MEMBRANE PROJECTS WITH AN INDUSTRIAL FOCUS
In The Curriculum

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Educational initiatives are crucial to the continued technical growth and wide-scale commercialization of membrane processes. This paper discusses innovative use of membrane technology in a project-oriented curriculum, building on the prior work of Slater, *et al.*, who developed membrane experiments in a conventional chemical engineering laboratory setting.[1-7] At Rowan University, the authors have integrated membrane technology throughout the engineering curriculum and involved student teams in a unique multidisciplinary laboratory project experience—the clinics.[8]

Chemical engineering education is traditionally a process- or systems-oriented curriculum, producing graduates who can apply their process expertise in many industries. Some versatility has been lost over the last several decades due to the overwhelming emphasis on unit operations and design problems pertaining to the petroleum industry. Separation-process needs exist both in the traditional process industries and in emerging areas such as biochemical engineering, specialty chemical manufacture, hazardous waste management, food and beverage processing, microelectronics production, and biomedical engineering.[9,10] Growth in these technologies will depend on engineers who are well-educated in the field and have a working knowledge of membrane applications in these areas. Education should have a multidisciplinary perspective where students from other fields can apply their expertise to solving membrane-related process problems.[11]

The need for more instruction in membrane technology and in many other advanced separation processes has been previously addressed.[12,13] Many schools have graduate courses in advanced mass transfer and some have courses in membrane technology, but introducing it to the undergraduate chemical engineering curriculum is rare. A 1995 study[14] revealed that only 2.6% of lecture time in an undergraduate mass transfer course is on the subject of membrane processes. ABET's Criteria 2000 specifies many of the outcomes that are included in this curriculum development: an ability to function in multidisciplinary teams, designing and conducting experiments, understanding safety and environmental issues, analyzing and interpreting data, and using modern engineering tools.[15]

ROWAN UNIVERSITY'S ENGINEERING CLINIC

Rowan University is 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.[16] The engineering program is taking a leadership role by using innovative methods of teaching and learning, as recommended by ASEE,[17] to prepare students for entry into a

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rapidly changing and highly competitive marketplace.

To meet these objectives, the four engineering programs of chemical, civil/environmental, electrical/computer, and mechanical engineering have a common engineering "clinic" throughout their programs of study. At the freshman level, sudents 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 to related topics of product/process function. The junior and senior clinics provide an 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 University, Pomona.[18] Our flexible clinic model allows departmental and interdepartmental initiatives that satisfy programmatic and faculty/student/university developmental needs. These clinics also provide an opportunity for industrial involvement in the sponsoring and mentoring of projects.[8]

Figure 1. *Student conducting membrane separation study of vegetable product stream.*

This ambitious program takes a leading-edge technology such as membrane processes and uses it as the focal point of curricular innovation in our College of Engineering. We have involved teams of engineering students in process research, development, design, and analysis of experimental systems. Students have gained an understanding of the fundamental aspects of membrane technology, process design, and application to new and emerging fields. Our curriculum is considered to be project-intensive and industrially oriented, with a strong hands-on component. One of the most important attributes obtained through this type of activity is a focus on "soft skills." Students working on designing, fabricating, and starting up an experimental system have a much richer environment of interacting in a team setting. Team dynamics improve and management skills are incorporated into the project. Students' informal and formal communication skills are also enhanced. Our Chemical Engineering Industrial Advisory Board has endorsed this concept from the technical side and in preparing students in other areas such as teamwork and communication skills.

PROJECT IMPLEMENTATION

The major focus of the innovative aspects of this project is the junior and senior engineering clinics where multidisciplinary teams (3-4 students/team) work on open-ended 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, are led by that department's faculty, and typically involve an industrial mentor. The teams are matched by the faculty Project Manager (PM) to achieve the best results in the individual projects. Teams may combine various fields of expertise within a classic discipline (environmental, water resources, and structural in CEE; biochemical and polymer in ChE; science with engineering in Chem and ChE) as recommended by the recent report of the NRC.[8] In some cases, student "consultants" from other disciplines assist on a limited basis, representing the realistic role found in industry. Students are required to produce a written report or paper/journal publication and present an oral report at the end of the semeter.

Several selected membrane-oriented clinic projects are summarized below. A full listing of Rowan clinic projects can be obtained at <http://sun00.rowan.edu/programs/chemical/clinic.html>.

Advanced Vegetable Processing Technology

In a project sponsored by Campbell Soup Company, a team of students researched cutting-edge technologies, such as novel membrane processes, for processing soups and juices. The multidisciplinary team consisted of two undergraduate chemical engineering students, one civil engineering student, and one biology student. In addition, one master's student served as PM. Campbell Soup has its corporate R&D facilities in nearby Camden, New Jersey, facilitating frequent progress meetings with the project sponsors.

Through this project, students investigated advanced membrane separation techniques as well as enzymatic, thermal, and physical/mechanical treatment techniques applied to vegetable processing. Their responsibility included HAZOP analysis, project planning, budget formulation and management, literature and patent reviews, experimental design, and development of a proposal for a second phase of the clinic project (see Figure 1). In addition to the engineering expertise the students acquired through this project, they gained familiarity with Food and Drug Administration regulations, good manufacturing practices, and labeling requirements.

Engineers from Campbell's demonstrated a high level of commitment to the project by attending monthly progress meetings where the students gave oral presentations on their progress. This was followed by brainstorming and discussion sessions where the industrial representatives and faculty refocused and fine-tuned the project. This industrial interaction helped maintain a high level of motivation among the students and maintained the focus and a fast pace of productivity. In addition to the progress meetings, the student team also conducted a "lunch-and-learn" seminar at Campbell's to share their research with engineers, scientists, and marketing representatives from the company. The ethusiastic response of the audience at Campbell's reaffirmed the industrial relevance and impact of the team's clinic research project.

Campbell Soup Company is a strong supporter of our program, not only by supporting the clinic project mentioned above, but also by employing both full-time and internship students from our program. In the summer following the vegetable processing project, two undergraduate students accepted summer internships at Campbell's. The students had the rewarding experience of successfully implementing two of the technologies developed at Rowan into Campbell's processing facilities in California and New Jersey.

<u>Metals Purification Processes</u>

Various metals purification projects have been sponsored by Johnson Matthey, Inc. A precious metals "refinery" is operated at West Deptford, New Jersey, which is less than ten minutes from our campus. This close proximity facilitates numerous interactions and projects that we have with Johnson Matthey. The company has sponsored three years of engineering clinic projects with the objective of investigating novel techniques that have the potential to replace current "traditional" refinery process units.

At the refinery, precious metals such as Pt, Pd, and Rh are purified from feed streams containing many unwanted metal species and other impurities. The feed streams are made up of spent catalysts from which precious metals are recovered and recycled to feed stream from mines. In the refinery, there are many dissolution, selective-precipitation, and filtration steps. Using innovative membrane processes, the plant capacity, product purity, and processing costs have the potential to be improved. In essence, students have an opportunity in the engineering clinic to conduct engineering projects that are equivalent in scope to those done by engineers in the plant. Our most successful project resulted in Johnson Matthey adding several new processing units to their refinery.

One of the Johnson Matthey projects involving membranes was electrodialysis process development for separation of a precious metal chloride salt solution that was contaminated with unwanted acids and salts. The traditional separation and purification steps used in the production of these metal compound solutions include multiple precipitation and dilution steps that are time-consuming and labor intensive and result in a significant loss of product. Development of an alternative separation and purification technique was the aim of this project.

The specific objectives of the projects were

- *To design and build an electrodialysis unit for the separation and purification of the desired process stream*
- *To investigate the performance of electrodialysis in the removal of the salt contaminant from the product on a laboratory scale*

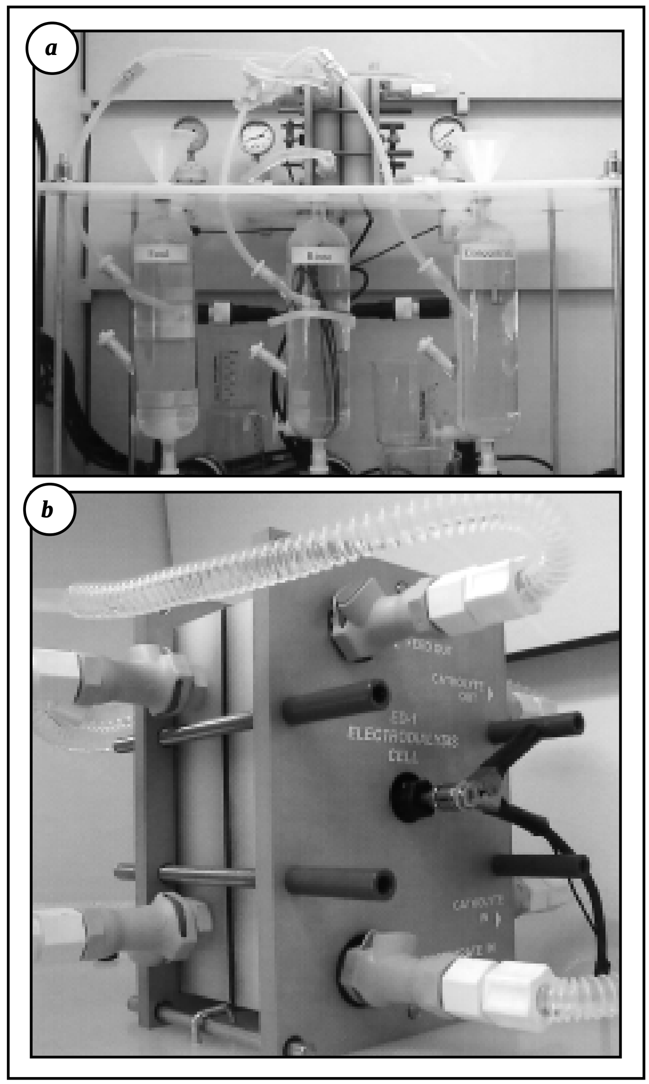

Figure 2. (a) *Electrodialysis process system used in precious metals separation clinic project.* ***(b)*** *Electrodialysis cell used in the process system.*

- *To perform an economic analysis of the proposed process in comparison with the traditional technique*
- *To scale up the process to pilot scale*

The potential outcomes include reduction of operating costs, increased product yield, and increased product output by an order of magnitude.

The first phase of the project involved the design and assembly of a laboratory-scale electrodialysis unit and preliminary benchmark testing (see Figures 2a and 2b). The second phase of the project involved investigation of process parameters on the yield and selectivity of the product. Typical student results for the removal of an ammonium chloride contaminant are shown in Figure 3. Subsequent experiments were conducted to investigate the impact of size-selective and charge-selective ion exchange membranes on the retention of desired product. Based on the experimental results, the process was scaled up to pilot scale and an economic investigation was conducted to examine the trade-off between capital costs and operating costs as well as the overall economic feasibility of the process. The process demonstrates the potential for reduced operating costs and increased product yield and selectivity and is currently being evaluated further by Johnson Matthey.

Johnson Matthey has provided significant support to our chemical engineering department and was a "charter member" of the PRIDE program (Partners with Rowan in Developing Engineers). They have employed Rowan chemical engineering students both as interns and as permanent employees.

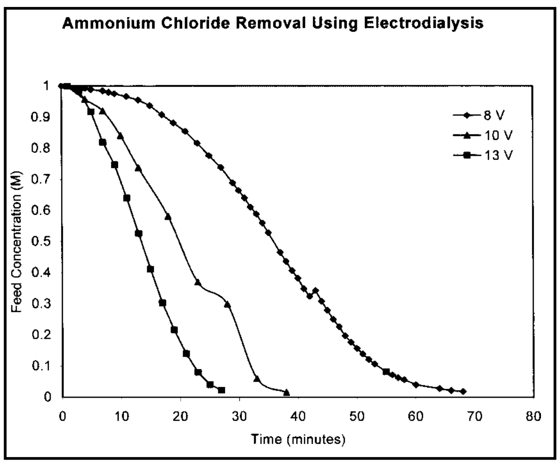

Figure 3. *Typical student data showing the effect of voltage on the removal of an ammonium chloride contaminant from a precious metal feed solution.*

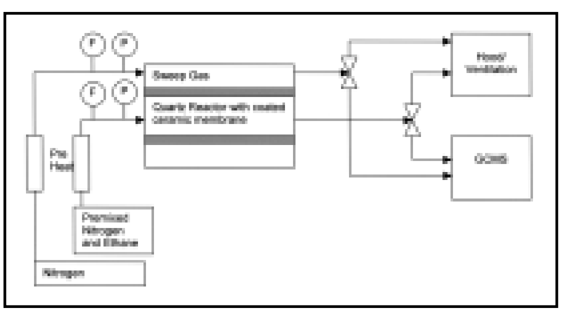

Figure 4. *Process flow diagram of the ceramic membrane reactor project.*

Ceramic Membrane Reactor System

In this project, a ceramic membrane reactor has been designed and constructed by a team of three undergradute students. The reactor, used for the production of ethylene from the dehydrogenation of ethane, is modeled after that of Champagnie and colleagues.[19,20] Equilibrium as a reaction constraint and methods to shift equilibrium in favor of desired products are taught in chemistry and chemical reaction engineering courses, but a student rarely uses these techniques in experiments. This reactor, when integrated into an undergraduate course on reaction engineering, demonstrates the advantages of using advanced membrane technology in combination with reaction kinetics. The basic operational principle behind the ceramic membrane reactor is that removal of a reaction product (hydrogen) through the membrane drives the reaction beyond the equilibrium constraints set by the feed composition and reaction temperature and pressure.

Ethane dehydrogenation was chosen as an example for a number of reasons. The most compelling was that ethylene is a chemical that is familiar to the students, and at over 50 billion pounds per year it is one of the top five chemicals in annual worldwide sales,[21] making the problem recognizable as a practical one. Another point is that the reaction is very endothermic, and temperatures in excess of 1000 K are needed for the reaction to approach completion. The student team first explored the feasibility of the membrane reactor concept through modeling studies, using the assumption that Knudsen diffusion describes the operation of the membrane. Students modeled the system in HYSYS, using an alternating series of equilibrium reactors and separators to approximate a simultaneous reaction/separation. These studies suggest that the membrane reactor should be able to achieve a given conversion at temperatures hundreds of degrees Kelvin lower than needed in a conventional plug flow reactor of the same volume. Students readily appreciate the desirability of operating at lower temperatures, both in terms of cost and safety. Thus, this project integrates many process design concepts. The process flow diagram of the system is shown in Figure 4.

The reactor consists of a quartz shell surrounding a platinum-coated ceramic membrane tube. The ceramic membrane was obtained from US Filter and has a pore size of 5nm. Students worked in conjunction with Johnson Matthey and students and faculty from the Department of Chemistry to devise and carry out a workable plan for coating the catalyst tubes using a choroplatinic acid process. The reactant and product concentrations are measured using an HP 6890 GC/MS. The only other equipment required included Fisher heating tapes, temperature controllers, and mass flow meters. The total cost of the system, including reactor and catalyst (but excluding the GC/MS, which was previously on site) was less than $2000.

In addition to illustrating important chemical engineering concepts, this setup also demonstrates some interesting practical issues to the students. One point is that although "isothermal reactors" are routinely posed in problems and modeled by undergraduate students, students do not necessarily appreciate the difficulty involved in carrying out a reaction that is truly isothermal. In this case, the reaction is very endothermic and is carried out well above room temperature—both factors that complicate maintaining an isothermal reaction. Another issue is the difficulty of creating gas-tight seals when working with materials (such as the ceramic membrane) that expand significantly with increasing temperature. Working with the chemical engineering lab technician, the students devised a procedure for sealing the reactor after it had already been brought to temperature. After the experiment is complete, the temperature is maintained and the system is purged with nitrogen before the seal is broken. Throughout the "design-and-build" phase of this project, the student team worked with various technicians in the college, from machining parts to electronic controls.

ASSESSMENT

Of significant importance to chemical engineering educators is satisfying the new EC2000 requirements of ABET, the most vexing of which are the "soft skills" represented by Criterion 3, f-i. The projects mentioned above can effectively satisfy these criteria, and the outcomes can be effectively assessed in a sustainable way. Our program has firsthand experience with this and has used various assessment instruments to verify the results. Table 1 indicates how the membrane projects meet the EC2000 requirements.

TABLE 1
ABET Criterion 3 (a-k) in the Membrane Projects

	Criterion	*Membrane Project Implementation*
a	Apply math, science and engineering	• Projects apply basic mathematics such as in calculating fluxes. Chemistry is applied in understanding the nature of the solutions to be separated and membrane structure. • Chemical engineering is applied from membrane mass transfer to process transport analysis.
b	Design/conduct experiments and analyze data	• The membrane projects involve experimentation—students must design the studies to be conducted and collect, correlate, and analyze their experimental results. Modern software tools are used.
c	Design process	• In most of the projects, the students design the bench-scale process unit to be used. In some of the projects, students present a final scale-up "paper" design for plant implementation that may include multiple sequential processes.
d	Function of multidisciplinary teams	• Inherent in the Rowan clinic program is that students perform the project in multidisciplinary or multifunctional teams. Each students has a role simulating actual industrial membrane project staffing.
e	Formulate/solve engineering problems	•While many of the projects have their original problem statements formulated by industry, the student teams may refine the problem and obviously will be the ones solving the process problem.
f	Professional and ethical responsibility	• Students learn about many aspects, such as safe handling and disposal of chemicals, safety, and process responsibility.
g	Communicate effectively	• All students must give an oral report and submit a final written report at the end of each semester. • Additionally, students engage in meetings with industrial representatives and present/defend their findings. • Senior Clinic counts as the "writing intensive" part of our curriculum.
h	Impact of engineering on society	• Through these projects, students learn the impact of membrane technology on society, such as in waste management, water reuse, purification of pharmaceuticals, and energy conservation.
i	Life-long learning	• The membrane projects have stimulated students to consider continuing their education, and many of them have gone on to pursue Masters or Doctoral degrees.
j	Contemporary issues	• Membrane processes are used in many contemporary problems facing society, such as environmental management, health care, and the production of potable water.
k	Modern engineering tools	• Membranes are indeed a modern engineering process and therefore satisfies this broad category. Other modern engineering tools used in the membrane projects include analytical instrumentation, computer data acquisition/control, and computer hardware and software.
l	University-specific criteria: Undergraduate research/emerging fields	• A unique criteria added at Rowan University was to engage undergraduate students in research in emerging fields, which these membrane projects effectively do.

Student feedback from the clinic projects mentioned above has been extremely positive. The experiential outcomes of our clinic projects have been assessed in several ways. We have conducted student focus groups, and representative comments from students on the membrane projects include: "The clinics gave me industrial hands-on experience that has helped me understand chemical engineering better." "I liked working in a team and having an industrial focus to my project." "I learned project management and research skills through the clinic and was more excited because it was a real industrial problem our group was solving.

Senior exit interviews have also been conducted. The responses from several questions related to the curriculum development described in this paper from twelve graduating seniors involved in the projects are:

- In the area of experimental research methods, can you write literature reviews, design experiments, and present research results? 91.7% Yes; 8.3% Maybe
- In the laboratory, can you make appropriate measurements, record information in a meaningful format, perform necessary analysis, and convey an interpretation of the results to an appropriate audience? 91.7% Yes; 8.3% Maybe
- Can you select a process component based on chemical engineering principles that is of an appropriate size and type to meet desired needs? 91.7% Yes; 8.3% Maybe
- Can you conduct experiments in a safe manner and understand safe practices and hazards? 100% Yes
- Can you interact synergistically with students from other disciplines, backgrounds, and cultures to achieve a comon goal? 100% Yes
- In Classroom, design, and laboratory activities, can you identify known variables, formulate key relationships between them, solve engineering problems, and assess the reasonableness of their problem solutions? 100% Yes
- Can you write effective documents, including memos, e-mails, business letters, technical reports, operations manuals, and descriptions of systems, processes, or components? 100% Yes
- Can you give effective oral presentations? 100% Yes
- Are the Junior/Senior Clinic projects a valuable experience in your preparation as a chemical engineer? 100% Yes

SUMMARY

Through the support of NSF and several industries, multidisciplinary student projects were initiated that challenged student teams to solve realistic industrial problems. These projects are versatile and can be modified slightly for use as laboratory experiments to provide the curricular development. The clinic projects help the 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 use modern engineering tools. In a primarily undergradute institution such as Rowan University, these projects provide an opportunity for faculty/student scholarship.

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