

NEW JERSEY INSTITUTE OF TECHNOLOGY, NEWARK, NJ  
OTTO H. YORK DEPARTMENT OF CHEMICAL,  
BIOLOGICAL & PHARMACEUTICAL ENGINEERING

ChE 604:     MEMBRANE SEPARATION PROCESSES, Spring 2018 (January 18 onwards)

Lecture Time:                   Thursday, 6:00 pm to 9:05 pm (FMH 404)  
Instructor:                     Professor K. K. Sirkar, (Tel. No.) (973) 596-8447, Rm. 371T  
Office Hours:                 Tuesday, 4:30-5:30 pm; Wednesday, 5-6 pm

Course Outline:                This graduate course in Chemical, Biological and Pharmaceutical Engineering Department will deal with the science, technology, engineering analysis and design of the following membrane separation processes: reverse osmosis, nanofiltration, ultrafiltration, dialysis, electrodialysis, Donnan dialysis, liquid membrane permeation, microfiltration, gas permeation through polymeric membranes, pervaporation, membrane-based equilibrium separation processes, membrane reactors and hybrid membrane processes. Significant coverage of membrane structure/function for each application as well as membrane fabrication will be provided. Examples of relevance to Biomedical, Biopharmaceutical and Pharmaceutical industry will also be provided.

Prerequisites:                 Undergraduate courses ChE 360, 365, 370, 460 or their equivalents.

Textbooks:                    1. There will be a set of notes that you can buy; expected cost ~ \$30.  
  
                                      2. Many of the modeling developments will be available in the book: Kamallesh K. Sirkar, "Separation of Molecules, Macromolecules and Particles: Principles, Phenomena and Processes", Cambridge University Press, 2014. Identified as (Sirkar).  
  
                                      3. W.S.W. Ho and K.K. Sirkar (eds.), Membrane Handbook, 1992, Chapman and Hall, NY; Springer, Boston, 2001. This book will have basic information on most membrane processes to be studied.

Lecture Details:

One week:                         Introduction to membranes, membrane structures and membrane separation processes. General characteristics of membrane separation processes (Chapter 1 in Membrane Handbook (1992, 2001); Chapter

1 in Meares (1976); Chapters 1 and 2 in Rautenbach and Albrecht (1989); Chapters 1 and 2 in Mulder (1997)).

- One and half weeks: Principles of reverse osmosis. Transport in RO membranes. Concentration polarization. Geometrical configurations of RO modules. Design of tubular, hollow fiber and spiral wound modules. Applications. Nanofiltration. (Ho and Sirkar, Chapters 21-25 (1992, 2001); Merten, pages 1-30, 55-58, 86-90, 93-105, 130-137, 145, 160-184; Sourirajan (NRC) pages 199-200 and first two chapters; Spiegler and Kedem (1966); Spiegler's book, Chapter on Hyperfiltration; Sourirajan (NRC) Chapter 4, Chapter 27 (by J.W. McCutchan); Chapter 4 by Harris et al. in Meares's book Membrane Separation Processes; Soltanieh and Gill (1981)). Also Sirkar: Chap. 3.4.2, 5.4.1, 6.3.3.3, 7.2.1.2.
- One and half weeks: Principles of Ultrafiltration. Transport in UF membranes. Solute retention in microporous and diffusive UF. Gel polarization. MEUF. UF module configurations. Design of UF modules. UF processing schemes and applications (Ho and Sirkar (eds.), Chapters 26-30 (1992, 2001); Prog. in Sep. and Purification, Vol. 1, E.S. Perry (ed.); article by A. Michaels; Chapter 3 by W.F. Blatt in Meares's book, Membrane Separation Processes; pages 47-96 by Blatt et al. in Flinn, Membrane Science and Technology (1970)). Also Sirkar: Chap. 3.4.2.3, 5.4.2, 6.3.3.2, 6.4.2.1, 7.2.1.3.
- One week: Principles of dialytic separation. Batch and continuous dialyzer analysis. Effect of secondary chemical equilibria. Hemodialysis. Hemodialfiltration. Buffer exchange (Ho and Sirkar (eds.), Chapters 11-15 (1992, 2001); Meares, Chapter 2, pages 39-77; article by Sprigg and Li; Karger, Synder and Horvath, pages 486-491; Michaels (1966)). Also Sirkar: Chap. 3.4.2.4, 4.3.1, 5.4.3, 8.1.7.1, 8.2.4.1.
- Two and a half weeks: Principles of electro dialysis through ion exchange membranes. Types of ED. Electrodialytic transport, selectivity and polarization. Stack resistance. Design of ED stack. (Ho and Sirkar (eds.), Chapters 16-20 (1992, 2001); Spiegler (1966), Chapter 6; pages 199-289 by Schaffer and Mintz; Meares, Chapter 6; pages 259-293 by Solt; Li, Recent Developments in Sep. Sci., Vol. 2, pages 157-170, article by McRae and Leitz). Principles of Donnan dialysis. Transport and boundary layer considerations. Role of chemical reactions. Applications. References to be given in class. Also Sirkar: Chap. 3.4.2.5, 4.3.2, 5.2.6, 8.1.7.2.
- One week: Separation through immobilized (supported) liquid membrane,

emulsion liquid membrane and hollow fiber contained liquid membranes. Equipment for considerations for LMSP. Process design. Facilitation. Applications. (Chapters 36-40, 42 and 44 in Membrane Handbook (1992, 2001); Meares, Chapter 9, pages 327-350 by Chan and Li; Casamatta et al., Chem. Eng. Sci. (1978), Vol 33, 145-152; Casamatta et al., AIChE J., 24 (6), 945 (1978); Li, Recent Developments in Sep. Sci., Vol. 1, article on Liquid Membrane Water Treating by N.N. Li and A.L. Shrier). Also Sirkar: Chap. 5.4.4, 8.1.8.

One week: Microfiltration principles. Types. Cross-flow and dead-end microfiltrations. Theory. Applications. Design (Membrane Handbook, Chapters 31-35.). Also Sirkar: Chap. 6.3.1.4, 6.3.3.1, 7.2.1.4.

One and a half weeks: Gas permeation separation through polymeric membranes. Gaseous diffusion separation. Role of defects. Separation of vapors. Dual sorption. Permeator arrangements. Design of permeators. Cascades/separations schemes. Applications. (Ho and Sirkar (eds.), Membrane Handbook, Chapters 2-6 (1992, 2001); Pan and Habgood, I&EC Fund., 13, 323 (1974); Meares, Chapter 8, pages 295-326 by Stern; Li, Recent Developments in Sep. Sci., pages 107-156 by Rogers, Fel and Li; Pratt, Countercurrent Separation Processes, Chapter on Gaseous Diffusion). Also Sirkar: Chap. 3.4.2.2, 3.4.2.4, 4.3.3, 5.4.5, 6.3.3.5, 6.4.2.2, 7.2.1.1, 8.1.9, 8.2.4.2.

One week: Pervaporation. Mechanism. Azeotrope separation. Applications. (Membrane Handbook, Chapters 7-10 (1992, 2001); Greenlaw et al., J. Membrane Sci., 2, 141 (1977), etc.; Huang, Pervaporation Membrane Separation Processes (1991); Mulder, Basic Principles of Membrane Technology, pages 234-244 (1991)). Also Sirkar: 3.4.2.2, 6.3.3.4.

One week: Microporous/porous membrane based solvent extraction, gas absorption/stripping, and membrane distillation and membrane adsorption. (Chapters 41 and 46 in Membrane Handbook). Also Sirkar: 3.4.3, 8.1.2.1, 8.1.2.2.1, 8.1.4.

One week: Membrane reactors. Types. Analysis of equilibrium shift. Reactors. Reduction of product inhibition in bioreactors. Cell culture devices. (Chapter 43, Membrane Handbook (1992). plus other references to be given in class.). Hybrid membrane processes (references to be given in class).

Recommended Reference Books (kept in reserve section of library)

1. S.T. Hwang and K. Kammermeyer, Membranes in Separation, Techniques of Chemistry, Vol. VII, Wiley-Interscience (1975). Reprinted, 1984 by R.E. Krieger Publishing Company, Inc., Melbourne, FL 32902.
2. P. Meares (ed.), Membrane Separation Processes, Elsevier, Amsterdam (1976).
3. K.S. Spiegler (ed.), Principles of Desalination, Academic (1966). Pages 345 onwards, "Hyperfiltration"; 2nd edition (1979) Part A Chapter 6, pages 257-357 for ED.
4. S. Sourirajan (ed.), Reverse Osmosis and Synthetic Membranes, NRC, Ottawa, Canada (1977).
5. R. Rautenbach and R. Albrecht, Membrane Processes, Wiley (1989).
6. M. Mulder, Basic Principles of Membrane Technology, 2<sup>nd</sup> Ed., Kluwer/Springer (1997).
7. R.Y.M. Huang (Ed.), Pervaporation Membrane Separation Processes, Elsevier Science Publishers, New York (1991).

Recommended References for Further Reading (kept in the reserve section of library)

1. Progress in Separation and Purification, Vols. 1, 2, 3 and 4, E.S. Perry and others (eds.), 1968 onwards, Interscience.
2. S. Sourirajan, Reverse Osmosis, Logos Press, London (1970).
3. U. Merten, Desalination by Reverse Osmosis, MIT Press (1966).
4. Separation and Purification Methods, Vols. 1 and 2, E.S. Perry and C.J. Van Oss (eds.), Marcel Dekker (1972).
5. C.J. King, Separation Processes, 2nd Edition, McGraw-Hill (1980).
6. H.R.C. Pratt, Countercurrent Separation Processes, Elsevier (1967).
7. Recent Developments in Separation Science, Vols. 1, 2, 3A, 3B, N. Li (ed.), CRC Press (1972) (1975) (1977).
8. J.E. Flinn (ed.), Membrane Science and Tech., Plenum Press, New York (1970).

9. R.W. Rousseau (ed.), Handbook of Separation Process Technology, Wiley, New York (1987).

References 10 to 21 are kept in a bound volume in the reserve section of the library.

10. J.E. Flinn and R.H. Cherry, Jr., CEP Symp. Series, Vol. 65, No. 91, p. 90-97 (1968).
11. K.S. Spiegler and O. Kedem, Desalination, 1, 311 (1966).
12. M. Soltanieh and W.N. Gill, Chem. Engg. Commun., 12, (1981).
13. J.W. McCutchan and V. Goel, Desalination, 14, 57 (1974).
14. M.R. Doshi, W.N. Gill and V.N. Kabadi, AIChE J., 23 (5), 765 (1977)
15. A.S. Michaels, Trans. Am. Soc. Art. Int. Org., XII, 387 (1966).
16. W.J. Ward, AIChE J. 16 (3), 405 (1970).
17. A.M. Hochhauser and E.L. Cussler, AIChE Symp. Ser., Vol. 71, No. 152 (1975).
18. G. Casamatta, D. Bouchez and H. Angelino, Chem. Eng. Sci., 33, 145 (1978).
19. G. Casamatta, C. Chavarie and H. Angelino, AIChE J., 24 (6), 945 (1978).
20. C.Y. Pan and H.W. Habgood, I&EC Fundamentals, 13, 323 (1974).
21. F.W. Greenlaw, W.D. Prince, R.A. Sheldon and E.V. Thompson, J. Membrane Sci., 2, 141 (1977).

### **Examinations and Grading**

There will be two written open-book exams, each lasting about 90 min + to 120 min and a final written open-book exam for 180 minutes.

Possible Exam Dates:	Mar 1 or 9	(Exam 1)
	Apr 5 or 12	(Exam 2)
	May 4-10	Final Exam

A term paper/project may be required. The distribution for grading without the term paper is likely to be as follows: Exam 1 (30%), Exam 2 (30%), Final Exam (40%). If term papers are used, the grading distribution will be changed.