizations of this type by taking into account the absorption or liberation of metal ions by the electrode, which takes place when the electrode potential changes. The concentration variation is thereby reduced and as will be easily seen, this effect must approximately be equivalent to a constant capacity of the order of the static capacity corresponding to the thickness of the dipole layer, by which the electrode potential is produced. By this effect the polarization capacity of a non-polarizable electrode should therefore become constant and equal to about 10 m.f. when the frequency is very high or the concentration of the metal ion very low. A series of experiments has been reported by Krüger which shows the continuous change from the inverse square root law to constancy for mercury in solutions of decreasing strength of mercuric sulfate. However, it is to be noted that in certain cases other effects are probably also of importance in producing constant capacities, as for instance the presence of non-conducting oxidation films (monomolecular) on the surface of the electrode (compare (13)). Especially extended investigations have been made with platinum, when the polarization under different conditions of the platinum (its content of occluded hydrogen) may depend on the variations of the hydrogen ion concentration or on the variations of the pressure of the hydrogen gas at the surface of the platinum. In certain experiments (14) the square root

pedance of the inter- and the intracellular liquid, with which the capacity of the corpuscular membrane is in series. We may, therefore, conclude that the capacity per sq. cm. of corpuscle surface is independent of the frequency between 3600 and $4\frac{1}{2}$ million cycles.

It is also found that the capacity is not changed, when the corpuscles from defibrinated blood are transferred to Ringer's solution or to an isotonic sugar solution. On the basis of these experimental data and our present knowledge of polarization² it seems unlikely that the observed capacity should be due to a polarization at the surface of the red corpuscles rather than to the static capacity of a membrane surrounding the corpuscle. Furthermore (compare equation (2) of the following paper (7)), even if the capacity were due to a constant polarization at the corpuscle surface, the observed capacity would be independent of the frequency only when the resistance of the corpuscle membrane is low as compared with the impedance of the capacity over the whole range of experimental frequencies. Different considerations seem to indicate that this is not the case; however, knowing as little as we do about the nature of the membrane, it is impossible to draw definite conclusions.

In the following we shall calculate how thick the membrane must be if the observed capacity is due solely to the static capacity of the membrane. Assuming a value of 3 for the dielectric constant of the membrane (a value which is, of course, rather uncertain, especially since the mem-

law is found to hold, in others we have the constant capacity or intermediate cases (11). Finally for the sake of completeness, we may mention that cases are also found in which the capacity varies faster than with the inverse square root. According to Krüger (12) this condition is realized when there are present in the solution complex compounds which are slightly dissociated into compounds of which one is the substance on which the polarization depends. In this case the variation of concentration of this substance is counteracted by the dissociation or production of the complex compound and the capacity therefore is higher. The calculation shows that in the ideal case it varies inversely as the first power of the frequency. Krüger has realized this condition experimentally with mercury in solutions of complex mercury salts (for instance in N KCNS + $\frac{1}{100}$ M HgCNS); it is also approximately realized for the case of palladium black saturated with hydrogen gas (15), in which the hydrogen is present mainly in the molecular form, dissociating slightly into atomic hydrogen, on which the electrode potential depends.

brane appears to be monomolecular), and by means of the formula $C_o = \frac{3}{4\pi \cdot x \cdot 9 \cdot 10^5}$ microfarads, we obtain for x , which represents the thickness, the value $3.3 \cdot 10^{-7}$ cm. This value corresponds to from 20 to 30 carbon atoms, if we assume that the distance between two neighboring carbon atoms of an organic molecule is 1 to $1\frac{1}{2} \cdot 10^{-8}$ cm., a value which Langmuir (16), for instance, derived by his investigations of the spreading of different fatty acids on the surface of water. It is evident, therefore, that our value for the thickness corresponds to a monomolecular membrane.

At present nothing is definitely known concerning the nature of the membrane, and therefore it is impossible to draw conclusions regarding the probability that this is the correct value for the thickness. We may only note that this value for the length of a single molecule of lipins (such as lecithin, cholesterol, etc.) such as chemically may be related to the membrane substance, is about what one would expect from what is known of their chemical formulæ. In this connection we may also mention that du Noüy (17) derives a value of $3.8 \cdot 10^{-7}$ cm. as the diameter of a serum protein molecule by investigating the surface tension of diluted serum protein solutions.

SUMMARY.

1. The specific capacity of a suspension is that capacity which, combined in parallel with a certain resistance, electrically balances 1 cm. cube of the suspension.

2. The following formula holds for the specific capacity of a suspension of spheroids, each of which is composed of a well conducting interior surrounded by a thin membrane of a comparatively high resistance:

$$C = C_o \alpha q \left(1 - \frac{r_1}{r} \right) \quad (1a)$$

C , specific capacity of suspension; C_o , static capacity of one sq. cm. of membrane; r , r_1 specific resistances respectively of suspension and of suspending liquid; $2q$ major axis of spheroid, α constant tabulated in Table I.

3. The following formula holds practically for any suspension whatever the form of the suspended particle.

$$C = C_{100} \left(1 - \frac{r_1}{r} \right) \quad (1b)$$

C_{100} being the specific capacity of a suspension with a concentration of 100 per cent.

Formulæ (1a) and (1b) hold only for the case, when the frequency is so low, that the impedance of the static capacity of the membrane around a single particle is high as compared with the resistance of the interior of the particle. The formulæ hold also for a suspension of homogeneous particles, when polarization takes place at the surface of each particle, provided the polarization resistance is low as compared with the impedance of the polarization capacity.

4. A description is given of a method for measuring the capacity of a suspension at frequencies between 800 and $4\frac{1}{2}$ million cycles. By means of a specially designed bridge, a substitution method is employed, by which in the last analysis the suspension is compared with the suspending liquid which is so diluted as to have the same specific resistance as the suspension, consecutive measurements being made in the same electrolytic cell.

5. Formula (1b) is verified by measurements of the capacity of suspensions of varying volume concentrations of the red corpuscles of a dog.

6. By means of the above measurements, the value of C_0 is calculated by equation (1a).

7. It is found that C_0 is independent of the frequency up to $4\frac{1}{2}$ million cycles and that it is also independent of the suspending liquid. These results furnish considerable evidence of the validity of the theory, that C_0 represents the static capacity of a corpuscle membrane.

8. On this assumption and using a probable value for the dielectric constant of the membrane, the thickness of the membrane is calculated to be $3.3 \cdot 10^{-7}$ cm.

BIBLIOGRAPHY.

1. Fricke, H., The electric capacity of cell suspensions, *Phys. Rev.*, 1923, xxi, 708.
2. Fricke, H., A mathematical treatment of the electric conductivity and

- capacity of disperse systems. I. The electric conductivity of a suspension of homogeneous spheroids, *Phys. Rev.*, 1924, xxiv, 575.
3. Fricke, H., A mathematical treatment of the electric conductivity and capacity of disperse systems. II. The capacity of a suspension of conducting spheroids surrounded by a non-conducting membrane for a current of low frequency, *Phys. Rev.*, 1925, xxvi, No. 5.
 4. Fricke, H., The electric capacity of suspensions of red corpuscles, *Phys. Rev.*, 1925, xxvi (in press).
 5. Fricke, H., and Morse, S., The electric capacity of tumors, *J. Cancer Research*, 1925, ix (in press).
 6. Fricke, H., The electric conductivity of disperse systems, *J. Gen. Physiol.*, 1923-24, vi, 741.
 7. Fricke, H., and Morse, S., The electric resistance and capacity of blood for frequencies between 800 and $4\frac{1}{2}$ million cycles, *J. Gen. Physiol.*, 1925-26, ix, 153.
 8. Warburg, E., Ueber das Verhalten sogenannter unpolarisierbarer Electroden gegen Wechselstrom, *Ann. Phys.*, 1899, lxxvii, 493.
 9. Neumann, E., Ueber die Polarisations Capacität unkehrbarer Elektroden, *Ann. Phys.*, 1899, lxxvii, 500.
 10. Gildemeister, M., Ueber elektrischen Widerstand, Kapazität und Polarisation der Haut, *Arch. ges. Physiol.*, 1919, clxxvi, 84.
 11. Wien, M., Ueber die Polarisation bei Wechselstrom, *Ann. Phys.*, 1896, lviii, 37.
 12. Krüger, F., Über Polarisationskapazität, *Z. physik. Chem.*, 1903, xlv, 1.
 13. Günther-Schulze, A., Die Ermittlung der Durchmesser elektrolytischer Ionen mit Hilfe von Kapazitätsmessungen, *Z. Physik*, 1921, vi, 229. Beiträge zur elektrolytischen Ventilwirkung. II. Die Polarisationskapazität des Tantals, *Z. Physik*, 1921, vi, 237.
 14. Jolliffe, C. B., A study of polarization capacity and resistance at radio frequencies, *Phys. Rev.*, 1923, xxii, 293.
 15. Wien, M., Ueber die Polarisationscapazität des Palladiums, *Ann. Physik*, 1902, viii, 372.
 16. Langmuir, I., The constitution and fundamental properties of solids and liquids. II. Liquids, *J. Am. Chem. Soc.*, 1917, xxxix, 1848.
 17. du Noüy, P. L., Surface tension of colloidal solutions and dimensions of certain organic molecules, *Phil. Mag.*, 1924, xlvi, 264.