CHEMICAL AND ENVIRONMENTAL ENGINEERING
A Logical Combination

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An often-debated subject among academia's engineers who are conducting environmental research is what to do with environmental engineering. Where does it belong in the engineering curriculum? What are the "core" environmental engineering subjects? Should the "first degree" in environmental engineering be a Bachelor's degree or a Master's degree?

While many engineering schools have chosen to combine environmental engineering with civil engineering to address these issues, at the University of Arizona we have taken a different approach by merging environmental engineering with chemical engineering. This unique merger was initiated on July 1, 1993. As the difficult environmental problems facing this country and the world shift from a focus on "end-of-pipe" solutions to a focus on process modifications for pollution prevention and waste minimization, engineers with *process* and *unit operations* backgrounds will become increasingly important. For this reason, environmental engineering education within the context of a chemical engineering department is a logical organizational structure. So too, the emphasis on the *chemistry* and *transport processes* in many aspects of environmental concern points to chemical engineering as a logical department within which to align environmental engineering.

Two very important advantages exist in a combined program of this type:

- *Environmental engineering is taught from a chemical engineering perspective, focusing particularly on process design and control in industrial applications and their environmental impact*
- *Chemical engineers are taught that environmental concerns are not an "aside" in the design process, but rather must be considered from the outset, just as safety and economic issues are*

Many of the environmental research concerns of today are directed toward problems of air and groundwater transport, chemistry, and physics. Numerous departments (including chemical engineering, civil engineering, hydrology and water resources, and mining/geological engineering) have major research efforts in these areas. But industries and governmental agencies with environmental mandates are concentrating ever more substantial efforts in the areas of pollution prevention and minimization. To properly address these issues, a *process engineering* approach must be taken. The concept of environmental management and control must become part and parcel of an engineer's education from the outset; design courses, unit operations, reaction engineering, and transport phenomena all must be taught with consideration for the environmental impact of the overall process (as well as safety, economics, quality control, etc.).

A phrase in industry describing this new paradigm is "design for environmentability," or DFE. Many engineering

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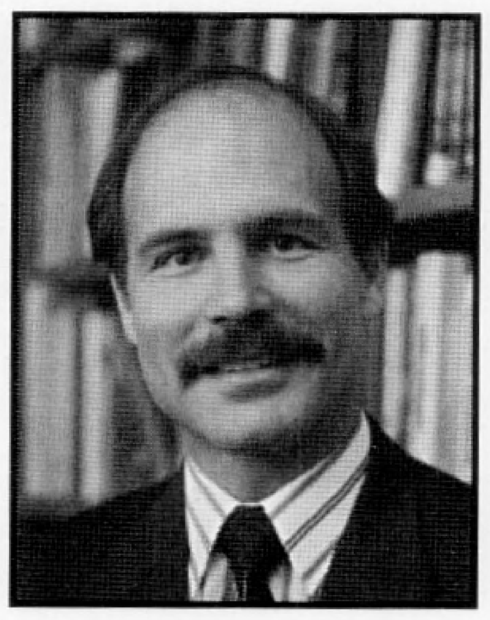

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fields provide varying levels of emphasis in the process or unit operations fields—chemical engineering is not alone. But no engineering field is more deeply rooted or more thoroughly exposed to the fundamental process engineering principles and applications than is chemical engineering.

It is apparent that a great deal of synergism is possible by combining environmental and chemical engineering programs into one department. Not only are similar research objectives more readily pursued, but graduate and undergraduate students also have the opportunity to pursue engineering degrees identified directly with the environmental field, drawing on the expertise of faculty with both chemical engineering and environmental engineering perspectives.

First we will describe the key elements for a successful merging of two existing programs, and second, representative research and coursework areas related to environmental issues will be detailed. Finally, examples of new directions in research and curriculum development within a combined chemical/environmental engineering program will be given.

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KEY ELEMENTS FOR A SUCCESSFUL MERGER

Reorganizations and mergers of departments, especially involving smaller departments, are commonplace as universities continue to study alternative structures to reduce administrative overhead. But any merger of this type must make sense from a programmatic point of view. The successful merger of existing and well-established chemical and environmental engineering programs requires certain key elements. The merger at the UA involved two programs that were each in existence for over thirty years. While specific circumstances will obviously vary from one institution to another, success is greatly enhanced if the following factors are a part of the current administrative structure:

- *Faculty in both programs are totally supportive of the merger.* Each faculty member recognizes the benefits from such a merger, even if it may not directly affect his/her research, teaching responsibilities, etc.
- *A large portion of the faculty are involved in complementary research programs.* Collaborative research can certainly be conducted across departmental boundaries, but having complementary research projects involving chemical- and environmental-engineering faculty within the same department greatly strengthens research activities in these areas.
- *Faculty in both programs come from complementary educational backgrounds.* Rarely do environmental engineering graduate students have undergraduate degrees in environmental engineering. Much more common are degrees in "classical" engineering fields such as chemical, civil, or mechanical engineering. Among our environmental engineering faculty, half have degrees in chemical engineering.
- *Faculty in both programs bring comparable strengths to all aspects of the educational enterprise.* All faculty are active in research, all participate in teaching undergraduate and graduate students, and all are involved in the various service aspects of the program, including outreach to pre-college students and the community. At Arizona, the research activities of the department (about $2 million annually) equitably support both chemical and environmental engineering graduate study, and a strong and rigorous undergraduate chemical engineering program exists (over 260 students).
- *The newly formed program has the strong support of the College, especially the Dean.* In reorganizing existing programs, strong administrative leadership is a prerequisite to dealing smoothly with issues such as space and resource reallocation, faculty governance, etc.
- *The university offers an MS program that is more than a "consolation prize."* As will be described below, the MS program is most often the "entry level" degree in environmental engineering. Providing a rigorous research and coursework curriculum at the MS level is difficult if the MS program at an institution is predominately a vehicle for students who cannot complete the PhD program. In the Arizona program, approximately half of the seventy graduate students in chemical and environmental engineering initially pursue a rigorous, research-oriented MS as the first graduate degree.

RESEARCH ACTIVITIES

In this section we will discuss ongoing research activities at the University of Arizona. These research topics are representative of the types of areas in which chemical and environmental engineering can both contribute in a synergistic fashion. These topics are typically funded by EPA, NSF, DOE, USGS, NIH, ONR, ACS, water utilities, local governmental agencies and various utilities, consulting firms, and industries. At the UA, about one-third of our research support comes from industry.

Transport Through Porous Media

Capillary Phase Separation and Transport of Hydrophobic Contaminants in Microporous Sorbents • Numerical modeling of contaminant transport and aquifer remediation suffers from a deficiency of inadequate description of soil-contaminant interactions. Past models have attempted to describe soil particles as porous spheres characterized by representative, average properties. This research investigates the effects of intra-particle micropores smaller than 30 Å in diameter on contaminant desorption rates and adsorption/desorption hysteresis.

Microbial Transport • The attenuation of suspended microorganisms during advective flow through porous media is of environmental interest from the perspectives of disease transmission, dispersion of microbes with novel metabolic properties for in-situ remediation of hazardous wastes, oil field repressurization, and origin of bacteria in deep subsurface habitats. Of particular interest are the effects of chemically modifying bacterial surfaces, air sparging, iron content in sediments, groundwater chemistry, and NAPLs (non-aqueous phase liquids) in groundwater on bacterial transport in both saturated and unsaturated soils. A novel method in which bacteria are labelled with radioisotopes is used to study these and other aspects of bacterial transport.

Optimization of Pumping Rates and Extraction Well Spacing During Contaminated Aquifer Remediation • Laboratory-measured mass transfer parameters are used for the optimization of pumping rates and extraction well spacing during contaminated aquifer remediation. Rates of TCE desorption from aquifer sediments obtained from a local Superfund site are measured to determine the effect of intra-granular mass transfer limitations on contaminant remediation. Numerical modeling is used to optimize pumping rates, thereby reducing the volume of water requiring treatment.

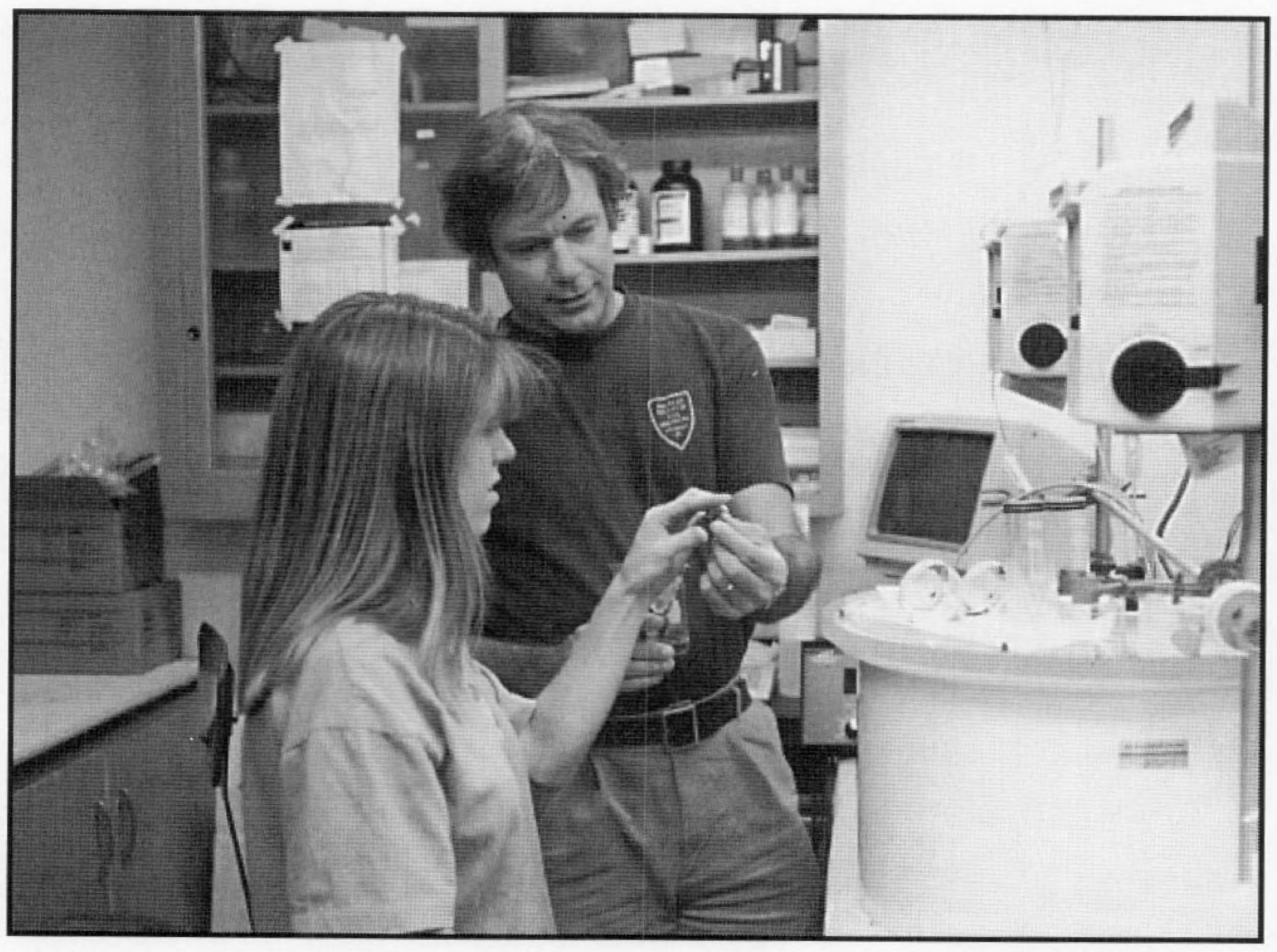
Bioremediation

Biodegradation of Aromatic Chemicals • Biological treatment of highly toxic aromatic compounds is a cost-effective method of pollutant destruction. Current research focuses include: biodegradation of BTEX (benzene, toluene, ethylbenzene, and xylene) by chlorate-reducing microorganisms (those anaerobic microorganisms capable of using chlorate as an electron acceptor); pentachlorophenol degradation by various species of white rot fungi, and cometabolic degradation of high-energy explosives.

Anaerobic Bacterial Respiration • As in higher organisms, respiration is among the primary avenues of energy generation by bacteria. But bacteria are frequently able to respire anaerobically by substituting a variety of terminal electron acceptors for molecular oxygen. Denitrification is an example of such a process. In this case, nitrate ion serves as an external electron acceptor for respiration. Work has centered on the use of alternate electron acceptors such as ferric and manganic oxides for bacterial respiration.

Fixed-Film Bioreactors • The degradation of wastewaters in fixed-film bioreactors, such as trickling filters, is limited by the mass flux of organic components into the biofilm. Computer models of trickling filters have been developed that use the size distribution of biodegradable dissolved organic compounds in wastewaters. Procedures have been developed to separate soluble organic matter present in wastewater into apparent molecular weight fractions using ultrafiltration techniques. Biodegradability of size fractionated organics is determined using BOD and HBOD tests.

The HBOD Test • The biodegradability of wastewaters entering and leaving every wastewater treatment plant in the country is evaluated using a cumbersome and time-consuming dilution technique developed in the early 1900s called the Biochemical Oxygen Demand (BOD) test. We have developed a new method of determining BOD, called the Headspace BOD (HBOD) test, that is based on sealing known volumes of air in the headspace of test tubes.



Associate Professor Bob Arnold and graduate student Kara Warren study microbial transport through porous media.

Combined Adsorbent-Oxidation Processes • The capabilities of activated carbon to remove a wide range of organic molecules even in dilute solution is well documented. Our research focuses on biological activity on the exterior of activated carbon surfaces, the combinatorial use of sorption and oxidation, both chemically and biologically, and the maximization of the pollutant removal capability of each unit process while minimizing system processing costs.

Oxidative-Reductive Methods for Remediation

Remediation of Chlorinated Groundwater Contaminants via Reductive Dechlorination • Metallic iron may serve as a reductant for the dehalogenation of chlorinated contaminants in aqueous systems. For many contaminants, such as TCE, the available iron surface area limits the rate of

Assistant Professor Kimberly Ogden (right) and PhD student Doug Young determine the rate of degradation of TNT by bacteria.

transformation, and extended contact periods on the order of days are required to achieve practical levels of transformation. By employing high specific surface area iron-impregnated silica gels, and palladized iron in column reactors, the rates of transformation can be increased. This research examines the potential application of these iron-impregnated silica gels and palladized iron for use in in-situ wellbore reactors and surface treatment systems.

Subsurface Remediation Using Air Sparging • The injection of air directly into contaminated aquifers, termed air sparging, can accelerate the rate of aquifer remediation. In laboratory column experiments, we are determining mass transfer coefficients for air sparging by measuring the effects of sparging on remediation times of NAPLs in contaminated porous media.

Membrane Processes • Filtration processes employing microfiltration, ultrafiltration, nanofiltration, and reverse osmosis are subject to fouling with concomitant loss of productivity and permeate quality. Therefore, proper pretreatment of membrane process influent is essential. Reduction in fouling potential by particle electric charge manipulation, partial oxidation of polymeric materials of both natural and man-made origin, and use of various filtration devices will provide the required level of pretreatment. Research into the proper selection and sequence of unit processes is an ongoing area of study.

Chemical/Physical Methods for Remediation

Heterogeneous Catalysis • Adsorbed toxic or hazardous compounds are converted to innocuous compounds using either solar or synthetic illumination to photoexcite surfaces such as semiconductors (*e.g.,* titanium dioxide). Solar parabolic troughs and laboratory-size reactors with ultraviolet lights are employed to study reaction mechanisms. Inactivation of microbials, especially viruses, has been demonstrated to be a viable treatment option in drinking-water production.

Polishing Wastewater Effluents Using Soil-Aquifer Treatment • Indirect potable reuse of treated wastewater is a strategy for meeting projected water supply needs in semiarid regions like the American Southwest. Such reuse relies upon natural biochemical and physical processes that accompany percolation of treated wastewaters through unsaturated sediments and subsequent transport through aquifer material. Work investigates the mechanisms by which soil-aquifer treatment removes and/or transforms residual organics, nitrogen species, and pathogens or indicator organisms from treated wastewater during simulations of soil-aquifer treatment.

Chemical and Biological Destruction of Explosives and Propellants • Demilitarization agreements require the disposal of weapons that contain mixtures of explosives and metals. A combined process involving base hydrolysis and biodegradation is currently being investigated. To date, solid explosives consisting of TNT (2,4,6-trinitro-toluene), HMX (1,3,5,7-tetra-aza-1,3,5,7,tetranitrocyclo octane), and RDX (hexahydro 1,3,5 trinitro 1,3,5 triazine) have been studied.

Recovery and Recycle of Metals • Metals are frequently removed from industrial waste streams with nonselective resins or polymers. Specific water soluble chelators are being developed for recovery of arsenic and proteins. Kinetic binding rates and transport of these chelators in porous media are under investigation.

Combustion-Generated Air Pollutants

NOx Abatement by Combustion Modification • In the combustion of fossil fuels, a large fraction of the NOx originates from fuel-nitrogen, and the fuel stoichiometric ratio plays a major role in determining NOx levels. Research on the fundamental mechanisms of NOx formation has helped elucidate the role stoichiometric ratio plays. Practical control strategies, such as low-NOx burners, reburning, and combined thermal/catalytic methods are being studied and developed.

Thermal Treatment of Hazardous Wastes • Incineration has received substantial negative publicity as a pollution control methodology, in spite of its proven success in treating a large class of hazardous wastes. Research focuses on methods for scaling up models describing gas phase transient mixing. Particular emphasis is placed on products of incomplete combustion (pics) and toxic metals emissions.

Mechanisms and Control of Toxic Metals from Coal Combustion • As with incineration of municipal and hazardous wastes, the combustion of pulverized coal potentially generates airborne toxic metals, particularly from more volatile species such as alkalis, Pb, and Hg. Emissions potential is influenced in part by interactions between the various inorganic constituents in the coal. Additionally, at various stages in the combustion process, inorganic sorbents that interact with more volatile species can be added, rendering those species more easily collectable by conventional pollution control devices.

Pollution Prevention by Industrial Process Modifications

Traditionally, semiconductor manufacturing has been considered a light, modern, and clean industry with little environmental impact. This has led to a high density of this industry in the west and the southwest areas of the US where water is scarce. Until recently, the usage was small and the treatments were considered adequate. But the water usage has increased significantly, and the potential contamination by a variety of chemicals is also increasing.

The long-terms goal of our research program is to develop the tools and techniques needed to overcome the technical obstacles and problems of water recycle. We have presented a systematic and realistic strategy for implementation of water recycling in semiconductor fabs in three "phases" and the research/development plan needed for each phase. The specific objectives are: 1) characterization of key impurity compositions; 2) development of new purification methods for removing recalcitrant impurities; 3) optimization of purification methods in each recycling phase; 4) simulating the dynamics of contaminant distributions and the effect of recycle; 5) recovery and reuse of certain process chemicals.

COURSEWORK IN ENVIRONMENTAL TOPICS

A chemical and environmental engineering department should offer a variety of courses with an environmental emphasis. Both required and elective courses should stress fundamental concepts in chemical engineering. An MS or PhD student in chemical engineering typically begins the program with courses in the fundamental areas of transport phenomena, thermodynamics, and kinetics. Similarly, a student entering the environmental engineering MS or PhD program begins with a set of required courses focusing on transport phenomena, water chemistry, microbiology for hazardous waste treatment, water treatment, wastewater treatment, and water reclamation and reuse. In addition to required courses, a number of elective courses with an environmental focus should be available to students in both programs.

A major research focus of the department has been air pollution and aerosols, and graduate-level courses relating to these fields are regularly offered. The **aerosols course** focuses on those processes that give rise to, and influence the behavior of, particulate pollutants in the atmosphere and in industrial processes. One aspect of the **combustion course** deals with pollutants generated from all types of combustion processes. Finally, the **air pollution course** presents a broad perspective on the atmospheric transport and chemistry of air pollutants.

Another typical focus in an environmental program is biocolloid transport and bioremediation. A course on **biodegradation of hazardous materials** is offered. It discusses the chemical and microbiological considerations that affect the thermodynamics and kinetics of hazardous waste transformations. Two more general biotechnology courses are also offered, one in bioreactor engineering and the other in bioseparations. The **bioreactor course** covers both pharmaceutical applications of bioreactor theory and biodegradation processes. The **bioseparations course** also integrates biotechnology and environmental remediation.

The last area of environmental electives involves environmental policy and law. One course, **Introduction to Hazardous Waste,** covers all aspects of liquid and solid hazardous waste treatment and disposal. Another course, **Law for Engineers and Scientists,** covers a multitude of legal matters important to chemical and environmental engineers.

Faculty routinely offer one-credit seminar courses for graduate students. Recent seminars have been in combustion engineering, bioreactors, bioseparations, ultrapure water and gas, electrochemical transport, and anaerobic respiration by facultative anaerobes.

NEW RESEARCH THRUSTS

In order to bring prominence to a merged chemical and environmental engineering program, it is important to establish an identifiable research thrust on which many of the faculty can focus. One major departmental initiative in the past five years has been in developing the expertise to apply DFE tools to the microelectronics/semiconductor industry. In semiconductor fabrication, the manufacture, use, and final disposition of each device must be considered with regard to its environmental impact. In order to effectively accomplish this, semiconductor device manufacturers must develop a specific set of measurable quantities that define improvements in DFE objectives and develop the expertise (through DFE tools) to assess specific DFE objectives.

At the top of the list of desirable assessment tools for DFE are material and energy balance models. Unlike many other industries, the semiconductor industry is not routinely able to balance energy and material usage around either individual manufacturing tools or around the entire factory. For example, quantitative chemical usage in plasma etch systems is not well understood. While chemical input rates can be readily obtained, estimation of usage within the process and subsequent discharge of unused chemicals or chemical by-products is sometimes difficult. Process models, verified by selected measurements, must be developed in order to reliably close energy and material balances around the individual processes and the fab as a whole.

In addition to developing reliable material and energy balance models, real-time metrology/monitoring methods are also being developed. By so doing, process-specific optimization and control strategies can be incorporated.

FUTURE DIRECTIONS IN EDUCATION

As stated previously, the primary objective in a merger of this type should be to broaden the perspective of undergraduate and graduate students. At the University of Arizona we have an exciting opportunity to be a model that many other chemical engineering departments can follow. In order to enhance the education of our students, we plan on effecting innovations that all have as a common theme the increased integration of the chemical and environmental engineering disciplines. Formal lines delineating the two disciplines will become more and more blurred with time. This change will take place via several avenues:

1. Initiating a minor program in environmental engineering for our BS chemical engineering recipients.

> Based on extended discussion with our Industrial Advisory Committee and their subsequent recommendation, we have decided not to initiate a BS Environmental Engineering program. According to the IAC, BS chemical engineering recipients with an environmental engineering focus would be capable of tackling a broader range of problems in industry than students with the more focused environmental engineering degree. A four-course environmental engineering option is already available within a BS chemical engineering program at UA, and a minor will be available within the next academic year.

2. Offering more core chemical engineering courses taught by the environmental engineering faculty and more environmental engineering courses taught by the chemical engineering faculty.

> Our level of educational success and effectiveness will depend on a paradigm shift in the attitude of our faculty, e.g., a shift that eliminates the mindset dictating that chemical engineers teach only chemical engineering courses and environmental engineers teach only environmental engineering courses. An open and receptive attitude toward these changes prevails in our relatively young department and faculty.

3. Increasing the number of joint projects that involve both chemical and environmental engineering students and faculty.

> Already a number of faculty from both sides have successfully proposed collaborative research projects. The two most recently funded joint efforts involve work on Superfund (supported by NIEHS) and on bacterial transport in porous media (supported by DOE). These joint projects afford a number of positive benefits to the education of our students and to the quality of our research program. First, students are exposed to the systems approach to research in which different perspectives are brought to the table in order to solve an engineering problem. Second, students have the opportunity to perform research in teams and to gain that experience in academia before entering industry. Finally, our current projects have benefited in terms of the way research results are analyzed and additional insight is gained through the collaboration between chemical and environmental engineers.

4. Expanding our seminar series that focuses on environmental concerns in chemical engineering design.

> For the past two years our weekly seminar series has been equally populated by chemical and environmental engineering speakers. This year, particular topical emphasis will be given to areas such as environmental concerns in the microelectronics industry since the bulk of this industry is located in the southwestern United States, and much of our ongoing environmental research is applied to this industry.

SUMMARY

The combination of chemical and environmental engineering is indeed a logical decision. Our department has already seen added benefits by formalizing the tie between the two disciplines. Benefits from this merger include an increase in the number of research projects involving joint supervision of students, a breakdown of the artificial barriers that often typically exist between departments (*i.e.,* barriers that inhibit communication and a free flow of ideas), and a blending of the teaching responsibilities between the chemical and environmental engineering faculty.

At the beginning of this article we asked a number of questions regarding the role of chemical engineering in an environmental engineering education. We have tried to show that environmental engineering can be an ideal complementary discipline for the chemical engineer, both at the undergraduate and graduate levels. At the undergraduate level, chemical engineering students are exposed to environmental concerns in the design process and learn to incorporate these factors from the outset. At the graduate level, the additional perspective gained by chemical and environmental engineers addressing the same research problem is invaluable. Core subjects, in our opinion, expose students to the principles of water and wastewater treatment, air pollution, hazardous waste treatment, environmental biology, and environmental transport phenomena.

We believe that the formation of a Chemical and Environmental Engineering Department at the University of Arizona presents unique opportunities to significantly influence the education of our students. Additionally, our program can serve as a model for change in terms of the role of environmental concerns in chemical engineering design and process control and the education of environmental engineers from a chemical engineering perspective. ❐