Int. J. Engng Ed. Vol. 10, No. 5, pp. 405–415, 1994
Printed in Great Britain.
0742-0269/91 $3.00+0.00

Experiences with Undergraduate Research in Senior Project Courses*

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In conjunction with their chemical engineering studies at Manhattan College, undergraduate students have the opportunity to work with faculty members on open-ended projects. This paper discusses curricular requirements associated with senior project courses, and highlights the authors' experiences with undergraduate research over the last decade. Senior projects fall into two categories: development of novel laboratory experiments, and research in new and emerging technologies. Projects of both types focus on modern separation processes, biochemical engineering and environmental applications of chemical engineering. Laboratory development projects also include computer interfacing and computer enhancement topics. Undergraduate research benefits the students, the faculty and the institution in a number of ways.

INTRODUCTION

MANHATTAN College is a private, independent college, originally founded by the Brothers of the Christian Schools. It is a comprehensive institution with programs in arts, sciences, business, education and engineering. The College is a member of the Oberlin Group, a group of 50 liberal arts colleges that are noted for distinguished research and for presenting a remarkable record in the education of the scientist. Manhattan College ranks first in New York State and 14th nationally among private, primarily undergraduate colleges in the number of graduates who have gone on to earn science and engineering doctorates (Source: National Science Foundation). The College also has a strong record in preparation of students for direct entry into the workforce. Manhattan ranks third among liberal arts colleges and first among Catholic colleges in the number of graduates who hold top corporate positions with American businesses (Source: Standard and Poors).

In keeping with this tradition of distinguished research and strong pre-professional programs, the Chemical Engineering Department has taken a leadership role in offering undergraduate research opportunities for students in the School of Engineering. Most of the chemical engineering students who are interested in completing a research project do so for credit in their senior year; therefore, we refer to 'senior projects' throughout the paper. Some students start research projects in their sophomore or junior year, either on a volunteer basis or through the campus work-study program.

*Accepted 7 August 1994
This paper is based on a publication in the 1994 ASEE Annual Conference Proceedings.

Undergraduate research benefits the students by helping them make career decisions and by providing them with unique educational experiences. Students who are undecided between graduate education and industrial employment find that their senior projects help them with this decision, and give them an edge in applying for doctoral fellowships or interviewing for industrial positions. Completion of an independent project gives the student a unique accomplishment to feature on a résumé or graduate school application, which is especially important in today's uncertain economy. Other students seek research opportunities as preparation for entry into medical college. Many of the students are co-authors on peer-reviewed publications and are inducted into Sigma Xi, the Scientific Research Society.

Manhattan College grants master's degrees in engineering, education and business. Most of the graduate students work in the metropolitan area and take courses at night as part-time students. The graduate program in chemical engineering is industrially oriented with a graduate design project required for full-time students and a course work only program offered for practicing engineers. Full-time graduate students may substitute a research project for the required design project, but only one or two students take advantage of this option each year. Colleagues often ask, 'Don't you find it difficult to do research without a doctoral program?' Undergraduate research benefits the faculty members in a primarily undergraduate institution because student participation is critical for scholarly productivity. If a faculty member has a strong record of involving students in his or her research program, Manhattan College values this activity in the promotion and tenure process.

Undergraduate research also benefits the institution, especially in recruiting and retention efforts.

Chemical engineering students are invited to speak on their undergraduate research experiences at Accepted Students Days and in the freshman orientation course. Research students also give laboratory tours and demonstrate their projects at Open House and Engineering Awareness Day. The enthusiasm and pride that these students have in their accomplishments makes a very positive impression on prospective students and their families. Undergraduate research benefits the department through development of new laboratories and recruitment of chemical engineering majors. In recent accreditation visits by the Engineering Accreditation Commision of the Accreditation Board for Engineering and Technology (ABET), chemical engineering evaluators have commented favorably on the fact that several faculty members are involved in research with undergraduate students.

CURRICULAR REQUIREMENTS

The Chemical Engineering Department offers students the opportunity to do research projects for academic credit during their senior year. Fifty-two students have completed undergraduate research projects in chemical engineering since 1983 (Table 1), and 94% of these students earned academic credit for senior projects. With permission of a faculty advisor and the department chairperson, students can register for CHML-430, Chemical Engineering Project I (three credits), and/or CHML-431, Chemical Engineering Project II (two credits). CHML-430 counts as a technical elective and is usually taken in the fall semester. All chemical engineering students are

Table 1. Participants in undergraduate research (1983–1994)

Paul P. Antonnechia	Michael S. Kelley
Joseph J. Arduino	Deborah A. Kachmar
James E. Barden	Silvia G. Lombardo
Mary Seperac Barden	Valerie C. Lanzon
Sana V. Barakat	Robert D. Lucas
Clayton A. Brooks, III	Louis S. Mazzella
William Calvo	Edward Mazzorana
Michael A. Capone	Thomas J. Meloro
Kevin G. Carroll	John F. Naughton
Antonella A. Caruso	Paula Croke Norman
Marco J. Castaldi	John D. Paccione
Robert E. Coppola	Nicola J. Peill
Ralph Crispino	Ruth E. Richardson
John M. Demarais	Lynn M. Ricci
Kevin Devine	Sandra Faccinelli Rossi
Carmine T. DeVito	Catherine Ruebenacker
Rita L. D'Aquino	Elizabeth Schaub
Robert Fabinski	Diana Matarazzo Scouby
Albert Ferrari	Christopher C. Vega
Kevin A. Frankel	Michael N. Venezia
Christopher E. Gould	Anthony M. Vincitore
Carmine V. Grippo	Peter Wisniewski
Meegan T. Hammond	Margaret L. Wells
Deborah Agne Hendricks	Robert G. Wendel
Patrick J. Hickey	Annmarie L. Witt
Thomas G. Huggins, Jr	John M. Zielinski

required to complete the first semester of the senior laboratory course. CHML-431 may be substituted for the second semester of the senior laboratory course, provided that the project has an experimental component. In the spring semester, undergraduate research students are required to present their results to their peers during the oral presentations for the senior laboratory course. Written reports are required in both semesters.

Due to the time commitment required from the students in order to succeed in research, the catalog description limits these courses to 'students of superior ability'. This is interpreted as students with a 3.0 or higher grade point average (GPA); however, permission may be granted to highly motivated students who are enthusiastic about doing a research project but rank somewhat lower in their class. Students who are employed more than 10 hours per week during the academic year are not permitted to register for senior projects regardless of their academic records. The authors have worked with students with various academic records, and find that students who are enthusiastic about doing a senior project and know how to organize their time are successful. In several instances, the opportunity to get involved in research has stimulated average performers to get excited about their studies and dramatically improve their academic records.

Senior projects must be approved by a departmental committee and are required to meet certain criteria. Independent investigations include literature, theoretical and/or experimental studies. The projects are required to be open-ended with one-third to two-thirds counted as engineering design. Research is inherently open-ended in that the results are not known in advance and there are different methods of arriving at a solution. In order to take credit for this aspect, a project must be set up so that the undergraduate student makes an intellectual contribution to the decisions on the research path rather than serving as an extra pair of hands for a graduate student or faculty advisor. Projects in which a new experimental system is built or assembled are rated higher in design content than continuing research on an existing system.

In the past 11 years, the chemical engineering program has undergone two ABET accreditation visits, and both program evaluators commented favorably on the senior project courses. Chemical engineering enrolment dropped in the late 1980s and increased in recent years. Since 1983, the number of undergraduates doing research projects has varied from two to nine annually depending on student interest and faculty schedules (Fig. 1). This number as a percentage of the graduating class increased dramatically in 1990 (Fig. 1). Due to the small class size during the 1989–90 academic year, only one senior 'elective' was offered per semester. All of the 1990 graduates were given the option of doing a senior project to compensate for their limited course selection, and eight seniors took advantage of this opportunity. The 1989–90

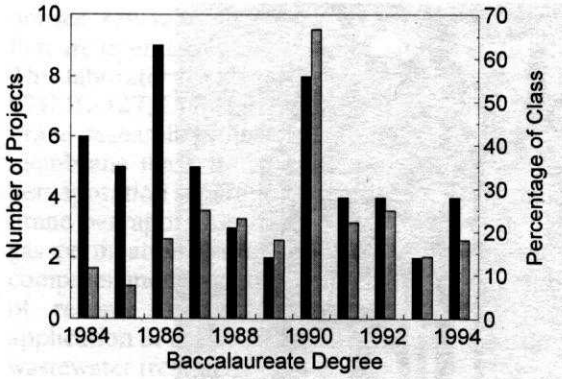

Fig. 1. Undergraduate projects. ■ Number of students, ⊠ Percentage of graduating class.

academic year was also the year of record for our last accreditation visit, and senior projects replaced a required laboratory course for 67% of the graduating class. Thus, our experience shows that undergraduate research satisfies accreditation requirements provided that standards for its conduct are agreed upon in advance and carefully monitored.

LABORATORY DEVELOPMENT PROJECTS

Financial support for undergraduate research projects has come from various sources, including corporate donations to the department and faculty research grants from industry, research grants and laboratory development grants from government agencies, capital funding from the college, and departmental operating funds. The authors of this paper have developed new teaching laboratories in biochemical engineering and advanced separation processes with four grants from the National Science Foundation's Instrumentation and Laboratory Improvement Program (1985–1992). This work, which was presented at American Society for Engineering Education conferences and published in various journals, is discussed in more detail below [1–12].

The authors received an NSF Undergraduate Faculty Enhancement grant to run a workshop entitled, 'Undergraduate Faculty Enhancement in Membrane Technology', at Manhattan College in 1991. This eight-day workshop, which was attended by 15 chemical engineering faculty members from other institutions, included laboratory experiments in microfiltration, ultrafiltration, reverse osmosis (pilot-scale and hand-held) and gas permeation [13]. Three undergraduate students developed and tested the laboratory portion of the workshop in conjunction with their senior projects. Several of the experiments were based on prior work, while the microfiltration experiment and the hand-held reverse osmosis demonstration were new.

Students have worked on computer interfacing projects with Dr Jack Famularo for the Unit Operations Laboratory [14], i.e. the facility that houses our required two-semester senior laboratory course. Major improvements were made to the Unit Operations Laboratory with grants received from Mobil Research and Development Corporation between 1981 and 1987. Four students worked from 1983 to 1986 on experiments in unsteady-state heat conduction, heat exchanger computer control and chromatographic analysis of distillation data. These projects involved writing programs for data acquisition and control in machine language on microcomputers. During the 1989–90 academic year, another student worked with Dr Famularo to develop a computer-interfaced experiment involving transient characteristics of thermocouples. This project utilized LabVIEW software and National Instruments hardware on a Macintosh computer system.

The authors have supervised several students who completed computer enhancement projects for the Unit Operations Laboratory. These students revised experiments that had a history of yielding confusing data, and wrote spreadsheet programs so that future students could check the validity of their data during the laboratory period. Students have also worked on various process experiments for the senior laboratory courses, including spray drying for 'instant' coffee production and rotary drying of wet cornmeal.

Biochemical Engineering Laboratory

Starting in 1986, the authors developed a Biochemical Engineering Laboratory with funding from the National Science Foundation and Manhattan College. A number of experiments were developed for this laboratory by undergraduate students working on senior research projects (Fig. 2) [8,9]. These experiments are listed below:

- Fermentation in a batch stirred tank reactor.
- Fermentation in a continuous stirred tank reactor.
- Cell growth in an airlift fermentor.
- Agitation and aeration in biological reactors.
- High-pressure liquid chromatography (HPLC).
- Concentration of yeast cells by microfiltration.
- Cell harvesting: tubular bowl centrifugation.
- Cell disruption: high-pressure homogenization.
- Concentration of proteins by ultrafiltration.
- Chromatographic separation of protein mixtures.

Manhattan College offers an interdisciplinary master's degree program in biotechnology that was introduced in 1989. The Biotechnology Graduate Program is a co-operative effort of the Biology, Chemistry, and Chemical Engineering Departments. The Biochemical Engineering Laboratory is an interdisciplinary effort that was originally developed to support an undergraduate option in biotechnology. This facility is used for the laboratory portion of a chemical engineering elective course entitled Biochemical Engineering, a course

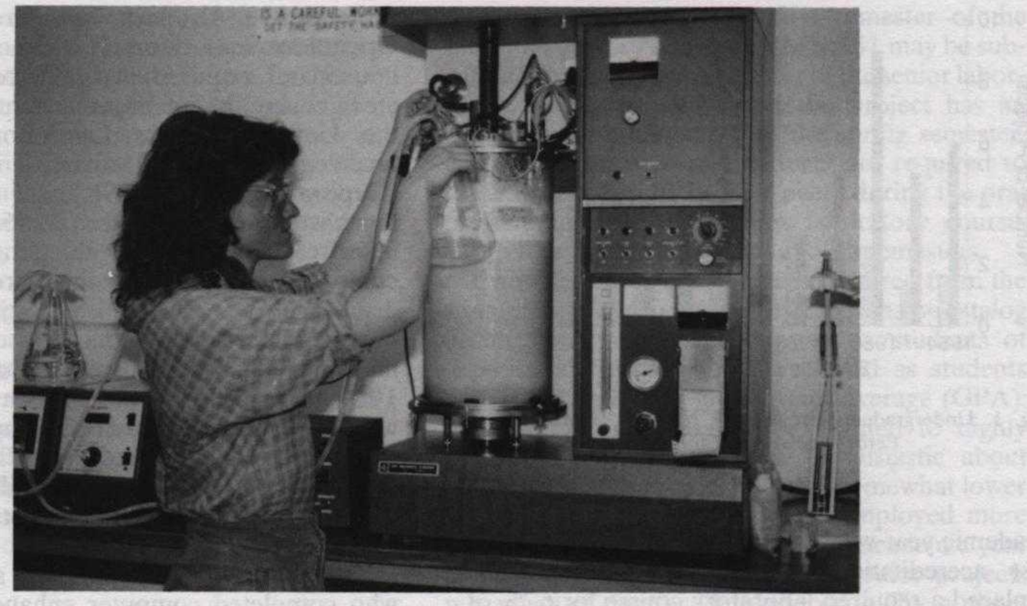

Fig. 2. Nicola Peill is shown working with a New Brunswick Scientific batch stirred tank fermentor in the Biochemical Engineering Laboratory. Experiments developed by Nikki and Michael Venezia (not shown) during the 1986–87 academic year are run in conjunction with an elective course in biochemical engineering.

that was initially offered as separate graduate and undergraduate courses. With the introduction of the Biotechnology Graduate Program, the biochemical engineering courses were combined. The revised course is open to chemical engineering seniors with a 3.0 or higher GPA, chemical engineering graduate students and biotechnology graduate students. This laboratory is also used for senior projects and graduate research in biochemical engineering.

Each of the experiments in the Biochemical Engineering Laboratory was developed by one or two students working on senior projects. They searched the literature to find current publications related to their assigned experiment, then chose an appropriate set of operating conditions based on the literature. The equipment typically came in boxes with incomprehensible assembly instructions, but the students managed to install their experimental systems with supervision of a faculty advisor and assistance from the engineering technicians. After running the systems under various operating conditions and collecting typical process data, the students wrote experimental procedures, conclusions and results. The biggest projects were development of the three fermentation experiments.

Dr Stephen Walsh, who was previously affiliated with the Chemistry Department, participated in the laboratory development. An interdisciplinary research project related to developing methodology for analyses of fermentation broths using HPLC was conducted by a biochemistry undergraduate working with a chemical engineering graduate student. The graduate student had worked on the batch fermentation experiment as a senior project and continued working on the fermentation aspects of the interdisciplinary project.

Advanced Separation Process Laboratory

Undergraduate students at Manhattan College learn about membrane separation processes in two required courses. Elective courses are also offered at both the undergraduate and graduate levels. These courses are:

- CHML-404, Chemical Engineering Laboratory II (required).
- CHML-439, Selected Topics in Mass Transfer (required).
- CHML-427, Modern Separation Processes (elective).
- CHMG-709, Membrane Process Technology (elective).
- CHMG-726, Separation and Recovery Processes (elective).

Membrane processes are viewed as emerging technologies, primarily because the typical chemical engineer has had no classroom instruction or laboratory experience with these processes. Reverse osmosis is in its fourth decade and is used for seawater and brackish water desalination, industrial wastewater treatment, and production of ultrapure water. Ultrafiltration and gas permeation have been used on a commercial basis for over 30 and 15 years, respectively, while pervaporation is a newly commercialized process. To address this deficiency in the curriculum, the authors developed an Advanced Separation Process Laboratory with experiments on membrane processes [4–7,13].

The Advanced Separation Process Laboratory is used for senior projects and graduate research, and houses several membrane process experiments that are operated in conjunction with CHML-404. This laboratory is also used for demonstrations in CHML-427, CHML-439 and CHMG-709. Membrane research projects focus on topics such as membrane mass transfer analysis, application of pervaporation separations to biotechnology, membrane pervaporation transport and system design, gas permeation system design and optimization, computer modeling and mathematical simulation of reverse osmosis membrane systems, and application of membrane technology to hazardous wastewater treatment.

The reverse osmosis (RO) system in the Advanced Separation Process Laboratory was designed and assembled by Slater and Paccione [10]. It is a pilot-scale system that is designed to accept spiral wound or hollow fiber membrane modules from a number of vendors. The system can operate in various flow schemes. Feed flow, solute concentration, temperature, pressure and recovery can be varied independently. RO is the major process used in the Middle East for production of potable water from seawater, so this is the application that was selected for an instructional experiment. Students in CHML-404 run the RO system with a spiral wound membrane using saltwater as feed. They vary operating pressure and feed concentration, and measure the effects of these two variables on permeate flux and solute rejection. Project students have also studied cadmium removal from wastewater using the RO system (Fig. 3) [15].

The use of membranes in gas separation was commercialized by Monsanto in the mid-1970s with the development of the hollow-fiber Prism system. Permea, Inc. (currently a subsidiary of Air Products and Chemicals, Inc.) developed a laboratory-scale version of the commercial membrane gas separation unit. The basic system consists of four hollow-fiber membrane modules which are mounted together on a common manifold (Fig. 4). Several students worked on design and development of instructional experiments for the Permea system. This experiment was introduced in CHML-404 in 1992. Experiments are conducted with compressed air to separate the air into purified nitrogen and enriched oxygen streams. Stage cut and operating pressure are the primary operating variables, and their effect on separation efficiency is examined [3,4].

There are two pervaporation systems in the Advanced Separation Process Laboratory, a small permeation test cell that was used for research projects discussed in the next section and a bench-scale system that was purchased recently with an NSF instrumentation grant. The new system was constructed by Zenon Environmental, Inc., and modified by Zenon based on recommendations from Slater and co-workers after initial testing. Several projects utilizing the Zenon system involved development of experimental protocols for laboratory instruction. Dehydration of an organic solvent was selected for the initial experiments. Membrane system performance parameters of selectivity and flux can be readily evaluated [1,2]. Research projects completed on the Zenon system examine separation of aqueous mixtures of organic solvents common to pharmaceutical and specialty chemical production (Fig. 5) [16,17].

Several bench-scale ultrafiltration units were purchased from Amicon Inc., a W. R. Grace Company. These include thin-channel, spiral-wound and hollow-fiber geometries, plus a stirred-cell batch system [5,6]. The thin-channel and stirred-cell configurations are typically used for laboratory research, while the spiral-wound and hollow-fiber configurations are typical for industrial usage. We

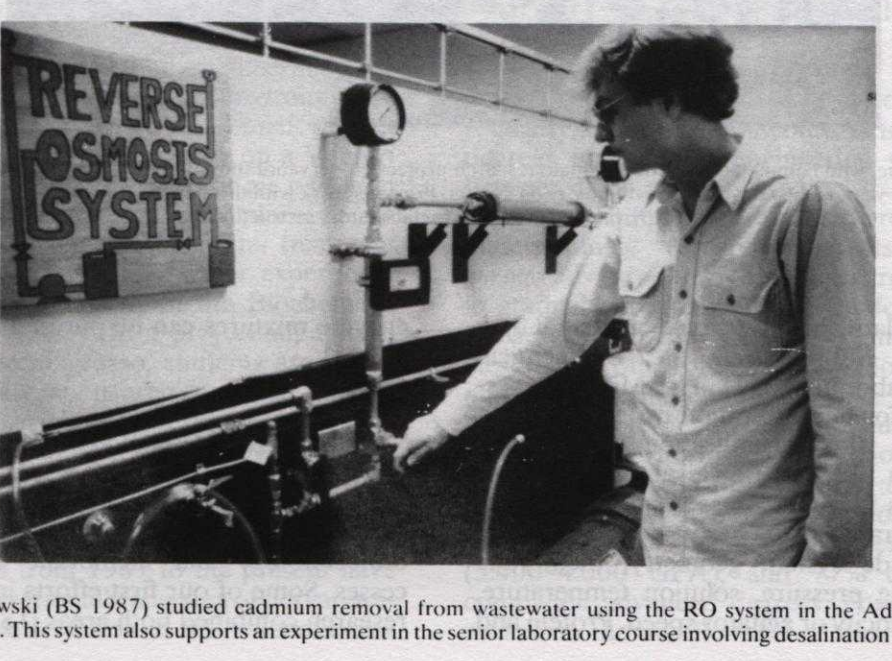

Fig. 3. Peter Wisniewski (BS 1987) studied cadmium removal from wastewater using the RO system in the Advanced Separation Process Laboratory. This system also supports an experiment in the senior laboratory course involving desalination of brackish water.

Fig. 4. The gas permeation experiment in the Advanced Separation Process Laboratory is featured in several college brochures. Pictured with the system are Diana Matarazzo, who completed an undergraduate reserach project on membrane pervaporation during the 1989–90 academic year, and her advisor Dr C. Stewart Slater.

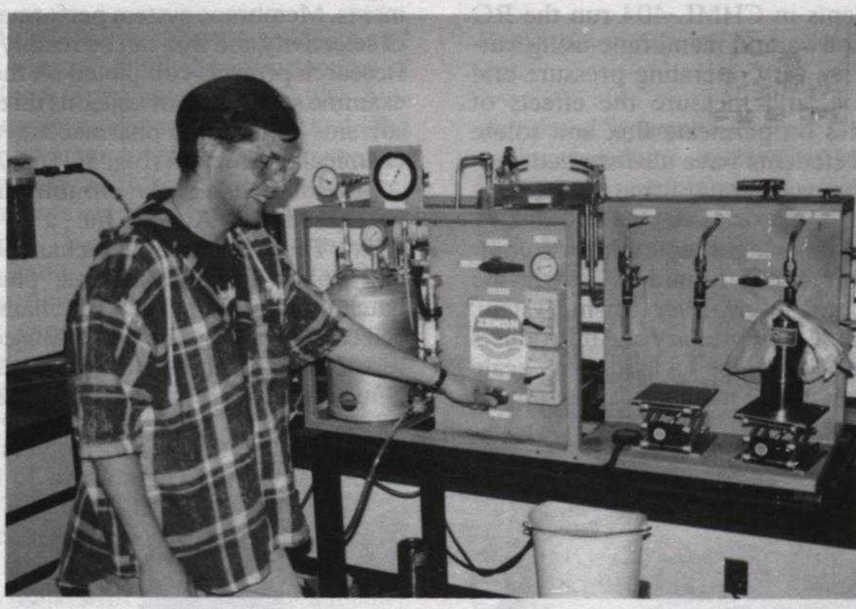

Fig. 5. Kevin Devine, who completed an undergraduate research project on pervaporation of pyridine and other solvents during the 1993–94 academic year, is shown working with the Zenon system. Previous work with this bench-scale system focused on developing experimental protocols for laboratory instruction.

also have two plate-and-frame type tangential flow systems from Millipore in the Biochemical Engineering Laboratory [11]. The Millipore systems are used for microfiltration experiments but can be fitted with ultrafiltration membranes. Experiments in ultrafiltration examine effects of various process variables on separation effectiveness and on ultrafiltrate or permeate flux. Process variables include system geometry, membrane types, operating pressure, solution temperature, and channel velocity or agitator speed. Protein and enzyme mixtures can be purified or concentrated [13,18].

NEW AND EMERGING TECHNOLOGIES

Most of the projects supervised by the authors' focused on chemical engineering fundamentals in biotechnology and membrane separation processes. Some of our first efforts in undergraduate research combined both areas [18–20]. Successful projects in ultrafiltration examined separation and purification of enzymes. Chromatographic separation of protein mixtures was also studied with research grants from the NSF and the National Institutes of Health (1983–1987). Recent projects have examined the use of a hybrid chromatographic membrane separation system (donated by FMC Corporation) for separation of protein mixtures.

Undergraduate research is an ideal vehicle for introducing new and emerging technologies into the curriculum. Graduate and undergraduate electives in biochemical engineering were introduced in 1985, two years after undergraduates started doing research related to this topic. Membrane process technology was introduced into the undergraduate curriculum in an elective course in 1990 and in a required course in 1991 (a graduate course was introduced in 1986). Undergraduate research students had studied membrane processes for seven years before formal introduction of this technology into undergraduate courses.

With the current emphasis on pollution prevention and remediation of hazardous waste sites, chemical engineering students need to learn about environmental issues within the curriculum. Our students have the opportunity to take three techical electives on environmental engineering topics, and a number of our alumni/nae seek employment and/or graduate work in that field. Student projects can be used to address environmental issues. Several undergraduate research projects on reverse osmosis were environmentally focused, including process modeling studies and joint projects with industry on wastewater remediation. An example of a joint project with a local industry was an experimental study that involved use of reverse osmosis for removal of cadmium from waste streams (Fig. 3) [15]. Another project involved mathematical modeling and computer simulation of a reverse osmosis system for concentration of industrial wastewater [21,22].

Other projects supervised by the authors have also focused on environmental engineering. One student who was interested in environmental engineering did a laboratory development project for the Unit Operations Laboratory on a Venturi scrubber, equipment that is used for air pollution control. Recently, a student who plans to do graduate work in biological wastewater treatment developed a biological mass transfer experiment using one of the fermentors in the Biochemical Engineering Laboratory. In a project supervised by Dr Ronald Occhiogrosso, students are working on industrially sponsored research that is examining the feasibility of using supercritical fluid extraction technology for removal of trace organics in recycled plastics (Fig. 6). These projects involve experimentation and/or computer-simulated studies.

Senior projects from 1987 to the present have researched the novel membrane area of pervaporation. Industrial participation in this research area has been high, with the initial studies sponsored by Air Products and Chemicals, Inc., and subsequent projects involving Exxon Research and Engineering Company and several other firms. The project sponsored by Air Products investigated the use of proprietary membranes for separation of various organic–water mixtures. Commercially available membranes were also used to study the separation of aqueous binary mixtures of ethanol, n-butanol, iso-butanol, tert-butanol, sec-butanol, ethyl acetate and acetone (Fig. 7). These projects examine the potential of pervaporation for selective permeation of organics from dilute aqueous systems, technology that is applicable to many important engineering areas including hazardous waste treatment, biochemical processing, water purification and beverage processing [23–28]. Pervaporation research has also investigated solvent recovery in the pharmaceutical industry, with Pfizer, Inc. as the corporate sponsor.

IMPACT ON UNDERGRADUATES

There are many ways that the opportunity to participate in research impacts undergraduate students. A number of undergraduates have been inducted as associate members of Sigma Xi, the Scientific Research Society, based on their participation in chemical engineering research. A few chemical engineering students are inducted into Sigma Xi based on undergraduate research with chemistry faculty, but they are not included in our statistics. Chemical engineering undergraduates have presented papers at regional meetings of the American Chemical Society, and co-authored refereed publications on their projects. Each year at the baccalaureate commencement, the Sigma Xi Medal is presented to a Sigma Xi initiate for excellence in research. Undergraduates majoring in chemical engineering received this medal in 1986 and 1989, an honor that usually goes to a premed student majoring in biology.

Most undergraduate research programs are aimed at encouraging graduate education, and this is clearly a significant outcome. A total of 293 BS degrees in chemical engineering were awarded between 1984 and 1994, with 18% of the undergraduates completing research projects. Of the undergraduate research students, 69% have earned advanced degrees or are currently enrolled in graduate programs. This includes three physicians, two patent lawyers, ten engineering doctorates, and one biochemistry doctorate. This outcome is magnified in importance by the fact that the senior project courses are not limited to the top students academically. Figure 8 shows the highest degree completed (or in progress) as a function of class rank. Thirty-five research students ranked in the top third of chemical engineering graduates (3.400–4.000 GPA), and 77% of this group completed advanced degrees. Fourteen students ranked in the middle third of their class (2.800–

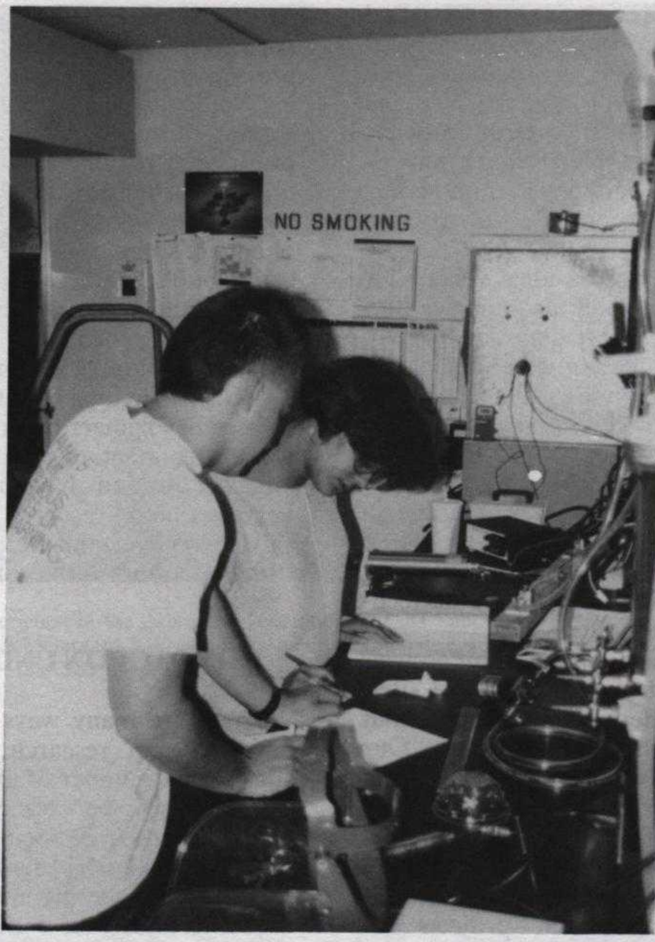

Fig. 6. One project with an environmental focus examined the feasibility of using supercritical fluid extraction (SCF) technology for removal of trace organics from recycled plastics. Pictured are Robert Lucas (BS 1994) who completed an undergraduate SCF project, and Martha Filpo (BS 1993, MS 1994) who did graduate research on SCF technology.

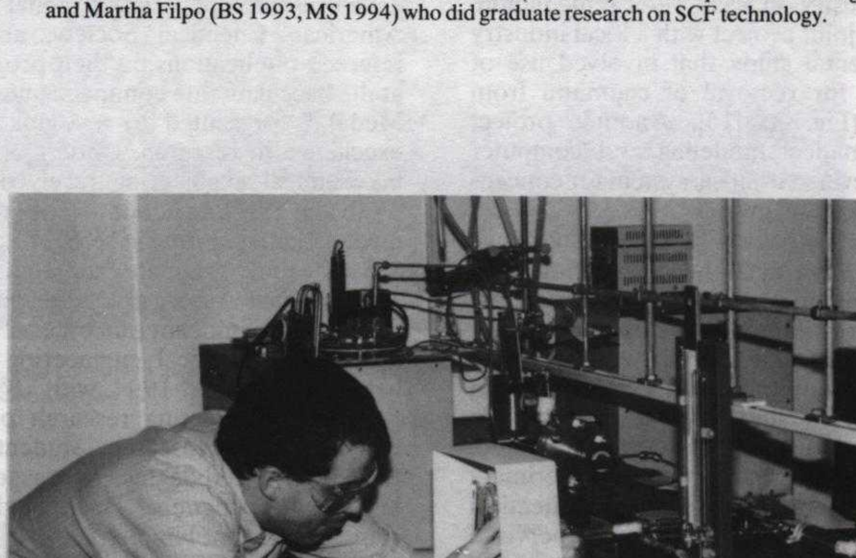

Fig. 7. Patrick Hickey used a small test cell for undergraduate research on pervaporation of alcohols through organophilic membranes during the 1988–89 academic year. He continued his pervaporation research at the master's level at Manhattan College during the 1989–90 academic year.

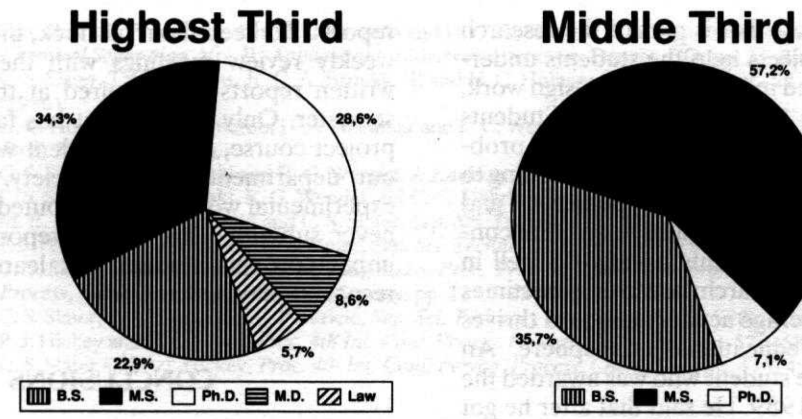

Fig. 8. Postgraduate education (highest degree earned) for undergraduate research students who graduated between 1984 and 1994. Highest third are students graduating with grade point averages between 3.400 and 4.000. Middle third are students graduating with GPAs between 2.800 and 3.399.

3.399 GPA), and 64% of this group completed advanced degrees. The remaining students accepted industrial positions at the baccalaureate level. Some students completed graduate degrees as full-time students, while others accepted industrial positions and attended graduate classes on a part-time basis. There are students in all three categories who capitalized on their project experiences to secure industrial positions.

It is important to realize that two to three times as many undergraduates as graduate students participate in research at Manhattan College. As stated earlier, the majority of the graduate students at Manhattan College earn their degrees on a part-time basis and the full-time students do not have a thesis requirement. Between 1984 and 1994, 208 master degrees were granted but only 11% of the graduate students registered for research. Eighteen of the graduate research students earned their baccalaureate degrees from Manhattan College, but only seven of these students completed undergraduate research projects. Two of the seven subsequently enrolled in doctoral programs. Working with a student for two consecutive years (senior year plus one year in a full-time master degree program) can be very beneficial for the faculty member in terms of research productivity; however, this benefit was only realized in 13% of the cases and it is not a primary goal of the undergraduate research program.

Undergraduate research is viewed very favorably by industry. Of the first two undergraduates who worked on chromatographic separations of protein mixtures, one went to work for Biogen and currently works for Regeneron, and the other worked for CIBA Geigy and is currently completing a master's degree in pharmaceutical engineering. One of the students who was instrumental in developing fermentation experiments for the Biochemical Engineering Laboratory set up a fermentation pilot plant at Maxwell House and is currently manager of the fermentation pilot plant at Thomas J. Lipton, Inc. One of the undergraduates who worked on the gas permeation project was hired by UOP, a company that licenses gas permeation units and other separation processes. Other alumni/nae work for Air Products, ABB Lummus, Cytec, Exxon, IBM, Lederly Laboratories, Lever Brothers, General Foods, Merck, Mobil, and Pfizer. Many companies value the hands-on experience that the research students have with process equipment, and hire them for this expertise rather than for the specific project that they completed.

In some cases, participation in undergraduate research has been the deciding factor in a student's decision between pursuing a doctoral degree or accepting an industrial position after graduation. One student who worked on the computer interfacing and control project agonized over her choice of doctoral fellowships before accepting a position at Air Products. Ten years later, she is still happy with her decision and has earned a master's degree as a part-time student at Lehigh University. One student who worked on the development of the Biochemical Engineering Laboratory went to work for Air Products after graduation, but resigned after working a few years and is currently a doctoral candidate in environmental engineering at California Institute of Technology. Another example of diverse decisions is witnessed by two alumni/nae who accepted positions at Exxon. A research student who worked on the continuous fermentation experiment is happily employed at this company, while another student who worked on the FMC separation project resigned from Exxon after one year and entered a doctoral program at the University of California at Los Angeles. All four of these graduates liked their projects and did outstanding work, but two decided on a career of research and two did not.

An important benefit of participation in undergraduate research that is more difficult to quantify is the learning process that is part of the research experience. The projects help the students understand what is required in independent design work, and learn effective time management. Students have the opportunity to work on open-ended problems, use their creativity in an engineering setting to formulate and test scientific hypotheses, and organize their experimental results to arrive at conclusions. The honors students usually do well in everything including research; however, sometimes a student with an average academic record thrives in this alternative educational atmosphere. An example of this is the student who was awarded the Sigma Xi Medal in 1989. He said that after he got involved in research, he really got excited about his education. His grades improved dramatically in his senior year, he earned a master degree at Manhattan College, and recently completed a Ph.D. in chemical engineering at Clemson University. At the Fourth International Conference on Pervaporation Processes, this extraordinary young man won an award for a paper based on his undergraduate research. At the Fifth International Conference, he won another award for a paper based on his master's research.

The senior project courses are not like master's theses where students can be held from graduating until they submit 'A' work. Most of our project students have done excellent work, but some procrastinate, then try to complete their entire project in the last few weeks of school. These students are graded accordingly as they would be in any other major course where their performance was marginal. The authors try to make it clear to potential undergraduate researchers that they must be prepared to put in time on their project every week, that research requires more effort than the typical elective course, and that research should not be viewed as an escape from writing laboratory reports. To keep them on track, the students have weekly review meetings with their advisor and written reports are required at the end of each semester. Only one student has failed the senior project course, and that student was president of our departmental honor society. He did some experimental work and contributed to a paper, but never submitted his written report. Perhaps, the impact on this student was learning to accept responsibility the hard way.

CONCLUSIONS

Undergraduate research is a valuable educational experience for engineering students, and prepares them for both graduate education and direct entry into the industrial work force. Faculty members working with research students benefit from interaction with the students and from increased scholarly productivity. The institution and the individual department also benefit from the opportunity to showcase the students' accomplishments in recruiting and retention efforts. Course credit for research projects requires careful planning and monitoring of course requirements. Projects supervised by the authors focus on chemical engineering fundamentals in biotechnology and membrane separation processes. These projects can serve as a model for research in other engineering disciplines.

Acknowledgements——Equipment for laboratory development projects was provided by grants from the National Science Foundation (DUE-8551851, DUE-8650428, DUE-8750858 and DUE-9051549), with matching funds from Manhattan College and the following industries: Air Products and Chemicals, Inc., Allied-Signal, Inc., E. I. Du Pont de Nemours and Co., Inc., Exxon Educational Foundation, Hoeschst Celanese Corp., and Mobil Research and Development Corp.

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