

with C_0 determined to an accuracy of one part in 10^7 for diameter ratios of 0.1 to 0.95. (Note that numerical errors in Smythe's earlier paper are corrected in a later paper.⁴)

In Fig. 1 we compare the various expressions for F by plotting $(F-1)$ as a function of $(d/D)^3$ on logarithmic coordinates. Also shown is the semiempirical equation presented by DeBlois and Bean as the best fit⁶ (at small diameter ratios) of their experimental results,

$$F_6 = 1 + 0.73(d/D)^3. \quad (6)$$

This figure shows that (1) Smythe's numerical results F_5 agree well with the experimental data F_6 at small $(d/D)^3$; (2) DeBlois and Bean's limiting theory F_4 does not coincide with F_5 , as $(d/D)^3 \rightarrow 0$; and (3) F_3 converges with the numerical results as $(d/D)^3 \rightarrow 1$, the error being less than -8% in F at $(d/D)^3 = 0.86$. Table I compares representative F values obtained from Eqs. (4)–(6).

Smythe also presents calculations for spheroids of eccentricity $\frac{1}{2}$ (prolate) and 2 (oblate), the axis of revolution coinciding with the pore axis. His results are unreliable for the prolate spheroid as $(d/D)^3 \rightarrow 1$ because of convergence problems; however, in this region one can use the results obtained from an area integration [the basis of Eq. (3)] to obtain

$$F_7 = \frac{1}{\epsilon(d/D)^3} \left\{ \frac{\sin^{-1}(d/D)}{[1 - (d/D)^2]^{\frac{1}{2}}} - \frac{d}{D} \right\}, \quad (7)$$

where d is the diameter of revolution. One can show⁷ that any potential function Ψ that is continuous in $\nabla\Psi$ and equal to the exact solution Φ far from the particle will give rise to a current distribution which has an energy dissipation greater than or equal to that of the true solution. Thus, the exact solution Φ will give the maximum resistance (i.e., F), and hence, Eq. (7) will always be smaller than the true solution, converging to the true value as $(d/D)^3 \rightarrow 1$. [For an oblate spheroid of $\epsilon = 2$, Eq. (7) yields a value of F only 5.3% below Smythe's numerical result for $d/D = 0.95$.]

Finally, mention should be made of the assumption that the particle (spheroid) travels on the center line. Happel and Brenner⁸ state that there is no preferred path for a particle traveling through a pore, and because of Brownian motion, the exact result for F must include all

orientations and radial positions for the particle. However, Fig. 1 indicates that the analytical model (F_3) describes the system reasonably well, at least for spheres, for which there are no orientation effects.

This work was supported in part by a grant from the Office of Saline Water, U. S. Department of the Interior. J. L. Anderson was the recipient of a National Institutes of Health Research Fellowship. We would like to acknowledge the very beneficial discussions we have had with Dr. C. P. Bean on various aspects of membrane transport.

¹ R. W. DeBlois and C. P. Bean, *Rev. Sci. Instrum.* **41**, 909 (1970).

² H. E. Kubitschek, *Research (London)* **13**, 128 (1960).

³ W. R. Smythe, *Phys. Fluids* **4**, 756 (1961).

⁴ W. R. Smythe, *Phys. Fluids* **7**, 633 (1964).

⁵ E. C. Gregg and K. D. Steidley, *Biophys. J.* **5**, 393 (1965).

⁶ Note that the pore diameter in DeBlois and Bean's membrane was determined by matching their theoretical equation (F_4) to their measured resistive pulses for a range of particle diameters. If F_5 were used to fit the experimental results the coefficient in F_6 would probably show a slight change, and, hence, the agreement between F_5 and F_6 in Fig. 1 would reflect this change.

⁷ J. C. Maxwell, *A Treatise on Electricity and Magnetism* (Academic Reprints, Stanford, California, 1953), 3rd ed., Vol. 1, pp. 424, 429.

⁸ J. Happel and H. Brenner, *Low Reynolds Number Hydrodynamics* (Prentice-Hall, Englewood Cliffs, N. J., 1965), pp. 205–207.

Subnanosecond Switch for Use in Shock Wave Experiments*

T. T. COLE AND J. W. LYLE

Lawrence Radiation Laboratory, University of California,
Livermore, California 94550

(Received 25 January 1971; and in final form, 26 March 1971)

A SUBNANOSECOND selenium switch has been developed for use in shock wave experiments (see Fig. 1). Bulk selenium makes a transition to the metallic state at a pressure of 128 kilobars, with a resistivity decreasing by a factor of about 10^{11} from the value at atmospheric pressure.^{1,2} A shock wave traversing the selenium film in a direction normal to the film induces the transition.

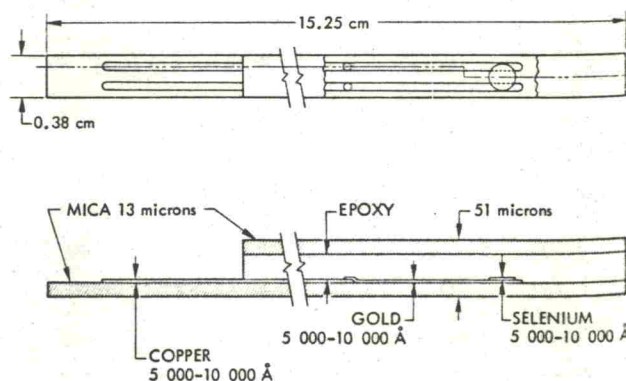


FIG. 1. Construction of the selenium switch.

TABLE I. A numerical comparison of the theory of DeBlois and Bean F_4 with Smythe's analysis F_5 , and DeBlois and Bean's fit of their experimental results F_6 .

$(d/D)^3$	F_4	F_5	F_6
0.001	1.001269	1.000797	...
0.005	1.006369	1.004008	1.0036
0.010	1.012797	1.008055	1.0073
0.050	1.066325	1.041728	1.036
0.100	1.14	1.087354	1.073
0.500	2.31	1.686712	1.36