

# A Project-Based Approach to Teaching Membrane Technology

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## Abstract

This paper describes a NSF-funded Instrumentation and Laboratory Improvement (ILI) project on membrane process experiments funded through DUE-9850535. We have addressed teaching students about the emerging field of membrane processes through team projects. The development plan involves the innovative use of membrane technology, integrating it both vertically and horizontally throughout the engineering curriculum and exposing students to it through the use of team-oriented experimental projects in multidisciplinary engineering clinics. We have initially introduced membrane separation principles in various courses through lectures and small-scale mini-labs and demos. This lays the foundation for more comprehensive study in the engineering clinics. The integration of membrane process experiments for multidisciplinary team projects occurs in the Junior and Senior level Engineering Clinic courses. Some of the realistic and challenging experimental projects started so far include: reverse osmosis system design and function in water purification, gas permeation processes, membrane bioreactors and hollow fiber membrane gas transfer for environmental control, ceramic membrane reactors used in petrochemical processing, and electrodialysis and ultrafiltration processes for separation in the specialty chemicals industry. In these process research and development projects students, learn how to function in a team to solve complex problems, interpret and analyze data, utilize modern technologies, and understand environmental issues. Some projects have included industrial mentors. To broaden the impact of the project, the Rowan team has also used membrane technology to help attract high school students to engineering through the development of innovative demonstration modules.

## Introduction

### Overview

The effective teaching of membrane processes is an important issue to be addressed by the academic community. Leading-edge industries are using membrane technology for new gains. Educational initiatives are crucial to the continued technical growth and wide-scale commercialization of membrane processes. This project seeks an innovative use of membrane technology, building on the pioneering work of the lead author, who developed membrane experiments in a conventional chemical engineering laboratory setting [Sla94, Sla93, Sla92, Sla89, Sla87]. At Rowan University, the co-PI's

will integrate membrane technology throughout the engineering curriculum and involve student teams in a unique multidisciplinary laboratory project experience – the clinics.

## Background

Synthetic membranes have a wide range of applications in industry. Membranes can separate components of a chemical solution or particles from a fluid; immobilize catalysts, biological or otherwise; control species transfer rate from one fluid to the other; and allow controlled contacting of two immiscible phases. Membranes can do one or more of these and other functions simultaneously or consecutively in one membrane or in uniquely designed modules. Membrane processes separate, concentrate or purify a process stream thus provide industry with alternate routes to high yield, productivity, and the ability to separate complex mixtures.

The potential capacity of membranes to solve a variety of technological problems is thus astounding. No wonder synthetic membranes provide the key to the commercial success of desalination of seawater by reverse osmosis, dialysis by an artificial kidney, large-scale gas separations in chemical process plants, purification of biopharmaceuticals, skin patches for controlled release of drugs, etc. Membrane technology has the potential to facilitate the transformation of chemical, petrochemical and pharmaceutical industries towards environmentally benign, "green," manufacturing in the 21<sup>st</sup> century and to create new levels of efficiency in manufacturing [Ame96].

## Educational Needs

Several studies have documented the need for expanded education in membrane technology [Sla94]. There exists proven membrane technology that could replace existing processes and make many operations more productive and efficient. One of the reasons many firms are not purchasing new technology is the "fear of the unknown." The majority of engineers involved in process development, design and production specifications have little or no background in membrane technology.

Chemical engineering education is traditionally a process or systems oriented curriculum, producing graduates that can apply their process expertise in many industries. Some versatility was lost over the last several decades due to the overwhelming emphasis on unit operations and design problems pertaining to the petroleum industry. Civil engineering programs have traditionally taught water resources, conventional water purification and wastewater treatment processes. Separation process needs exist both in the traditional process industries and in emerging areas, e.g., biochemical engineering, specialty chemical manufacture, hazardous waste management, food and beverage processing, microelectronics production, and biomedical engineering [Gar94,Heg92]. Growth in these technologies will depend on engineers that are well educated in the field. Students from other disciplines can be acquainted to membrane technology through applying techniques such as data acquisition, control, computer-aided design, etc. [Ame96].

Students need more instruction in membrane technology, and in many other advanced separation processes [Wan94,Kin87]. Many schools have graduate courses in advanced mass transfer and some have courses in membrane technology. The introduction of membrane technology into the undergraduate chemical engineering curriculum is rare. A 1995 study [Gri95] revealed that 2.6% of lecture time in an undergraduate mass transfer course is on the subject of membrane processes.

ABET's Criteria 2000 includes many of the outcomes that are included in this project: ability to function in multidisciplinary teams, ability to design and conduct experiments, understand safety and environmental issues, analyze and interpret data, and the use of modern engineering tools [EAC95].

## Rowan University's Engineering Clinic

Founded in 1923, as Glassboro State Teachers College, Rowan University has retained its focus on undergraduate education. Rowan has evolved into a comprehensive regional state university with six colleges: Business Administration, Communications, Education, Engineering, Fine and Performing Arts, and Liberal Arts and Sciences. The College of Engineering was initiated using a major gift in 1992 from the Rowan Foundation [Row95]. The engineering program is taking a leadership role by using innovative methods of teaching and learning, as recommended by ASEE [EDC94], to better prepare students for entry into a rapidly changing and highly competitive marketplace.

To best meet these objectives, the four engineering programs of Chemical (ChE), Civil and Environmental (CEE), Electrical and Computer (ECE), and Mechanical Engineering (ME) have a common engineering "clinic" throughout their program of study. Key clinic features include: (i) multi-disciplinary education created through collaborative laboratory and coursework; (ii) stressing teamwork as the necessary framework for solving complex problems; (iii) incorporation of state-of-the-art technologies (iv) and creation of continuous opportunities for technical communication. At the Freshman level students conduct engineering measurements and reverse engineer a process. The Sophomore engineering clinic is communications intensive and also introduces students to the design process of each discipline and related topics of product/process function. Junior and Senior clinics provide the opportunity for the most ambitious part of our project-intensive curriculum: team projects employing modern technologies that tie together many engineering and scientific principles. Institutions that have similarly named engineering "clinics" are Harvey Mudd College and California State Polytechnic Univ. Pomona [Ann95]. Our flexible clinic model allows departmental and interdepartmental initiatives that to satisfy programmatic and faculty/student/university development needs.

We plan an ambitious project taking a leading-edge technology such as membrane processes and using it as the focal point of curricular innovation in the College of Engineering. We will involve teams of engineering students in process research, development, design and analysis of experimental systems. Students will also understand the environmental implications of process component design and meeting stringent regulatory requirements. Students will gain an understanding of the fundamental aspects of membrane technology and its application to new and emerging fields.

## Development Plan

### Overview

The major focus of the innovative aspects of this project is Junior and Senior engineering students from various disciplines in particular Chemical Engineering, Civil and Environmental Engineering, and Chemistry. In the Junior and Senior level Engineering Clinics multidisciplinary teams (3-4 students/team) will work on open-ended experimental projects in various areas, many linked to industry or a faculty grant from a state or federal agency. These projects emanate from a particular discipline and are lead by that department's faculty and typically involve an industrial mentor. These teams are matched by the faculty Project Manager (PM) to best achieve the results in the individual projects. They may combine various fields of expertise within a classic discipline (environmental, water resources and structural) in CEE, (biochemical and polymer) in ChE or science with engineering (Chem and ChE) as recommended by the recent report of the NRC [Heg92]. In some cases, student "consultants" from other disciplines will assist on a limited basis, representing the realistic role found in industry. Several of the membrane-oriented clinic projects are summarized below. Students are

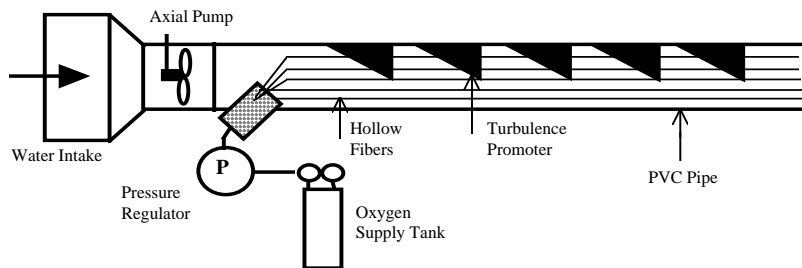
required to produce a written report or paper/ journal publication and present and oral report at the end of the semester.

## Gas Transfer through Membranes

**PM: Dr. Kauser Jahan (CEE)**

A novel, sealed-end bubbleless hollow fiber membrane gas transfer device was developed [Ahm92] and tested [Sem91] for the oxygenation of water. The membranes which are approximately 25  $\mu\text{m}$  thick and 100-400  $\mu\text{m}$  in diameter, are manufactured as fibers that have pores measuring 0.02-0.05  $\mu\text{m}$  in diameter over more than 30% of their surface area. The membrane pores do not wet when in contact with water because of the hydrophobicity of the polypropylene and as a result the pores remain gas filled and dry. This allows for very rapid transfer of gases across the membrane to the water.

A schematic diagram of the membrane gas transfer device is illustrated in the following Figure. The principal components of the device are: a pump, an external shell (PVC pipe), a gas supply cylinder with regulator and a bundle of sealed end hollow fibers. Approximately 500-2000 hollow fibers are potted with epoxy at the open end and connected to the gas supply. The length of the aerator can be varied from 2 to 8 ft. During operation, the pump forces water through the PVC pipe and over the fibers. Pure oxygen under pressure is maintained inside the fibers. The fibers are individually heat sealed at the downstream end such that the gas delivered to the fibers can not escape across the fibers for bubble formation. The individual fibers are free to move with the local flow patterns.



The flow past the fibers tend to induce a fluttering motion in the membrane fibers that encourages gas transfer between the fibers and the surrounding water. The fibers only occupy about 2% of the net cross sectional area of the pipe in which they are housed. When water is flowing through the module, however, the fibers are uniformly distributed throughout the section. The process provides 100% gas transfer efficiency.

Pressure control is critical to operational performance of the gas transfer system. If the pressure inside the fiber is allowed to exceed the limits then the membrane may rupture and gas will be lost as waste. On the other hand, if the pressure of the gas is low, the driving force for gas transfer will be impaired because the solubility of gases in water is directly proportional to the partial pressure.

Oxygen transfer characteristics of the constructed hollow fiber membrane modules were evaluated. The data were verified with dimensionless correlations developed for design of membrane modules for oxygen transfer [Ahm92]. The experimental details have been submitted for publication [Jah00]. Results of this study were presented by students at a poster competition sponsored by the New Jersey American Water Works Association for their Annual Conference held in May 1999 at Atlantic City. The poster titled "Membrane Applications in Water and Wastewater Treatment" was awarded the

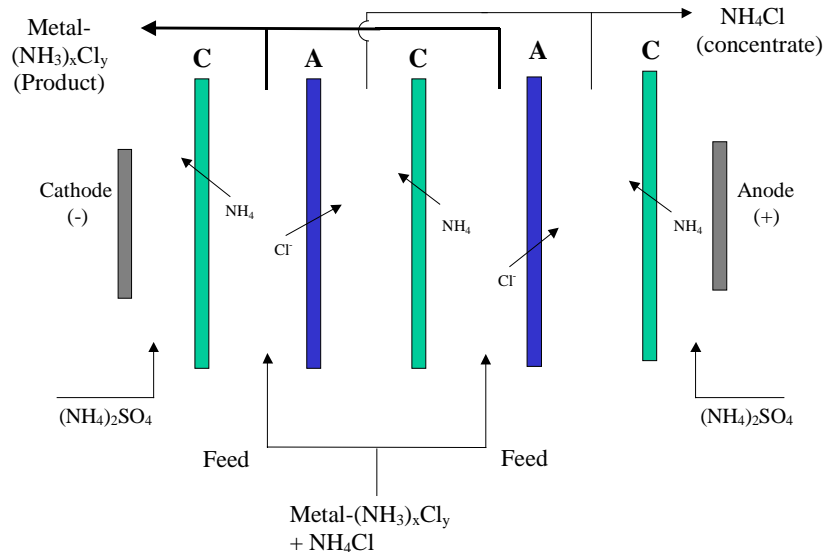
first prize. Current experiments are focused on gas transfer applications in biodegradation of contaminants.

### Electrodialysis for Precious Metals Recovery.

**PM: Stephanie Farrell (ChE), co-PM's Robert P. Hesketh (ChE), C. Stewart Slater (ChE), Kandalam Ramanujachary (Chem)**

A local pharmaceutical and specialty chemical company produces a variety of precious metal compound solutions which, in intermediate process steps, are contaminated with acids and salts. The traditional separation and purification steps used in the production of these metal compound solutions include multiple precipitation and dilution steps which are both time consuming and labor intensive. These separation and purification steps involve a loss of approximately 5-10% of the product. Development of an alternative separation and purification technique would be desirable, and is the aim of this project. If successful, this novel separation will reduce operating costs significantly, increase product yield, and increase product output by an order of magnitude.

The proposed novel separation technique is electrodialysis, an electrically driven membrane separation process that is useful for removing electrolytes from solutions. This project investigates the applicability of electrodialysis to the process for production of metal compound solutions. The objectives of the project are (1) to design and build an electrodialysis unit for the separation and purification of the desired process stream, (2) to investigate the performance of electrodialysis in the removal of the salt contaminant from the product on a laboratory scale, (3) to perform an economic



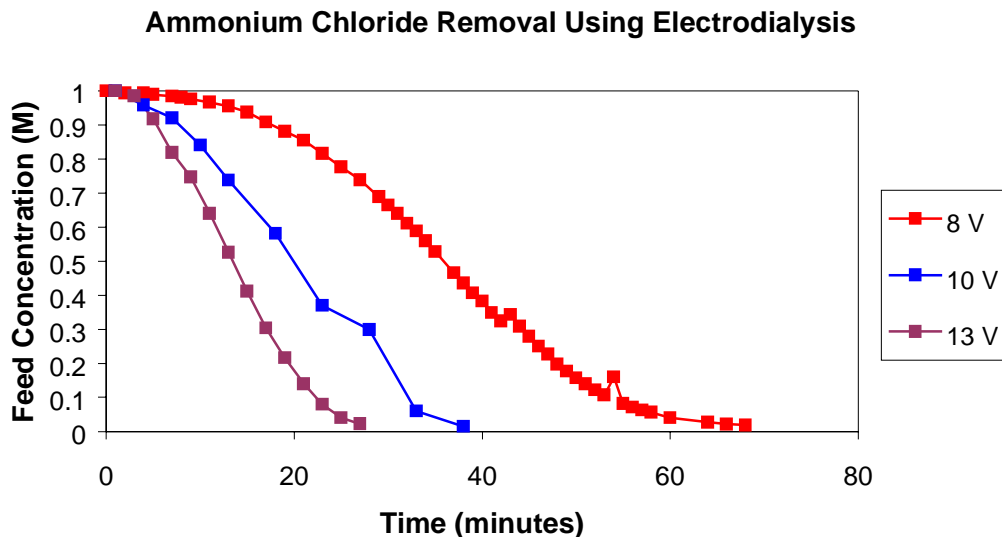
The electrodialysis process design

analysis of the proposed process in comparison with the traditional technique, and (4) to scale up the process to pilot scale.

The laboratory scale electrodialysis unit was purchased from Electrosynthesis Corp. and features a four-compartment cell stack, electrochemical process control system, and data acquisition capability. The cell stack has an individual membrane area of 0.01 m<sup>2</sup>, and houses up to ten membrane pairs. The membranes are Tokayama Soda AMX anion and CMX cation exchange membranes. The feed and concentrate stream ion concentrations are monitored throughout the run by on-line conductivity probes.

Preliminary experiments have been conducted to establish the separation performance of the electro dialysis system for the removal of ammonium and chloride ions contained in a feed stream. The membrane stack was configured with five membrane pairs, and runs were conducted in constant voltage mode. The effects of applied voltage and initial concentrate concentration as process parameters were investigated. The figure below shows ammonium chloride removal from the feed stream as a function of applied voltage.

Subsequent experiments were conducted to investigate the impact of size-selective and charge-selective ion exchange membranes on the retention of desired product. Tokuyama Soda



CM2 membranes were chosen as the size-selective cation exchange membranes, and were found to offer no significant improvement in performance in the separation. Tokuyama Soda CMS membranes were chosen as monocation exchange membranes, and resulted in a five-fold increase in the retention of the desired product.

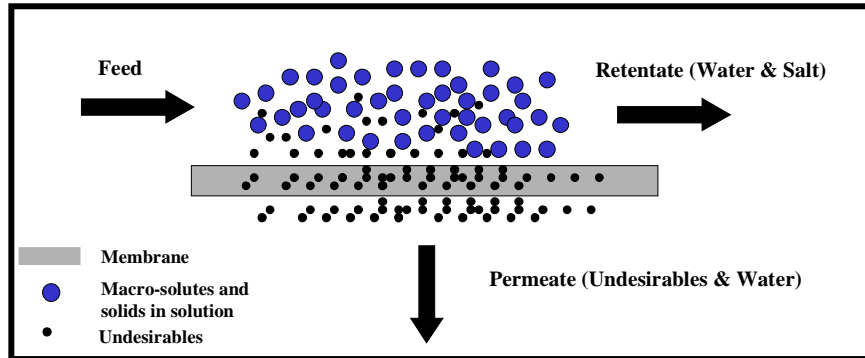
#### Ultrafiltration for Specialty Chemical Production

**PM: Robert P. Hesketh (ChE), co-PM's Stephanie Farrell (ChE), C. Stewart Slater (ChE), Kandalam Ramanujachary (Chem)**

Another important membrane technology of gaining industrial importance is ultrafiltration. This process is currently employed in the paper, sugar, textile, and paint industries. Ultrafiltration is also used in biomedical field in the recovery of enzymes and in liver and kidney development as well as hemodialysis and drug detoxification.

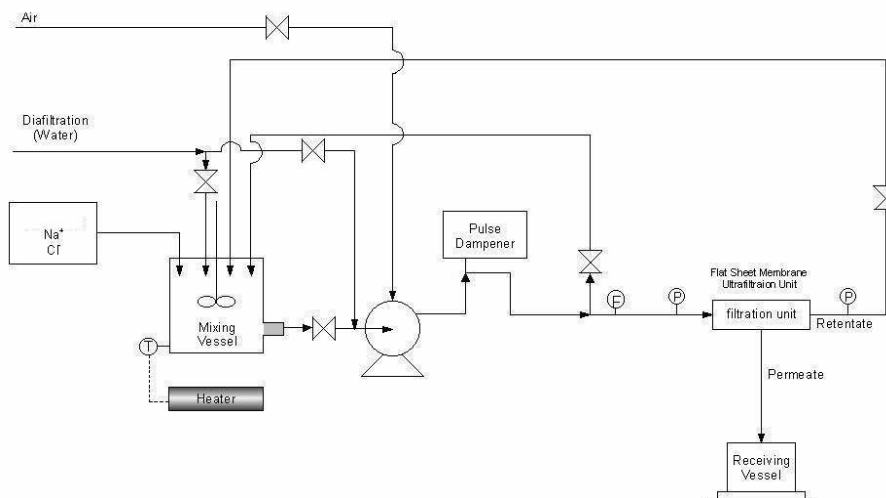
To give students experience with ultrafiltration an experiment is being developed to analyze the effect of flowrate and pressure on the permeate flowrate through the membrane. An industrial process fluid containing up to 20 wt% particulates and NaCl will be used. The goal of this separation is to remove the salt from the particulates.

In this process, the process fluid is fed continuously into the membrane unit. The ultrafiltration membrane completely retains the high molecular weight solutes and the low molecular weight solutes which are  $\text{Na}^+$  and  $\text{Cl}^-$  pass through the membrane with water. The volume in the feed tank will be held constant by adding water at a rate equal to the permeate rate. Two flow geometries are being



developed for this experiment: flat plate and cylindrical. For the flat plate geometry an Osmonics cell is employed in which flat membranes can be placed in the housing and sealed to a given pressure controlled by a hand hydraulic pump. In the cylindrical unit a tubular membrane is inserted and sealed at both ends. The polymeric and inorganic membranes that will be tested for this experiment include polysulfone (PS), polyethersulfone (PES), sulfonated polysulfone (SPS), polyamide (PA), cellulose acetate (CA), Zirconium Oxide (inorganic), and alumina (inorganic).

### Ultrafiltration Process Flow Diagram



## Ceramic Membrane Reactor System

**PM- Robert P. Hesketh (ChE), co-PM's Kevin D. Dahm (ChE) and C Stewart Slater (ChE)**

A catalytic membrane reactor has been designed and constructed in this project. Equilibrium limitations to reaction conversions and techniques used to shift equilibrium are taught in chemistry and chemical reaction engineering courses, but students do not typically use these techniques in experiments. This reactor will demonstrate the advantages of using advanced membrane technology in conjunction with reaction kinetics. In this experiment ethylene is produced by dehydrogenation of ethane in a ceramic membrane integrated reactor, modeled after that of [Cha90, 92]. The basic principle behind this membrane reactor is to remove the light reaction product hydrogen through the membrane and thus drive the reaction beyond the equilibrium constraint set by the reaction conditions.

This reactor consists of a stainless steel shell with a Platinum coated ceramic membrane tube. The ceramic membrane is obtained from US Filter with a pore size of 5nm. The tube was coated using a chloroplatinic acid process. The reactant and product concentrations will be measured using an HP 6890 Gas chromatograph and HP 5973 Mass spectrometer.

## Summary

Through the support of NSF and several industries, multidisciplinary student projects have been initiated by Chemical and Civil/Environmental Engineering and Chemistry faculty that challenge student teams to solve realistic industrial problems. These experimental projects are quite versatile and we can modify them slightly from year to year based on student assessment and to provide the curricular development effect. These Clinic projects help our forward looking EC2000 curriculum by providing a focal point for ability to function in multidisciplinary teams, ability to design and conduct experiments, understand safety and environmental issues, analyze and interpret data, and the use of modern engineering tools. In a primarily undergraduate institution such as Rowan University, these projects provide an opportunity for faculty / student scholarship.

## Acknowledgements

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## Biographical Information

**C. Stewart Slater** is Professor and Chair of Chemical Engineering at Rowan University. He received his B.S., M.S. and Ph.D. from Rutgers University. Prior to joining Rowan he was Professor of Chemical Engineering at Manhattan College where he was active in chemical engineering curriculum development and established a laboratory for advanced separation processes with the support of the National Science Foundation and industry. Dr. Slater's research and teaching interests are in separation and purification technology, laboratory development, and investigating novel processes for interdisciplinary fields such as biotechnology and environmental engineering. He has authored over 70 papers and several book chapters. Dr. Slater has been active in ASEE, having served as Program Chair and Director of the Chemical Engineering Division and has held every office in the DELOS Division. Dr. Slater has received numerous national awards including the 1999 Chester Carlson Award, 1999 and 1998 Joseph J. Martin Award, 1996 George Westinghouse Award, 1992 John Fluke Award, 1992 DELOS Best Paper Award and 1989 Dow Outstanding Young Faculty Award.

**Kauser Jahan** is an Associate Professor of Civil and Environmental Engineering at Rowan University. She completed her Ph.D. studies in the Department of Civil and Environmental Engineering at the University of Minnesota, Minneapolis in 1993. After completion of her graduate studies, she worked as an environmental engineer for the Nevada Division of Environmental Protection (NDEP). Her research interests include bioremediation of contaminated groundwater and soils; the fate and transport of pollutants in the environment; and applied microbiology in environmental engineering. She is also actively involved in encouraging women to the engineering profession. She was awarded the Lindback Foundation Junior Faculty Award in 1996 for conducting research on biodegradation of surfactants. She has also been nominated for the Lindback Distinguished Teaching Award this year. Dr. Jahan is a registered engineer in Nevada.

**Robert Hesketh** is Associate Professor of Chemical Engineering at Rowan University. He received his B.S. in 1982 from the University of Illinois and his Ph.D. from the University of Delaware in 1987. After his Ph.D. he conducted research at the University of Cambridge, England. Prior to joining the faculty at Rowan in 1996 he was a faculty member of the University of Tulsa. Robert's research is in the chemistry of gaseous pollutant formation and destruction related to combustion processes. Nitrogen compounds are of particular environmental concern because they are the principal source of NOX in exhaust gases from many combustion devices. This research is focused on first deriving reaction pathways for combustion of nitrogen contained in fuel and second to use these pathways to reduce NOX production. Robert employs cooperative learning techniques in his classes. His teaching experience ranges from graduate level courses to 9th grade students in an Engineering Summer Camp funded by the NSF. Robert's dedication to teaching has been rewarded by receiving several educational awards including the 1999 Ray

W. Fahien Award, 1998 Dow Outstanding New Faculty Award, the 1999 and 1998 Joseph J. Martin Award, and four teaching awards.

**Stephanie Farrell** is Associate Professor of Chemical Engineering at Rowan University. She received her B.S. in 1986 from the University of Pennsylvania, her MS in 1992 from Stevens Institute of Technology, and her Ph.D. in 1996 from New Jersey Institute of Technology. After receiving her Bachelor's degree, she worked on the design of a needleless injector to be used by the World Health Organization in a worldwide measles eradication project. She also spent six months working at British Gas in London before returning to graduate school. Prior to joining Rowan in September, 1998, she was a faculty member in Chemical Engineering at Louisiana Tech University. Stephanie's has research expertise in the field of drug delivery and controlled release, and she is currently focusing efforts on developing laboratory experiments related to membrane separations, biochemical engineering, and biomedical systems, for all level students at Rowan. Stephanie won the 2000 Dow Outstanding Faculty Award, 1998 ASEE Outstanding Campus Representative Award, and currently serves as Newsletter editor of the Mid-Atlantic Section of ASEE and the Rowan Campus Representative.

**Kevin D. Dahm** is Assistant Professor of Chemical Engineering at Rowan University. He received his B.S. in Chemical Engineering in 1992 from Worcester Polytechnic Institute, and his Ph.D. in 1998 from Massachusetts Institute of Technology, where he developed graph-theoretic methods for mechanistic modeling of hydrocarbon pyrolysis. Prior to joining the faculty of Rowan University, he served as an Adjunct Professor of Chemical Engineering at North Carolina A&T State University. He also served for one year as a Postdoctoral Researcher at the University of California at Berkeley, where he assisted in the development of Model.LA, a process simulation software package for use in the undergraduate chemical engineering curriculum.