CC/NUMBER 3
JANUARY 21, 1980

This Week's Citation Classic

Cole K S & Cole R H. Dispersion and absorption in dielectrics. I. Alternating current characteristics. *J. Chem. Phys.* **9**:341-51, 1941. [Dept. Physiology, Columbia Univ., New York, NY; and Res. Lab. Physics, Harvard Univ., Cambridge, MA]

A complex plane locus of real versus imaginary responses, less than a semicircular arc, for variable frequency input, is often called a Cole-Cole plot. Its origin is unknown; it was earlier fit to biological data and remains a simple presentation in many other fields. [The *SCI*® indicates that this paper has been cited over 805 times since 1961.]

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April 21, 1978

"The 'Cole-Cole plot' began in 1928. H. Fricke's electrical equivalent circuit for the impedance of red blood cells gives a semi-circular locus on the com-plex impedance plane, $Z^* = R_s + jX_s$ with R_s for the series resistance and $X_s = 1/C_s\omega$ for the reactance and capacitance. The impedance of human skin departed from R_∞ on the R_s axis at about 35° as frequency $f = 2\pi\omega$ decreased and I had to know about lower frequencies. Replacing the mem-brane capacity by Fricke's relation $z = z\,(j\omega)^{-\alpha}$ (1) for an electrode, the locus was still a circular arc — but with a depressed center. I published this in 1928.[1] and with biological examples in 1932.[2] Old measurements of dielectric transients gave $t^{-\beta}$, a Fourier transform of (1), so a cell membrane might be similar.

"My brother, Robert H. Cole, joined me for the summer in 1931 and we found α~0.8 for frog muscle, with E. Bozler.[3] Cell interaction was eliminated with the single squid giant axon giving α~0.8. Bob said he would continue—'but not with biological systems, I'm going to know what my materials are.' J.H. Van Vleck welcomed Bob at Harvard, and said, 'But he will not be diverted from his dielectric problem. I think that's your fault!'

"Bob found many more depressed center arcs and inadequate theories, calculated $z\omega^{-\alpha}$, often ignored, calculated dipole distributions after J. Kirkwood, touched on the Lagrangian formulation I. Wolff had told me about at Cornell, and more. He collected and analyzed transient data and calculations, and wrote up the papers and saw them into print —even though I would not be a junior author of either.[4] Later a board chairman greeted me with 'You're a Cole of Cole and Cole? We don't know or care which. You're both well-known, highly respected, and very welcome.'

"Since World War II, Bob and his students at Brown University have pur-sued theory and experiment over near to infinite ranges of frequency and time. He won the Langmuir Award of the American Physical Society and was chairman of the chemistry department as I stayed with biology.

"The use of the Cole-Cole plot prob-ably continues because it shows experi-mental facts in terms of four constants for the relaxation process in so many and diverse fields. In addition to dielec-trics and living structures, the arc plot appears in electrode polarization, semiconductor junctions, viscoelasticity, soils and sands, and others I don't remember."

1. **Cole K S.** Electrical impedance of suspensions of spheres. *J. Gen. Physiol.* **12**:29-54, 1928.
2. **Cole K S.** Electric phase angle of cell membranes. *J. Gen. Physiol.* **15**:641-9, 1932.
3. **Bozler E & Cole K S.** Electric impedance and phase angles of muscle in rigor. *J. Cell Comp. Physiol.* **6**:229-41, 1935.
4. **Cole K S & Cole R H.** Dispersion and absorption in dielectrics. II. Direct current characteristics. *J. Chem. Phys.* **10**:98-105, 1942.