Pulse-Transient Behavior of Brine-Saturated Sandstones

GEOLOGICAL SURVEY BULLETIN 1083-D

U. S. DEPARTMENT OF THE INTERIOR
March 3, 1849

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By GEORGE V. KELLER

EXPERIMENTAL AND THEORETICAL GEOPHYSICS

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Describes electrical polarization in sandstone and possible explanations of the source

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ABSTRACT

The electrical-transient response of 24 water-saturated sandstone cores was studied as a function of the salinity of the saturating solution. The transient response, or polarization expressed as the ratio of the integrated transient to the steady-state voltage applied to the samples, was found to decrease slightly with increasing salinity of the saturating solution. A comparison of electrical-transient data with measurements of porority, permeability, and cation-exchange capacity of the samples suggests that the mechanism of electric polarization is primarily an anion-trap phenomenon rather than an electro-osmotic effect.

INTRODUCTION

Before the development of induced-polarization techniques for geophysical prospecting, it was generally believed that the polarization method would provide a direct means for locating metallic-ore deposits. This belief was based on the premise that a prolonged transient response in the earth could be caused only by polarization at an interface between a metallic particle and an ionic solution. Large transients are associated with concentrations of sulfide minerals in the earth, but in many other examples, large earth transients have been observed where there are no metallic minerals.

Several mechanisms to explain large electrical polarization in ionic conductors have been suggested recently (Dakhnov and others, 1952; Keller and Licastro, 1959). Dakhnov suggests that when a voltage is applied to a rock, the resulting current causes electro-osmosis or fluid flow. Normally, cations are preferentially absorbed on the grain surfaces, so that the moving fluid is richer in anions than cations. As a result, there is an electrical current flow associated with the fluid flow. When the exciting voltage is removed, the fluid flow continues because of inertia, but because of friction the velocity decays exponentially. A transient voltage proportional to the decaying velocity transient of the fluid flow is generated.

Another mechanism to produce the same effect has been suggested by Keller and Licastro (1959). If a negatively charged clay particle is placed in a pore constriction in a rock, it may close that pore to the migration of anions but not to cations. Anions accumulate at such constrictions, and when the current is interrupted, the diffusion of ions away from these pileups will result in a transient voltage.

Enough is known about the electrical properties of rocks to confirm that both polarization mechanisms can take place in nature. However, the relative importance of the two mechanisms in electrical polarization is not known. It is reasonable to expect that the two types of polarization would be affected differently by such factors as the salinity of the water saturating a rock, the porosity, the permeability, the number of ions absorbed on grain surfaces, and possibly other rock characteristics. As an approach to determining the causes of electric polarization in common rocks, a series of measurements of transient response was made on a group of sandstone cores.

Samples for this study were provided by G. E. Manger. Porosities and water contents were measured at the Bureau of Mines' San Francisco laboratory.

MEASUREMENTS

Sandstone cores from the Morrison formation of Late Jurassic age from a drill hole in the Long Park area of Montrose County, Colo., were used for the transient studies. These cores were obtained from drill hole LP–530 in a "natural state" using an oil-base drilling mud (Manger and others, 1953). All the samples were taken from the upper part of the Salt Wash member of the Morrison formation, and consisted of fine- to medium-grained sandstone.

For electrical measurements, a disc 0.30 inch thick and 2.75 inches in diameter was cut from each core. The oil content was removed by leaching in toluol. The effective porosity of each sample was determined by measuring the volume of water which could be forced into the samples at a pressure of one atmosphere. In addition, the resistances of several of the cores saturated with distilled water were measured, and the corresponding resistivities computed. From these data, which are summarized in table 1, the original salt content of the cores was estimated.

In comparing the effective pore volume measured by water imbibition with the porosity measured at the Bureau of Mines laboratory, it is seen that on the average, the distilled water saturated about 80 percent of the pore space. Later saturations with saline solutions generally filled 95 percent of the pore space.

TABLE 1.—*Properties of cores saturated with distilled water*

Core No.	Depth (feet)	Porosity by water imbibition	Porosity USBM [1]	Resistivity [2] (10^3 ohm-cm)	Water [3] salinity (ppm)
200	289.1	0.189	0.207	------------	------------
201	250.8	.078	.113	10.4	4,000
202	283.4	.109	.194	------------	------------
203	235.4	.221	.278	------------	------------
204	240.0	.121	.050	------------	------------
205	258.0	.124	.168	------------	------------
208	252.5	.189	.220	16.6	840
209	256.0	.135	.156	------------	------------
210	257.0	.174	.156	------------	------------
211	255.1	.137	.150	45.2	580
212	253.2	.122	.087	34.3	1,000
213	297.0	.173	.197	------------	------------
214	285.4	.206	.218	46.2	250
215	290.0	.170	.204	24.6	700
216	298.7	.155	.209	21.9	960
217	295.1	.184	.207	------------	------------
218	299.6	.186	.217	------------	------------
219	291.8	.173	.231	------------	------------
220	280.6	.161	.184	------------	------------
222	292.7	.200	.211	29.0	4,500
223	281.5	.168	.183	75.0	230
224	293.3	.194	.213	------------	------------
225	284.4	.175	.220	------------	------------
228	260.6	.180	.210	------------	------------

[1] Porosities determined by the U.S. Bureau of Mines Laboratory, San Francisco, Calif.

[2] Resistivity of dried samples resaturated with distilled water.

[3] Resultant salinity of the water in the resaturated samples after taking the available soluble salts into solution.

The resistivity measurements indicate that the salt remaining in the cores from their connate water was sufficient to add only a few hundred to a few thousand parts per million of dissolved solids to subsequent water saturations. A salinity of 3,500 ppm (parts per million) sodium chloride was chosen as the lowest concentration that could be used to override the salinity remaining in the cores from their connate water. Transient measurements were made on the cores saturated with this solution, following which they were dried and resaturated with a solution containing 10,000 ppm sodium chloride. Transient measurements were repeated, the cores dried a second time, and a final saturation with a solution containing 50,000 ppm sodium chloride was done and a final set of transient measurements was made.

In recording electric transients a sample was placed in a core holder (fig. 36) consisting of two circular silver plates, each having an insulated silver strip across its face. Contact between a core and the silver plates is made through discs of blotting paper soaked in a dilute silver nitrate solution. The silver plates are used to supply current to a core and the insulated strips are used as pickup electrodes.

A block diagram of the recording equipment is also known in figure 36. An electronic timer, which can be set for intervals between 15 milliseconds and 15 seconds, operates a pair of relays to provide

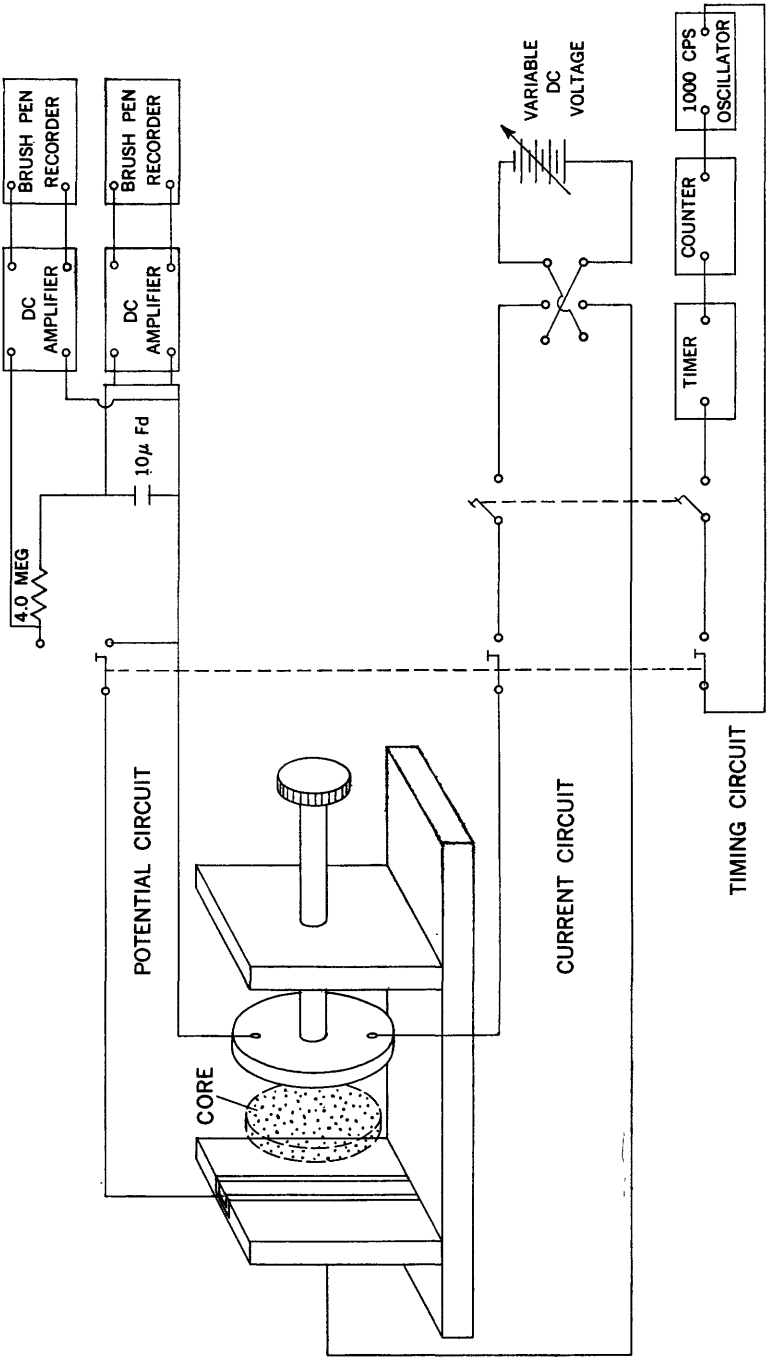

FIGURE 36.—Core holder and electronic circuits used in measuring the electrical transient behavior of drill cores.

a pulse of d-c current to the core. At the end of the pulse, another relay connects the pickup electrodes to the recording circuit, which consists of an integrating network, a pair of d-c amplifiers and a pen-recording oscillograph. This ocillograph records both the natural transient voltage across the pickup electrodes and its integral with respect to time (fig. 37).

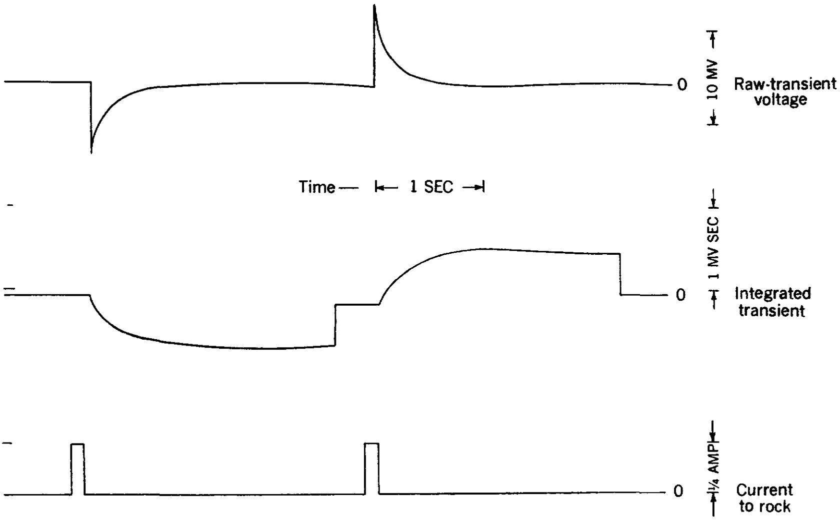

FIGURE 37.—Typical recording of data obtained in measuring electrical transient behavior.

In making measurements, a sample is pulsed with current for intervals of from 15 milliseconds to 15 seconds. Pulses are applied alternately with opposite polarity to avoid cumulative polarization at the current electrodes. A current of approximately ¼ ampere was used. Measurements of impedance at direct current and 1,000 cycles were made on each core both before and after the series of pulsings. A slight increase in resistance during measurements was noted, probably caused by drying of the sample. Also, the resistivities at 1,000 cycles were 5 to 20 percent lower than the d-c values, as is normally expected when electric polarization takes place.

After the transient studies the electrochemical properties of the cores were measured. The membrane electromotive force of a rock is defined as the voltage developed across a sample when it is in contact with two electrolytic solutions of different salinity. McCardell and Winsauer (1953) have shown that this voltage can be used to determine the number of immobilized charges on the clay particles in a rock.

Membrane emfs were measured by placing a core between two reservoirs containing saline solutions and determining the voltage between these reservoirs with a pair of calomel electrodes and a potentiometer. This voltage was measured intermittently for 30 minutes after the brine solutions were brought in contact with the rock, while the membrane emf approached a stable value. Measurements were made three times on each core, using salinity ratios of 50,000 to 10,000 ppm, 50,000 to 8,000 ppm, and 50,000 to 5,000 ppm.

The number of immobilized negative charges in the rock structure was computed using equations developed by McCardell and Winsauer (1953). According to McCardell, the membrane emf is the sum of three voltages: a phase-boundary voltage at each interface between the sample and electrolytic solution, and a diffusion voltage across the sample. The phase-boundary voltage, E_{PB}, at each interface is given by:

$$E_{PB}=\frac{KT}{c}\ln\left(\frac{a_0}{a}+\sqrt{1+\left(\frac{a_0}{2_a}\right)^2}\right) \tag{1}$$

where

K is Boltzman's constant
T is the absolute temperature
c is the ionic charge,
a is the concentration of each ion in the external solution,
a_0 is the number of bound charges in the rock, expressed as an equivalent concentration of ions in the solution.

The diffusion voltage, E_D, is given by:

$$E_D=\frac{KT}{c}-\left(\frac{\mu_+-\mu_-}{\mu_++\mu_-}\right)\ln\frac{(\mu_++\mu_-)\,a_c-\mu_-a_0}{(\mu_++\mu_-)a_d-\mu_-a_0} \tag{2}$$

where

μ_+ and μ_- are the cation and anion mobilities, respectively,
a_c and a_d are the concentrations of the more concentrated and more dilute solutions, respectively.

These equations were evaluated for the salinities used in these measurements and the immobile charge content of each core was determined (values are listed in table 2). The percentage of negative charges which are immobilized is high, ranging from 7.4 percent to 92 percent of the total cation concentration of 50,000 parts per million. There is a tendency for the low immobilized-ion percentages to be associated with high porosity. The data in table 2 also suggest that the rocks with larger median-grain sizes have a lower immobilized-ion content.

TABLE 2.—*Electrochemical measurements*

Core No.	Porosity	Immobilized-ion concentration ($n\times10^3$ ppm)	Median grain size[1]	Core No.	Porosity	Immobilized-ion concentration ($n\times10^3$ ppm)	Median grain size[1]
200	0.217	19.0	0.157-0.196	214	0.215	4.65	0.152-.163
201	.142	46	.086	215	.192	5.4	.157-.196
202	.217	15.7	.146	216	.233	3.70	.199
203	.282	5.9	.107-.156	217	.241	4.30	.157-.196
204	.150	19.5	.136-.168	218	.196	4.10	.156-.200
205	.152	15.0	.136-.154	219	.231	5.3	.157-.196
208	.222	9.3	.114	220	.202	4.10	.230-.277
209	.113	17.7	.136-.154	222	.220	4.70	.230-.277
210	.161	22.5	.136-.154	224	.244	5.5	.157-.196
211	.147	20.7	.118-.152	225	.213	4.60	.152-.163
212	.158	13.1	.118-.152	228	.198	6.8	.136-.154
213	.217	16.2	.157-.196				

[1] R. A. Cadigan, U.S. Geological Survey, written communication, 1956.

INTERPRETATION OF POLARIZATION DATA

In analyzing the raw-transient data, the charging curve system was used. This procedure consists of preparing a graph relating the integral of the transient expressed in volt-seconds per volt to the duration of the exciting pulse for each set of measurements (figure 38). For short pulses, the value of the integrated transient is directly

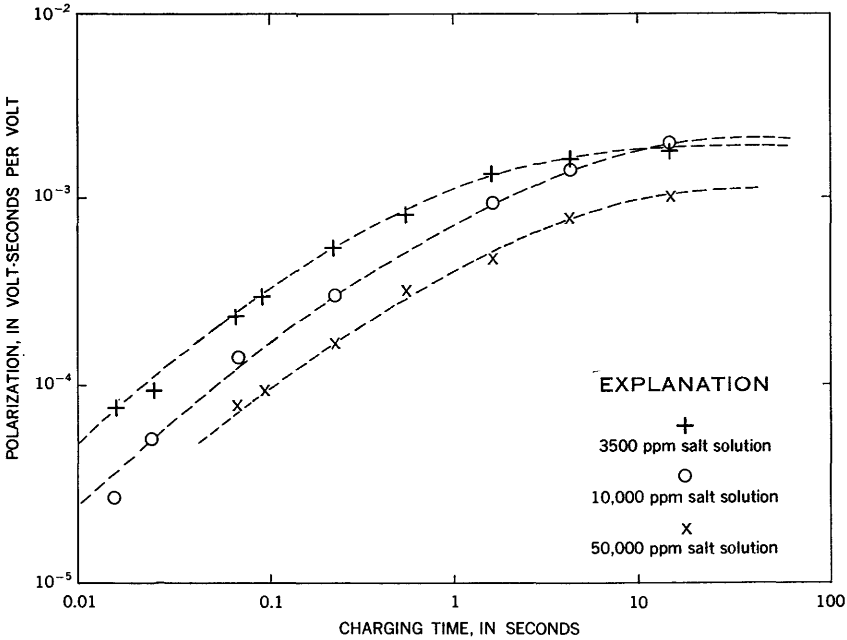

FIGURE 38.—Three charging curves measured on sample 212 as it was saturated with waters of three different salinities.

proportional to the pulse duration. For longer pulses the value of the integrated transient approaches an asymptote. The ratio of this asymptotic value to the exciting voltage may be used directly as a measure of the transient response of a material; or it may be converted to specific capacity by dividing by the additional factor RC_0, R being the electrical resistance of a sample and C_0 being its geometric capacity. Table 3 lists the asymptotic values of integrated transient and specific capacity for all the cores.

TABLE 3.—*Summary of transient measurements*

Core No.	Transient measurement for indicated salinity (ppm)					
	3,500		10,000		50,000	
	Intergrated transient (mv. sec/volt)	Capacity μfd/cm	Integrated transient (mv. sec/volt)	Capacity μfd/cm	Integrated transient (mv. sec/volt)	Capacity μfd/cm
200	5.0	1.31	2.70	2.05	----------	----------
201	1.47	0.313	1.70	.58	1.10	1.42
202	5.9	1.30	5.0	3.08	1.04	3.15
203	4.40	2.17	.88	.91	1.74	8.93
204	3.60	.68	3.80	1.35	2.92	4.23
205	2.30	.235	2.70	.28	1.48	2.19
208	.38	.124	.44	.39	.40	1.29
209	3.00	.68	2.90	2.18	2.26	1.85
210	1.88	.31	2.40	.78	2.92	4.89
211	3.50	.375	3.30	1.10	1.82	2.54
212	1.95	.173	2.20	.71	2.32	3.75
213	3.80	.96	1.80	1.64	.44	1.34
214	.83	.197	.81	.34	1.17	3.47
215	1.45	.282	1.50	.83	.96	2.28
216	.78	.414	.80	.34	1.38	4.84
217	2.80	.74	1.40	1.57	1.31	4.92
218	.53	.127	.48	.35	----------	----------
219	.84	.128	1.70	.78	.310	1.06
220	.58	.051	.33	.194	.303	.79
222	.98	.040	.41	.258	.283	.88
223	.87	.163	.93	.292	----------	----------
224	1.20	.348	.59	.47	.68	2.59
225	1.65	.545	.70	.315	.36	1.05
228	1.22	.178	.67	.230	1.48	3.76

Considering the errors in the measurements and the uncertainty involved in extrapolating the charging curves to an assymptotic value, the values presented in table 3 probably are accurate within ±20 percent. For a single sample the variation in polarization from salinity to salinity is of the same magnitude as the average error, but there is a tendency for the polarization to decrease with increasing water salinity. The data were grouped in three categories for high, moderate, and low values of polarization and the average value of polarization for each of the three groups was computed (fig. 39). The polarizations are about 50 percent smaller when a saturating solution containing 50,000 ppm NaCl is used than when a solution containing 3,500 ppm NaCl is used.

An earlier study of the dielectric constant of sandstones from the Morrison formation (Keller and Licastro, 1959) showed that the

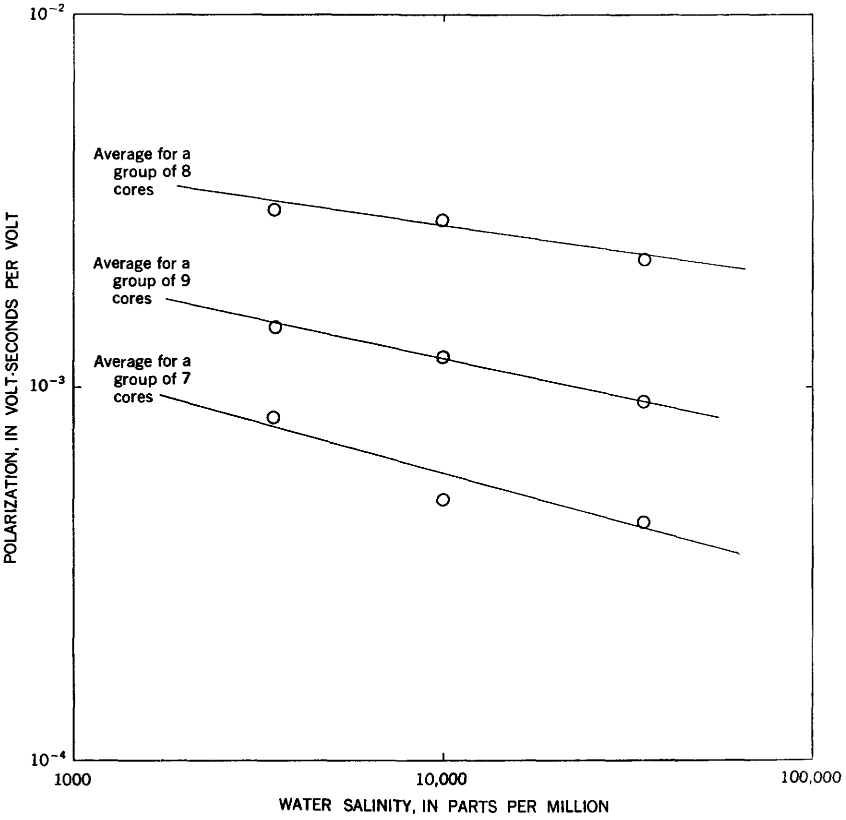

FIGURE 39.—Variation of electrical polarization with water salinity for three groups of sandstone samples saturated with saline solutions.

transient response can be represented quite closely by an equation originally developed by Wagner (1913). Wagner suggested that most materials have a log-normal distribution of relaxation times, rather than a single relaxation time, so that an electrical transient should obey the equation:

$$i(t)=E_0C_0\frac{\gamma b}{T_0\sqrt{\pi}}\int_{-\infty}^{\infty} e^{-b^2z^2-z-t/T_0e^{-z}}\,dz \qquad (3)$$

where

E_0 is the applied voltage,
C_0 is the geometric capacity of the system, γ is a constant of proportionality,
b is related to the inverse of the standard deviation of the distribution of time constants,
t and T_0 are the time and principal time constant, respectively, and
$z=ln\ t/T_0$.

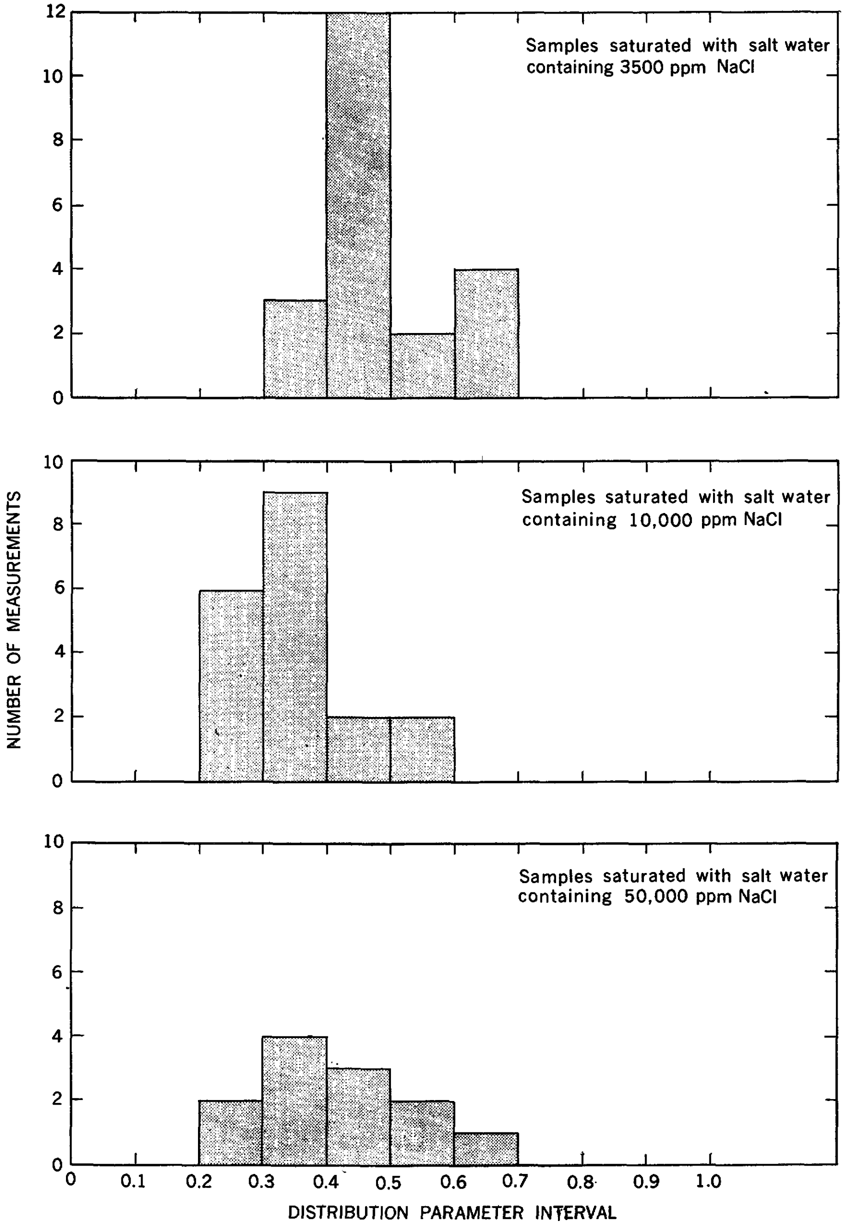

FIGURE 40.—Distribution of the values for the parameter *b* used in describing transient character for water-saturated sandstones.

In practice, the observed transient voltage is the sum of the two transients obeying equation 3: one positive transient caused by the leading edge of the current pulse and one negative transient caused by the trailing edge. The charging curve is then given by the equation:

$$q(t)=E_0C_0\frac{\gamma b}{T_0\sqrt{\pi}}\int_0^{\Delta t}\int_{-\infty}^{\infty} e^{-b^2z^2-z-t/T_0 e^{-2}dzdt} \tag{4}$$

Values of b and T_0 for each of the experimental charging curves were obtained by comparison with standard curves computed from equation 4. The distributions of each of these parameters, b and T_0, for each of the three water salinities, are shown in figures 40 and 41. The parameter b covers a very narrow range with most values falling close to 0.5. Relaxation times cover a much wider range, falling between 0.1 and 30 seconds. No significant variations were observed in either parameter for the different water salinities, although there is a tendency for longer time constants to be associated with higher resistivities (fig. 42). Also, slightly lower values of b are associated with the more saline water saturations.

Previous work (Keller, 1959) has suggested that, for a particular rock type, there is an inverse correlation between electrical resistivity and specific capacity. A correlation plot of these two factors, shown in figure 43, indicates that this relationship holds in a general way for sandstones of the Morrison, although for any given value for one of the factors, there is a tenfold range in the corresponding values for the other factor.

CORRELATION BETWEEN TRANSIENT DATA AND ROCK PROPERTIES

Of more importance than listing the range of the parameters describing electric polarization is the use of these data as a clue to the mechanics of the polarization. An idea of how rock texture and connate-water salinity may effect electrolytic polarization can be obtained by postulating simple models of rock structure incorporating the electro-osmotic and ion-trap concepts mentioned in the introduction.

For the purpose of constructing a model of the ion-trap mechanism a typical pore structure in a clastic rock may be considered as consisting of a relatively large storage void connected to other such voids by fibrous channels. Clay particles in constrictions in the connecting channels will effectively block migration of negative ions because of the small size of the channels and the force of electrostatic repulsion from the negative charges usually present on the clay particles. In such a situation the positive ions are free to move

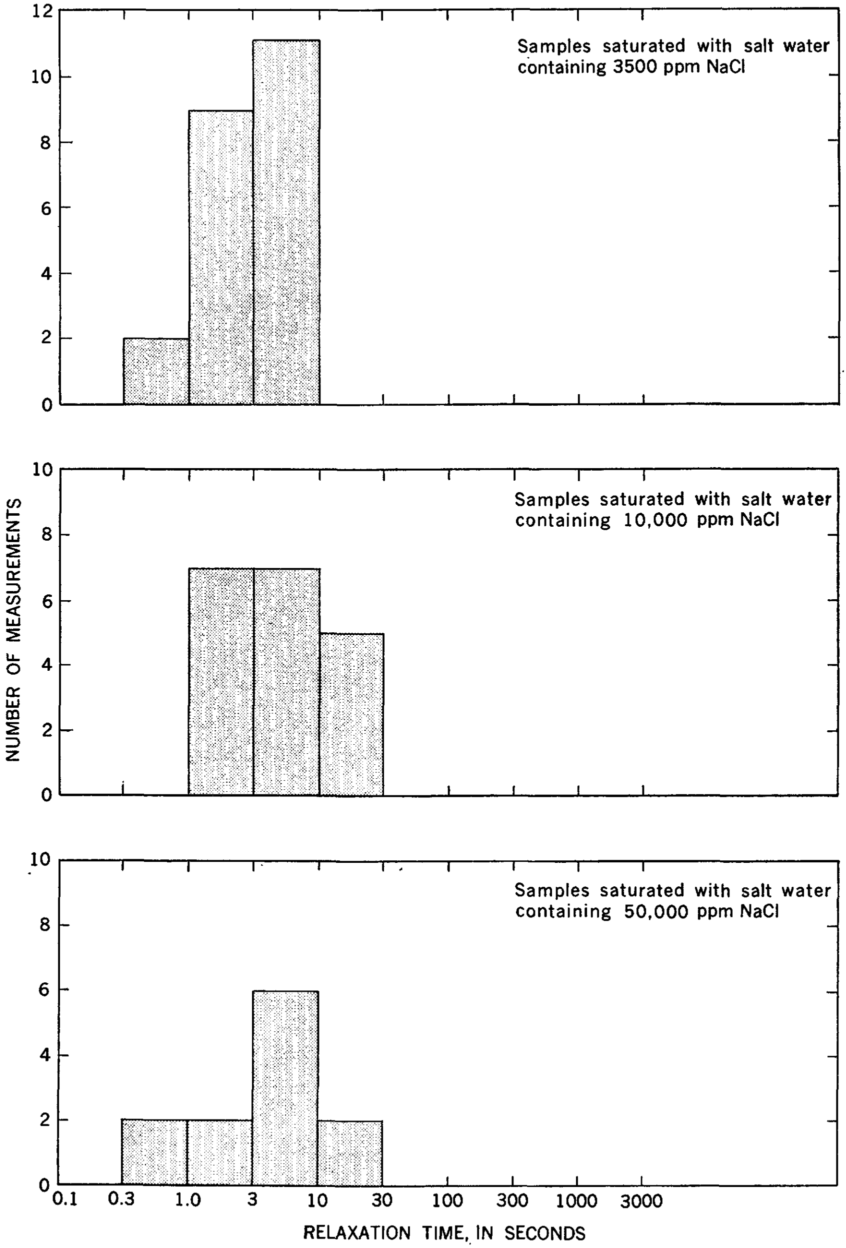

FIGURE 41.—Distribution of values for transient relaxation times in water-saturated sandstones.

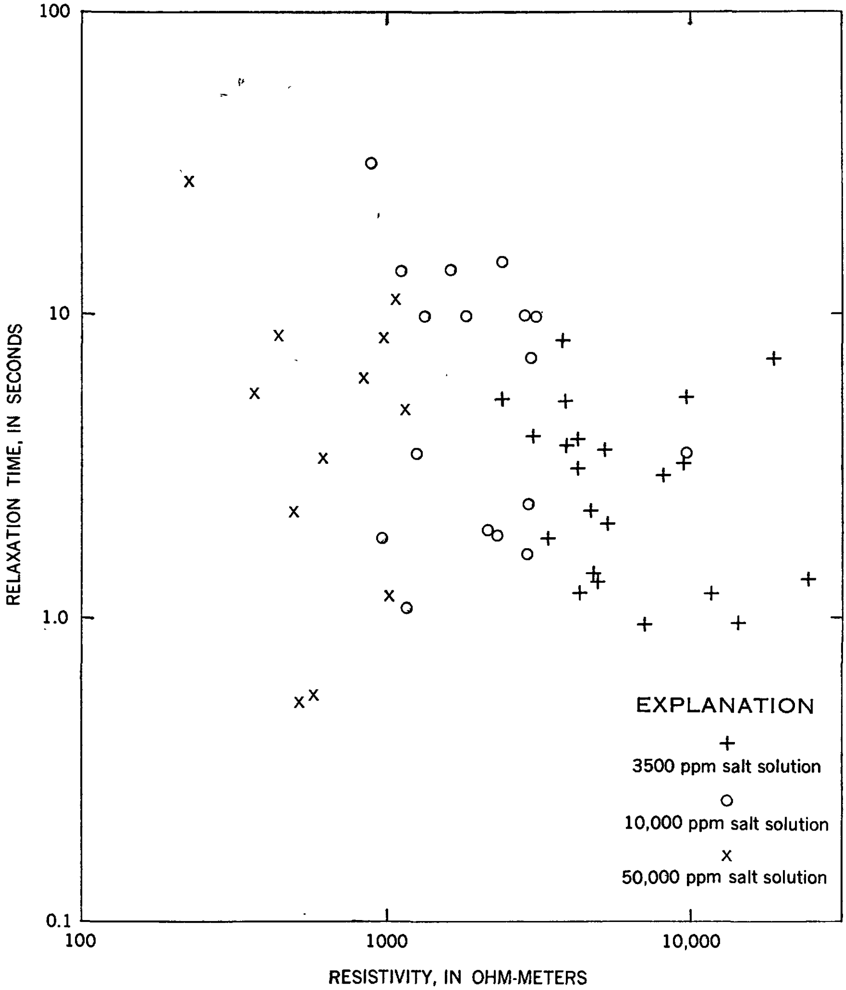

FIGURE 42.—Scatter diagram for values of electrical resistivity and transient relaxation time for samples of water-saturated sandstone.

through the rock under the influence of an external field but anions can migrate only until they encounter a selectively permeable pore constriction. A negative charge accumulates at the pore constriction as the anions migrate from one side to the other of the free area in a pore. When the external field is removed, the charge accumulations will return to equilibrium positions by diffusion, giving rise to a

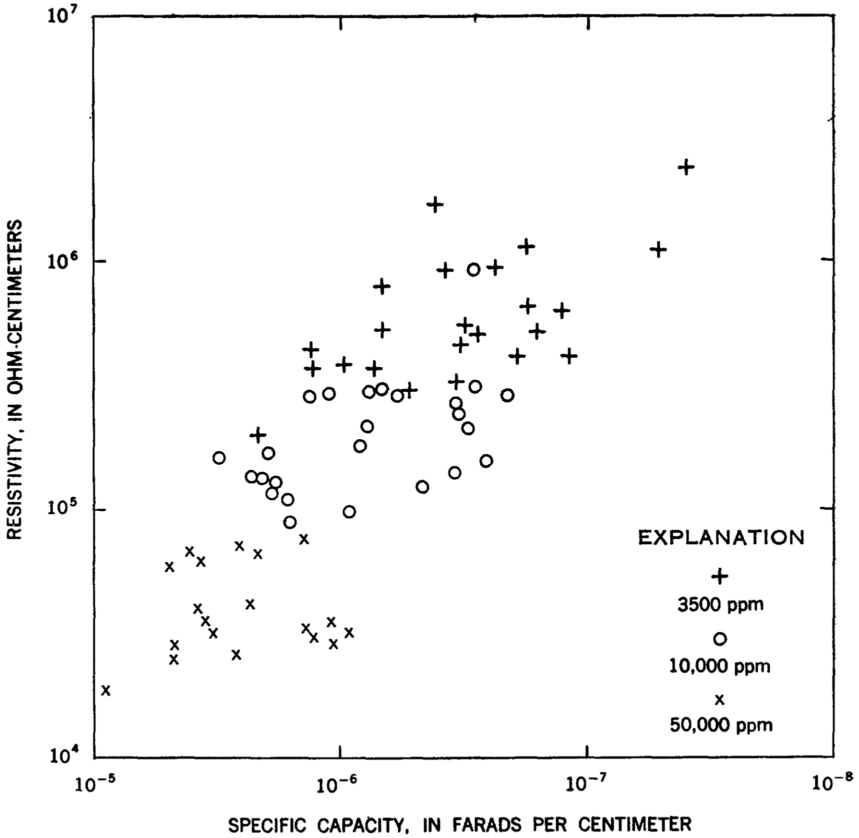

FIGURE 43.—Correlation between electrical resistivity and specific capacity for water-saturated sandstone.

prolonged transient current. Using this model, the charge stored by a current pulse is given (Keller and Licastro, 1959) by—

$$Q=\frac{8\phi\mu_-^2 ItN(a-a_0)}{\pi D^4(1+k)(\mu_+ + \mu_-)(2a-a_0)}\int_0^t \frac{E}{m}\,dt \qquad (5)$$

where

Q is the charge stored in the ion accumulations,
ϕ is the porosity,
E is the applied voltage,
I is the pulsing current,
t is the pulse duration,
N is the fraction of the pores blocked by anion traps,
D is the average storage pore diameter,
k is the ratio of the volume of connecting pores to the volume of the storage pores, and
m is the ratio of the voltage gradient in the connecting pores to the voltage gradient in the storage pores.
a, a_0, μ_+ and μ_- are the ionic concentrations and mobilities, respectively.

As a model for the electro-osmotic effects, the pore structure can be thought of as a bundle of capillaries wandering randomly through a rock. A part of the cations in the solution are fixed by absorption on the walls of the capillaries, leaving the liquid in the center of the capillaries enriched in anions. Motion of the fluid causes an electric current because of the lack of electrical neutrality. A relation between the electrokinetic phenomena and rock texture may be deduced by considering von Karmen's equation for electro-osmotic velocity and Darcy's equation for hydraulic velocity (see Pirson, 1947). When a voltage is applied across a bundle of capillaries, the resulting migration of ions causes a flow of water through the capillaries. The terminal velocity is—

$$v_0 = E\frac{\epsilon\zeta}{4\pi\eta} \qquad (6)$$

where

ϵ is the specific capacity of the liquid
η is the viscosity of the liquid
E is the applied voltage and
ζ is the zeta potential, defined as the voltage between the absorbed ions on the capillary surfaces and the ions in the free part of the liquid far removed from the absorption zone.

The flow velocity given by equation 6 creates an electrical current equal to—

$$I_0 = E\frac{a_0\epsilon\zeta}{4\pi F\eta} \qquad (7)$$

where

F is the Faraday constant
a_0 is the concentration of ions absorbed on the solid surface.

This current results in a voltage according to Ohm's law. Since the bundle of capillaries follows a devious route throughout the model of a rock, the voltage gradient along the capillaries is reduced by the tortuosity of the pore paths. Tortuosity is expressed analytically as the ratio of the length along a pore divided by the straight line length of a sample. Thus, equation 7 becomes:

$$e_{\max} = E\frac{a_0\epsilon\zeta\rho}{4\pi TF\eta} \qquad (8)$$

where

ρ is the resistivity of the rock.

Or, since

$$T = \phi^{-1}$$

and

$\rho = \rho_w \phi^{-2}$ by Archie's law (Archie, 1947),

then

$$e_{\max} = E \frac{a_0 \epsilon \zeta \rho}{4\pi \phi F \eta} \tag{9}$$

where

ρ is the resistivity of the brine saturating the pores, and
$e_{\max}$ is the electrokinetic (or polarization) voltage after the fluid flow has reached its terminal velocity.

When the polarizing voltage is removed, inertia prevents the fluid velocity from dropping to zero immediately. Instead, friction reduces the velocity gradually and the corresponding electrical current flow decreases gradually, giving rise to a transient voltage. To obtain the equation for fluid flow after the exciting voltage is removed, a viscous force proportional to fluid velocity is equated to the density of the fluid multiplied by the fluid acceleration. The solution to the differential equation is:

$$v = v_0 e^{-\frac{\eta}{K} t} \tag{10}$$

where

v is the fluid velocity as a function of time,
t is the time following the interruption of the exciting voltage, and
K is the permeability of the rock, defined by Darcy's law.

Since the electrokinetic current is proportional to fluid velocity, the transient voltage decays according to the equation:

$$e = E \frac{\rho_w a_0 \epsilon \zeta}{4\pi \phi F \eta} e^{-\frac{\eta}{K} t} \tag{11}$$

In terms of the function $\int_0^\infty \frac{e}{E} dt$ used to represent earth transients, we have—

$$\int_0^\infty \frac{e}{E} dt = \frac{\rho_w a_0 \epsilon \zeta K}{4\pi \phi F \eta^2} \tag{12}$$

These two simplified rock models result in transient voltages according to equations 5 and 12 which are related to measurable rock properties such as ϕ, K and a_0 in different ways. This fact gives us a method for distinguishing which mechanism, the ion-trap phenomenon or the electro-osmosis phenomenon, is the more important in the polarization of a rock. In the case of ion-trap polarization, the parameter $\int_0^\infty \frac{e}{E} dt$ should be proportional to the factor $\phi N \frac{(a - a_0)}{(2a - a_0)}$ for constant values of D, ρ_w, K and m. We have no direct method of measuring N, the fraction of the pores blocked by ion traps, but it should be roughly proportional to a_0/a, the fraction of cations immobilized in the rock. Values for the factor $\phi\frac{a_0\,(a-a_0)}{a\,(2a-a_0)}$ were computed and listed in Table 4. In the case of electro-osmotic polarization, the polarization should be proportional to the factor $\frac{a_0K}{a\phi}$ which also is listed in table 4.

If either of these processes is the principle cause of polarization, then there should be a direct proportionality between the polarization quantity $\int_0^\infty \frac{e}{E}\,dt$ and the corresponding factor listed in Table 4. Correlation plots for the polarization quantity as a function of the ion-trap number and of the electro-osmosis number are shown in figure 44.

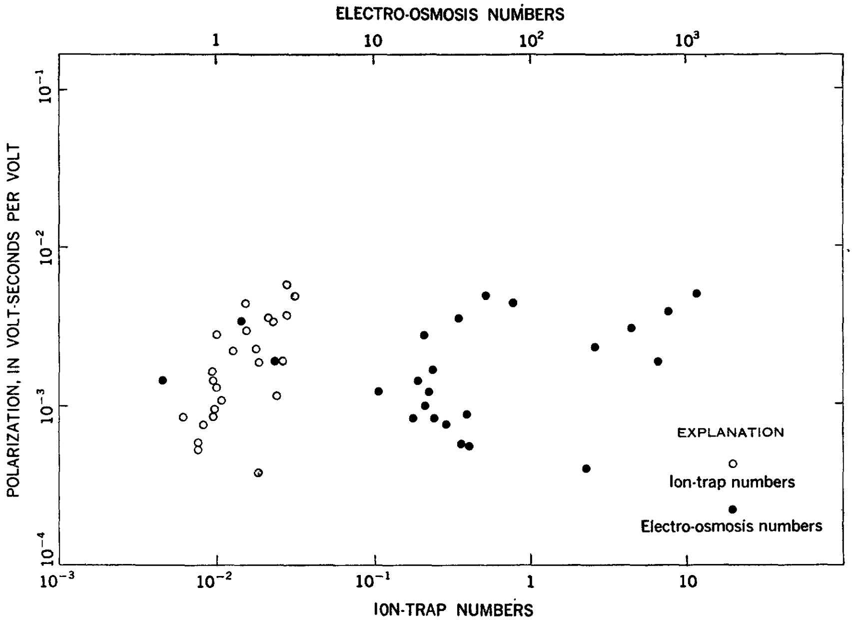

FIGURE 44.—Comparison of ion-trap numbers and electro-osmosis numbers with polarization data.

It is immediately obvious that the correlation between polarization and ion-trap number is better than the correlation between polarization and electro-osmosis number. The scatter of the electro-osmosis data about a correlation line covers three orders of magnitude while the scatter of the ion-trap data about a similar line covers only half an order of magnitude. Variations within a half order of magnitude are readily explainable in terms of the lack of precision of such meas-

TABLE 4.—*Figures of merit for ion-trap polarization and electro-osmotic polarization*

Core No.	Permeability[1] K(millidarcies)	Ion-trap number $\phi \frac{a_0 (a-a_0)}{a (2a-a_0)}$	Electro-osmosis No. $\frac{a_0 K}{a \phi}$	Polarization at 3,500 ppm (10^{-4} volt-seconds/per volt)
200	67.9	0.0316	1190	50
201	.07	.0096	.45	14.7
202	36.7	.0278	53	59
203	192	.0155	80	44
204	.55	.0222	1.42	36
205	132	.0182	260	23
208	270	.0187	226	3.8
209	143	.0156	448	30
210	243	.0261	680	18.8
211	12.5	.0225	35.2	35
212	1.46	.0175	2.42	19.5
213	522	.0284	780	38
214	404	.0096	172	8.3
215	354	.0098	198	14.5
216	925	.0083	294	7.8
217	591	.0099	211	28
218	952	.0077	401	5.3
219	537	.0116	247	8.4
220	910	.0078	370	5.8
222	506	.0098	217	9.8
223	1070	.0060	397	8.7
224	497	.0126	224	12.0
225	542	.0093	234	16.5
228	157	.0106	108	12.2

[1] Measured by U.S. Bureau of Mines Laboratory, San Francisco, Calif.

urements as pore diameter and the parameters k and m. Variations of more than three orders of magnitude are not so readily explained.

A further distinction between ion-trap and electro-osmotic polarization lies in the manner in which polarization depends on the salinity of the saturating water. In ion-trap polarization, defined in equation 5, the polarization should not vary with the salinity of the water except as the water salinity may effect such parameters as N and a_0. In electro-osmotic polarization, the amplitude of polarization is proportional to the water resistivity and zeta potential, both of which decrease rapidly with increasing water salinity. The fact that the polarizations observed in these experiments decrease only slightly with increasing salinity indicates that at most the electro-osmotic effect is a small part of the total polarization effect.

There are other, more sophisticated, differences in the way electro-osmotic and ion-trap polarizations differ according to equations 5 and 12. In particular, the type of salt in solution will have a profound effect on polarization since the mobilities of the ions enter into equation 5 and the zeta potential in equation 12 is controlled by the type of salt in solution.

SUMMARY AND CONCLUSIONS

In spite of the fact that measurements were carried out on a limited suite of rocks, some generalizations may be made regarding electrical polarization in brine-saturated sandstones. These include:

1 The polarization of a rock, expressed as the ratio of the integral of the transient voltage to the steady-state voltage, decreases slightly as the salinity of the water saturating it increases. As a corollary, the specific capacity of a rock differs only slightly from being inversely proportional to the resistivity of that rock. It is obvious that the transient measure of volt-seconds per volt generally used in field work is incapable of differentiating fresh-water sandstones from salt-water sandstones. On the other hand, if polarization measurements are combined with resistivity, the two conditions could be distinguished from one another.

2. The polarization in a sandstone results primarily from the pileup of ions at potential barriers within the pore structure, rather than from the fluid inertial transient resulting from electro-osmosis, as suggested by Dakhnov and others (1952).

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