CAPSTONE CHEMICAL PRODUCT AND PROCESS DESIGN COURSES: INDUSTRY-FACULTY INTERACTIONS

by

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ABSTRACT

The key role of *industrial consultants* in the capstone chemical product and processe design courses at Penn is described. Emphasis is placed on the timely design-problem statements they prepare and the advice they provide during the spring design-projects course. Also, the role of adjunct professors is reviewed. Several important industrial impacts are described over the past 65 years. Next, the interactions between many faculty advisors, who are not normally design-oriented, and our industrial consultants are examined. In several cases, these lead to product design-oriented projects, closely related to the research and teaching of our young faculty. Finally, the practices in other engineering disciplines at Penn and elsewhere are considered, with emphasis on the pedagogical constraints and practical limitations that prevent their adoption in our design courses.

INTRODUCTION

"Industrial Consultants" have helped teach chemical product and process design at Penn for approximately 65 years. This is in large-part due to the proximity of many chemical companies within or near Philadelphia, many of which are located along the Delaware River.

Two required design courses are taught at the senior level. The fall course, CBE 400, Introduction to Product and Process Design, is a lecture course, with many homework assignments, that introduces product and process design. It covers many of the topics in the textbook: Seider, W. D., J. D. Seader, D. R. Lewin, and S. Widagdo, *Product and Process Design Principles: Synthesis, Analysis, and Evaluation*, 3rd Ed., Wiley, 2009.

The spring course, CBE 459, Chemical Product and Process System Design Projects, has been devoted entirely to the solution of design problems in groups of three or four students. Timely problems are provided mostly by *industrial consultants* from the local chemical industry who visit Penn on Tuesday afternoons to assist our students throughout the spring semester. In recent years, as the focus has shifted somewhat from process toward product design, several of our young faculty have been providing design projects.

In the academic year, 2010-2011, our industrial consultants and faculty provided 14 projects, 11 of which were solved by 11 design groups. Our students were presented with all of the project statements and were provided the opportunity to bid on their first four choices. Within the limits of student schedules and preferences, we have done our best over many years to accommodate all. It is impossible to provide their first choice in every case as several projects are more appealing to the students than others. This often depends on what the student intends to pursue for a career after graduation. Each of the design groups was advised by a different faculty member. Throughout the spring semester, the design groups met weekly, on Tuesday afternoons for one hour, with their faculty advisors and one of our industrial consultants. Also, Adjunct Professor Len Fabiano assisted the design groups individually by appointment on Tuesday mornings and on Fridays all day, in addition to answering questions posed by e-mail throughout the week.

Near the end of each spring semester, the design groups submit a draft of their written design reports to their faculty advisors, who provide critiques. One week later, their final written reports are submitted to Professor Fabiano, who provides a detailed written critique and suggests a grade. One week later, all design groups make a 35-minute presentation (including 5 min for questions) to our industrial consultants, faculty, and fellow students. Other undergraduate students are encouraged to attend one or more of the presentations as a preview of what to expect in their senior year. Both our industrial consultants and faculty suggest grades for the oral presentations. Subsequently, Professor Fabiano and the faculty advisors decide on course grades. At the end of the semester, all of the design reports are bound and placed in the School of Engineering and Applied Science Library. Using Interlibrary Loans, many are borrowed by faculty and practitioners worldwide. Note that over the past three years, PDF files have also been circulated when requested.

Since 1978, the Melvin C. Molstad Prize has been awarded annually to the most outstanding design group(s) in the senior class. Also, since 2000, three of our best design groups have competed in the Engineering Alumni Design Competition. Finally, on many occasions, our best design has won the Zeisberg Award of our AIChE Delaware Valley Section, in competition with entries from schools in the Southeast Pennsylvania region.

More information on our design courses is provided on the web site: www.seas.upenn.edu/~seider/design.html.

Design Preparation Prior to the Senior Year

Throughout our curriculum, opportunities are sought to introduce design approaches and techniques that expose our students to the solution of open-ended design problems, and especially, to introduce them to widely-used design software packages, such as ASPEN PLUS and SUPERPRO DESIGNER. We begin at the freshman level in CBE 160, Introduction to Chemical Engineering, in which our students are introduced to the synthesis of process flowsheets and the importance of recycle, among other subjects, using ASPEN PLUS to perform the extensive calculations. At the sophomore level, in CBE 231, Thermodynamics, our students learn multiphase chemical equilibria, which are the basis for many design calculations. Then, as juniors, in CBE 350, Fluid Mechanics, the concepts of fluid mechanics are applied for the calculation of pressure drops and the design of piping networks. In CBE 371, Separation Processes, our students learn to design binary and multicomponent separation towers, also using ASPEN PLUS, among other separation processes. In CBE 351, Heat and Mass Transport, our students learn the basics of heat and mass transfer, which are applied for the design of heat and mass exchangers in CBE 400 and 459. At the senior level, in CBE 451, Chemical Reactor Design, our students learn to design CSTRs and PFTRs in several open-ended problems. Finally, in CBE 460, Chemical Process Control, our students learn to design feedback control systems to achieve performance specifications. [Note the availability of self-paced multi-media instructional materials that teach the usage of ASPEN PLUS by example. These can be downloaded from the Wiley web site associated with the Seider et al. textbook – http://www.wiley.com/WileyCDA/WileyTitle/productCd-EHEP000024.html. Click on Using Process Simulators in Chemical Engineering Software in the Instructor or Student Companion sites.]

Our industrial consultants and faculty then provide guidance and insights to help our students apply these fundamentals in their project solutions. Without the participation of our consultants, students would otherwise learn their practical applications after they join industry. Our course provides our students with a head start.

INDUSTRIAL CONSULTANTS

Over the past 65 years, we have been fortunate to involve many chemical engineers from the chemical industry, our so-called *industrial consultants*, as introduced above. Just since 1980, these persons have included:

Rakesh Agrawal	Air Products and Chemicals
E. Robert Becker	Environex, Wayne, PA
David D. Brengel	Air Products and Chemicals
Adam A. Brostow	Air Products and Chemicals
Robert M. Busche	Bio-en-gene-er Associates, Wilmington, DE
Brian K. Downey	Equity Res. – U.S. Oil and Gas Explor./Prod.
Leonard A. Fabiano	Consultant (formerly ARCO Chem., Lyondell, CDI Corp.)
Brian E. Farrell	Air Products and Chemicals
Mike Herron	Air Products and Chemicals
F. Miles Julian	DuPont
Arnold Kivnick	Pennwalt Corp.
David M. Kolesar	Dow (formerly ARCO Chem., Rohm & Haas)
Selma Kwok	Exxon/Mobil
Ralph N. Miller	DuPont
Robert Nedwick	Penn. State Univ. (formerly ARCO Chem. and Lyondell)
Frank Petrocelli	Air Products and Chemicals
Mark R. Pillarella	Air Products and Chemicals
Matthew J. Quale	Mobil Technology Company
Tiffany Rau	GlaxoSmithKline and Pall Corp.
William B. Retallick	Consultant, West Chester, PA
Wayne Robbins	Consultant (formerly DuPont)
Gary Sawyer	Lyondell Chemical Company
David G. R. Short	University of Delaware (formerly DuPont)
Peter Staffeld	Exxon/Mobil
Albert Stella	General Electric (formerly AlliedSignal)
Edward H. Steve	CDI Engineering Group
Steven M. Tieri	DuPont
Bjorn D. Tyreus	DuPont
Kamesh G. Venugopal	Air Products and Chemicals
Bruce M. Vrana	DuPont
Andrew Wang	Air Products and Chemicals
Steve Webb	Air Products and Chemicals
John A. Wismer	Arkema, Inc. (formerly Atochem North America)
Jianguo Xu	Air Products and Chemicals

Many were students at Penn. Len Fabiano, Arnold Kivnick, and Bill Retallick, served, or are still serving, as industrial consultants for over 30 years. Bruce Vrana is approaching his 18th year. Among their many contributions, described below, our consultants add insights to the fundamentals covered by our faculty in their engineering science courses.

It is significant to note that over the past 30-65 years the advent of rigorous simulation and design software has evolved from the 1950's through today. The transformation to a high degree of rigor over this period is well appreciated by all. Our industrial consultants bring a high value to the students in the realistic and practical application of these software packages.

The normal role of an industrial consultant is to visit Penn on alternate Tuesday afternoons during the spring semester; i.e., 5 visits, in addition to attending our Senior Design Presentation day at the end of the semester. Fortunately, many also contribute design problem statements – usually, in 2-3 pages. We seek, and normally receive, design problems that are timely, challenging, and have the *strong likelihood that their final designs will be economically attractive* – recognizing that student motivation and faculty enthusiasm are closely related to the feasibility and potential impact of the final designs. We request that the authors try to assure their problems are workable by undergraduate seniors without unduly gross assumptions – and, to the extent possible, that good sources of data are available for reaction kinetics and thermophysical and transport properties. We also request a few references; preferably providing an overview of the design problem and sources of data.

A PDF file, Appendix IIS.pdf, has been prepared that contains some of the best problem statements provided by our industrial consultants and faculty – a total of 71 design projects. [Note: This file is available from the Wiley web site associated with the Seider et al. textbook – http://www.wiley.com/WileyCDA/WileyTitle/productCd-EHEP000024.html. See the PDF files in the Instructor or Student Companion sites.] Some provide relatively little information, whereas others are fairly detailed concerning specific problems to be solved to complete the design. The reader should recognize that, in nearly every case, as the design team proceeded to assess the problem statement and carry out a literature search, the specific problems it formulated were somewhat different than originally stated. Still, these problem statements should be useful to students and faculty in several respects. For students, they should help to show the broad spectrum of design problems that chemical engineers have been tackling in recent years. For faculty, they should provide a basis for similar design projects to be created for their courses.

As seen in the contents, the projects have been assigned to one of the following areas, in some cases arbitrarily: Petrochemicals, Petroleum Products, Gas Manufacture, Foods, Pharmaceuticals, Biomedical, Polymers, Electronic Materials, and Environmental.

It is noteworthy that there have been occasions wherein exceptionally motivated students have recommended projects for themselves and for approval by the faculty. These specific cases have been very successful.

ADJUNCT FACULTY

Two Adjunct Faculty, who spent most of their careers in industry (over 30 years each), Dr. Arnold Kivnick and Mr. Leonard A. Fabiano, have played key roles in our design courses, beginning with the former in 1988 (retired in 2000), followed by the latter since then. Each year, both presented a few (approx. five) lectures in the fall and devoted approx. two days weekly during the spring project course. For this, they received small remunerations, unlike our other industrial consultants who received no fees. Note that funds were not provided to cover the costs of the student designs, with the exception of small allocations for printing their final design reports prior to binding in our School of Engineering and Applied Science Library.

Arnold Kivnick

The career of Arnold Kivnick was *pioneering* in product and process design at Penn. Upon receiving his Ph.D. at Penn in 1956, Arnold was employed by the Pennwalt

Corporation. At that time, he also began advising and working with our senior design groups – as one of our first industrial consultants. Throughout his 32 years at Pennwalt, Arnold served as one of our most faithful consultants. Subsequently, upon retiring from Pennwalt in 1988, Arnold became our first Adjunct Professor, assigned to work with our senior design groups, two days weekly in the spring throughout our design projects course, CBE 459. Arnold brought the experience of a seasoned process engineer and the passion of an engineer seeking to find the best solutions to process design problems. His unique style encouraged our student groups to achieve their best designs in a simulated industrial setting. Arnold successfully motivated our student groups to play the role of successful practicing engineers in industry. Our alumni recall him as stimulating them to achieve at levels far beyond their expectations using sound judgment and teamwork.

Len Fabiano

Upon the retirement of Arnold Kivnick in 2000, our department was very fortunate Len Fabiano was available to follow in Arnold's footsteps. After earning his B.S. degree in chemical engineering from Purdue University, Len worked toward his M.E. (Chemical) degree from the Stevens Institute of Technology. Then, he spent many years in industry, gaining experience in a broad range of cryogenics at Air Products and Chemicals, in petrochemicals at M. W. Kellogg Engineering Company, in organic and inorganic chemicals at Olin Chemical Corp., and in first-of-a-kind process technology commercialization at ARCO Chemical Company.

In many respects, like Arnold, Len has successfully shared his enthusiasm for process engineering with our students and faculty. For over 10 years, he too has stimulated our students to achieve at very high levels. It is notable that for over 30 years, Len was among the industry leaders promoting the development of process simulators. He became very proficient in their use and has provided our students with the assistance and guidance they have needed to apply them effectively. Also, he has continued to hone his process engineering skills as an active private consultant to the chemical industry.

INDUSTRIAL IMPACTS

The impacts of our industrial consultants over the past 30 years are exemplified by the contributions of several persons, a few of which are reviewed briefly in this section.

Bruce Vrana

Year after year, Bruce Vrana has provided 3-4 challenging projects, all of which are related to topical technologies. In recent years his focus has been on chemicals from renewable resources. While the technologies often parallel DuPont emphases, he gracefully avoids approaches specifically being pursued by DuPont. Also, Bruce has mentored Steve Tieri, his young colleague at DuPont, who graduated from Penn in 1998, and now provides a fresh outlook for our students as an industrial consultant.

Bruce brings over 30 years of experience to our students and does so in a very knowledgeable and creative way. He conveys much information to students working on his recommended projects, as well as to those working on other projects. Like our other consultants, he often communicates with our students as needed from his DuPont office.

William B. Retallick

Over 30 years, prior to stepping down in 2009, Bill Retallick's problem statements involved an array of timely subjects, including: combustion in gas turbines, recovery of waste energy, and natural gas and coal processing. His valuable experiences at Philips Petroleum (1948-1950), Consolidated Coal Research (1953-1964), Air Products and

Chemicals (1964-1974), and Oxy Catalyst (1974-1980), often enabled him to help our student groups achieve sound, practical designs.

Bill had a unique way of challenging our students while providing guidance – often responding to questions with insightful questions that challenged our students to reason with him as they gained insights leading to answers.

<u>John A. Wismer</u>

John Wismer, a 1978 Penn graduate, gained extensive process engineering experience at Arkema, Inc. As one of our industrial consultants, he analyzes student questions quickly and effectively, offering sound advice and direction – often recognizing less fruitful directions and helping to re-orient student groups on a proper route. He, also, is very skilled in the application of design software, often helping student groups recognize problems and achieve better results.

Most notably, especially in recent years, is the scope and timeliness of the projects John provides for our student groups – often involving cutting-edge technologies, such as micro-channel reactors for the conversion of natural gas to liquids, the growth and conversion of algae to alkanes, and the conversion of shale gas to liquids. His commitment to providing help, at group meetings or from his office, is well-recognized by our faculty and totally appreciated by our student groups.

Adam A. Brostow

Adam Brostow, at Air Products and Chemicals, brings a different bent to his project proposals and guidance – often involving cryogenic processes with heat and power integration challenges, resulting in unusual refrigeration and power-generation cycles. Adam is an active participant in *Engineers Without Borders*, traveling extensively to assist in developing countries. Also, Adam strives to achieve a novel TRIZ approach to design synthesis – one involving functional analysis and trimming. In short, Adam is our most "out-of-the-box" consultant, bringing new problems and perspectives to our student groups.

David M. Kolesar

Over the past two decades, at ARCO Chemical Company and Rohm and Haas/Dow Chemical, Dave Kolesar has achieved great expertise in the application of the *Aspen Engineering Suite* – both for steady-state and dynamic process simulations. Of our industrial consultants, Dave provides the last line of defense when simulation problems remain unresolved. Also, student groups welcome his expertise in helping to analyze their processes, both in their design meetings or from his office.

Tiffany Rau

Having received her B. S. Degree at Penn in 2003, Tiffany Rau worked toward her Ph.D. degree at Vanderbilt University in the biotechnology area. Subsequently, she worked at GlaxoSmithKline, as a process engineer, before joining the Pall Corporation in new-product development. Over the past 65 years, to our knowledge, Tiffany is our first industrial consultant from the pharmaceutical industry. She has formulated challenging problems involving batch scheduling in the design of pharmaceutical processes. Her unique background and perspectives have been a welcome addition to our design-projects course – one we hope others will emulate in future years. Her working knowledge of pharmaceutical processes has helped our students better understand their design projects and obtain effective solutions.

FACULTY ADVISORS

At Penn, over the past 65 years, most faculty members have served as advisors for one of our senior design groups each year – both young and senior faculty.

Young Faculty

Like most chemical engineering departments, in recent years, young faculty have had little experience in process design – rather the emphasis in their research has been biased towards small length and time-scales, often involving nano-structures, biotechnology, and materials technology. Upon first arriving at Penn, many are assigned to advise design groups working on large-scale, commodity chemical processes. Here, our industrial consultants play an important role – providing answers to questions and advice when our young faculty are less able to do so. A related benefit of these interactions gives these faculty an appreciation of the need to cover various subjects in their courses that prepare our students to carry out process designs.

Over the past decade, with our encouragement, several young faculty have preferred to author problem statements that are product-design oriented – more closely related to their research interests. In this section, we briefly review a few successes by our young faculty.

Scott L. Diamond – After advising a group on the design of a hydrogen process during his first year in 1999, Scott Diamond, an expert in biomolecular engineering, transport processes, and systems biology, proposed a project to design a process to manufacture 80 Kg/year of the pharmaceutical, tissue plasminogen activator, tPA. In this and subsequent projects prepared by Scott, our student groups designed the processing equipment and used batch process simulators, such as SUPERPRO DESIGNER, to create operating schedules without bottlenecks. In yet another project, a student group designed and built, in Scott's laboratory, an electronic device and disposable microfluidic chip that determines a patient's resistance to the anti-clotting drug, Plavix, using a small blood sample. These product-design projects are more closely aligned with Scott's research and teaching.

John C. Crocker – During the past decade, John Crocker has created design projects closely related to his applied–physics, biomolecular expertise. Two of his projects involved the design of labs-on-a-chip to carry out the high-throughput screening of millions of potential "small molecule" kinase inhibitors. The first used Fluidigm soft lithography to assay 1,000 candidate inhibitors daily. The second, just one-year later, used Raindance emulsion guns that create 20,000 aqueous droplets per second – increasing the assay rate to 1 million per day. John's groups have also designed strategies for inexpensively carrying out analyses of the human genome – by decomposing DNA strands and sequencing their base-pair structures. Unfortunately, the lack of time and funds have precluded the testing of these strategies.

Talid Sinno – Having carried out his doctoral research on the growth of single crystals in Czochralski crystallization, Talid Sinno focuses on transport phenomena in micro-structures. Over the past decade, Talid formulated projects involving CZ crystallization and physical vapor deposition. Three of his most recent projects used kinetic Monte-Carlo (kMC) techniques to simulate the adsorption, diffusion, and desorption of molecules on substrate surfaces. In each case, student groups have developed software products to assist chip-designers in achieving specified film thickness, roughness, and porosity. These specifications are needed to manufacture chips with surfaces that accommodate dense integrated circuits.

Matt Lazzara – Yet another specialist in the bio-transport area, Matt Lazzara, who focuses on cellular engineering, created a project for a student group to assist in the design of microfilters to separate specific biochemical mixtures. His group created computational models, using MATLAB and COMSOL, which when combined with experimental data determine unknown hindered-convective and diffusive coefficients of client-supplied test ultrafilter materials. Using these models, his group created a small startup company to provide more accurate predictions of filter behavior, thereby allowing its clients to optimize more effectively their filter operating parameters. Here, also, a software product was designed closely related to the research and teaching of a young professor.

Senior Faculty

Most of our senior faculty have continued to advise groups working on process design-oriented projects suggested by our industrial consultants, although they too have been encouraged to provide product design-oriented projects more closely related to their research and teaching, when appropriate. One of our faculty deserves a special note.

Stuart W. Churchill. Required to retire from our standing faculty in 1990, at age 70, Stuart has continued his research actively and teaching less actively over the past 21 years. While not teaching formal lecture courses, he continues enthusiastically to advise one of our senior design groups. Throughout his career, the breadth of his perspective has extended far beyond that of most engineering science researchers. He understands the importance of teaching students how to translate engineering science principles into process and product designs that satisfy consumer needs – and to seek designs that optimize profitability in the face of uncertainty. This perspective has been at the foundation of our two design courses.

PEDAGOGICAL CONSTRAINTS AND PRACTICAL LIMITATIONS

To carry out more comprehensive product and process designs, like the other departments in our School of Engineering and Applied Science at Penn, it seems clear that two semesters are very helpful, providing student groups approximately eight months of project time. This, however, cannot be justified in our chemical and biomolecular engineering curriculum, which is typical of most chemical engineering curricula in the United States. Its array of nine required engineering-science courses present the fundamentals of material and energy balances, thermodynamics, fluid mechanics, heat and mass transport, separation processes, chemical-reactor design, and chemical-process control. As mentioned in the *Introduction*, we seek opportunities to include open-ended, design-oriented problem solving in these courses, but are successful to just a limited extent. Our design lecture course, CBE 400, at the senior level, is needed to teach approaches to designing chemical products and processes. This course places emphasis on synthesizing trees of design alternatives, using process simulators for analyses of the most promising alternatives, and using detailed equipment design and cost estimation procedures. Only after this comprehensive course, with its many homework exercises, are our students prepared to tackle their design projects in the spring.

Given just 12 weeks (three months) to carry out their designs, it's normally not possible to undertake laboratory experiments and create working product and process prototypes – and would not likely become possible if industrial or government funding sources were to become available. Consequently, the emphasis of our design projects is on finding the best design alternative through analysis and simple optimization using profitability measures.

Increasingly, our design projects would benefit from the contributions of students in the other engineering disciplines. For example, students in bio-informatics and computer science would help significantly in the human-genome project, and students in material science and mechanical engineering would contribute to the project to deposit thin films on integrated-circuit substrates.

Also, it would be possible to create collaborations with various companies involving the solution of their design problems. With their financial support, funds would be provided for travel, equipment, experiments, and other specific needs. Our student groups would visit the companies and interact with scientists and engineers when solving their design projects. But here, also, the demands of our chemical engineering curriculum would preclude such an involvement without adding a co-op type semester to our 4-year curriculum.

In summary, the demands of the chemical engineering curriculum, which marries chemistry, biology, and physics with engineering principles, constrain our design offerings. Less time is available to solve design problems, the preparation of design prototypes is normally not possible, and the scheduling of interdisciplinary design groups has not yet been possible.

CONCLUDING REMARKS

The close interactions between our industrial consultants, faculty, and students in our capstone design courses have been exemplary, stimulating the creation of many innovative product and process designs over many years. Most student groups rise to the challenge, producing innovative and profitable designs far beyond those anticipated by undergraduate seniors. Some have even presented their results in papers at AIChE Meetings. Our consultants often bring timely design problems and provide advice and answer questions that help our students find good solutions. Increasingly, our faculty create timely problems related to their research and teaching interests. Here, our consultants often generate questions that lead our students to explain their design decisions more clearly. Either way, these synergistic interactions often stimulate the creation of very innovative designs. Our students often finish *strong* having created designs beyond their expectations, and having completed a *simulated* industrial design experience!