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This Week's Citation Classic

Spiegler K S & Kedem O. Thermodynamics of hyperfiltration (reverse osmosis): criteria for efficient membranes. *Desalination* **1**:311-26, 1966.
[Sea Water Conversion Laboratory, University of California, Berkeley, CA and Weizmann Institute of Science, Rehovot, Israel]

An analytical expression for solute rejection by a membrane as a function of applied pressure is developed. The friction model leads to an equation for the *reflection coefficient*, which characterizes solute-rejection ability, in terms of an equilibrium (exclusion) parameter and a kinetic (sieve) parameter. [The *SCI*® indicates that this paper has been cited in over 120 publications since 1966.]

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"The groundwork for this paper was laid during a luncheon break of the First International Symposium on Water Desalination in Washington, DC, 1965, in which both of us participated. There was intense research and development on the reverse-osmosis process (which separates saline water into fresh water and brine by molecular filtration under pressures of several tens of atmospheres) because of the discovery of membranes permitting high production rates, at the University of California, Los Angeles, by S. Loeb (now at the Ben-Gurion University of the Negev, Beersheba, Israel), and S. Sourirajan (now at the National Research Council, Ottawa, Canada).[1]

"We decided to write this paper because we felt that the basic concepts for a useful theory were already in existence, but had not yet been applied to the design of hyperfiltration units. Jointly with the late A. Katchalsky, one of us (O.K.)[2] had developed a quantitative analysis of the permeability of both homogeneous and composite membranes which was based on the thermodynamics of irreversible processes. The membrane constants in this theory were three parameters, *viz.*, Staverman's reflection coefficient, σ; the solute permeability; and the hydraulic permeability. The physical meaning of these parameters is easier to visualize than that of the phenomenological coefficients in the Onsager equations. In parallel, independent research, the other author (K.S.S.)[3] had applied the friction-coefficient concept, known from Einstein's theory of Brownian motion, to transport processes in membranes, so as to express the physical meaning of the phenomenological coefficients.

"Our theory combines elements of our own work with important contributions of other investigators. The theory pinpoints criteria for salt-rejecting membranes. The equations for water and salt flux across a *differential* membrane layer are derived from first principles, and integrated across the membrane, assuming constancy of three membrane parameters. This procedure is justified by the friction model of membrane transport processes. It is shown that ($1-\sigma$) is the product of an equilibrium term and a kinetic term.

"We believe our paper is frequently cited because it provides a conceptual backbone for evaluation of data and unit design in hyperfiltration and ultrafiltration technology, which are still in rapid development. It facilitated the bridging of an interdisciplinary gap by bringing parameters that could be readily visualized (such as the reflection factor) from the biophysical literature to the design equations of molecular-filtration technologists, who accepted these ideas as indicated by a recent critical review.[4] Moreover, the equation relating solute rejection to applied pressure fits results of both hyperfiltration and ultrafiltration experiments well.

"Although we produced this paper mostly by correspondence—discussing it in person only at the first planning session, and at a subsequent Gordon Research Conference—we enjoyed the collaboration and feel that the common elements in our background and interests made it possible to overcome the handicap of the large geographical separation."

1. **Loeb S & Sourirajan S.** *Sea-water demineralization by means of a semipermeable membrane.* Los Angeles, CA: University of California, 1960. Department of Engineering Report 60-60.
2. **Kedem O & Katchalsky A.** Thermodynamic analysis of the permeability of membranes to non-electrolytes. *Biochim. Biophys. Acta* **27**:229-46, 1958.
3. **Spiegler K S.** Transport processes in ionic membranes. *Trans. Faraday Soc.* **54**:1408-28, 1958.
4. **Soltanieh M & Gill W N.** Review of reverse osmosis membranes and transport models. *Chem. Eng. Commun.* **12**:279-363, 1981.