PROCESS DESIGN CURRICULUM AT PENN

Adapting for the 1990s

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It has long been the custom to require chemical engineering undergraduates to design a chemical plant or some similar entity. Such a requirement serves at least two purposes: one, to impose upon the students the need to use the theoretical knowledge to which they have been exposed in their course work in a more nearly practical setting than is usual in the normal course of study, and two, to acclimate them to the kinds of designs and economic analyses which many of them will be called on to perform when they enter industry.

There is another purpose, particularly important in view of the current emphasis on engineering science in the curriculum. Many students choose to study engineering because they want "hands-on" exposure to practical problems—in contrast to the idealized versions which scientists often solve. But because there is so much information the students must assimilate and master, the curriculum tends to reinforce the need for generalization and hence for mathematical expression and manipulation of that information. Inadvertently, this draws the students away from the practical problems that attracted them into engineering in the first place.

It is very difficult to strike a satisfactory balance between a thorough grounding in the basics (physics, chemistry, mathematics, and the scientific disciplines derived therefrom) on the one hand, and on the other the descriptive material concerning filters, pumps, boilers, tanks, reactors, towers, heat exchangers, and the myriad objects which make up the engineer's world. This search for balance is our justification for attempting to have the plant-design course make up, in part, for the "hands-on" courses (machine shop, engineering laboratories, plant visits) which have been curtailed or dropped entirely from the curriculum.

Most educational emphasis is, quite properly, on the work of the individual. Yet, much of modern industry functions through the work of *teams*, and only rarely does an individual work alone on a project. To prepare students for this fact of industrial life, design projects are assigned to groups of students (two or three at most) who must organize the job, subdivide the effort among themselves, function effectively as a team to execute the design, prepare the written report, and deliver the oral presentation. On a few rare occasions, this has even meant that one or two members of a team had to take over the responsibilities previously assigned to others who had either fallen short or dropped out of the group. This scenario is recognized by any engineer who has been part of an industrial organization; just as in the theater "the show must go on," a working engineer knows that the job must be done—by whoever is around to do it.

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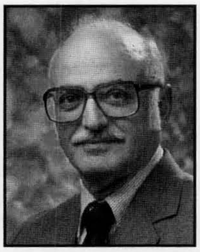

__Arnold Kivnick__ is an adjunct professor of chemical engineering at the University of Pennsylvania, and is resident consultant to students in the plant design course. He received both his BS and PhD degree at Penn, and prior to retirement his industrial career was largely at the Pennwalt Corporation. His areas of interest there were process engineering, process evaluation, and start-ups and trouble shooting.

Thus, the design project is more than just another course offering; it is the logical conclusion of the undergraduate chemical engineer's education, embodying a major part of the material covered in all the previous chemical engineering courses and demanding (and hopefully inculcating) skills and disciplines which the student has rarely needed previously. At Penn, and at many other schools, both written and oral reports are treated as if they were industrial reports—in effect, the results of the students' first job in "industry."

As a result of a recent ABET decision to provide flexibility in design instruction, many curricula can be expected to shift emphasis toward a more comprehensive design experience at the senior level. Furthermore, as computers enable students to solve more open-ended problems throughout the curriculum, it should be possible to provide a more formal treatment of the design approach at the senior level. A senior-level two-course sequence has been offered in chemical engineering for many years at Penn, as well as at other schools, and now other departments will likely consider such a sequence.

FALL LECTURE COURSE

The objective of the fall lecture course is to provide a smooth transition into the spring design project. In previous courses (which emphasized the engineering sciences) the students have been exposed to design techniques through the solution of several open-ended problems, often using the computer, but they have not yet received training in a systematic approach to process synthesis, the use of flowsheet simulators in process synthesis, or the application of economic principles in venture analysis. These and other related subjects are covered in the fall lectures and are accompanied by numerous homework problems (summarized in Table 1).

The course begins with an introduction to process synthesis as described by Seider.[1] To summarize briefly: through a case study we introduce the synthesis of reaction paths, the distribution of chemicals, the synthesis of separation trains, the synthesis of networks of heat exchangers, the insertion of power-related units (pumps, compressors, and turbines), and task integration. Then we introduce the ASPEN PLUS simulator, with emphasis on the synthesis of the reactor section of a chemical plant followed by a separation train. Here also, we use the approach described by Seider.

With one-third of the semester completed, including the solution of three problems with ASPEN PLUS, we then undertake a more formal coverage of process synthesis. We present heuristics for the design of individual separators, together with the tree of separation-train alternatives, and then describe the ordered-branch search strategy of Rodrigo and Seader[2] and solve an illustrative problem.

TABLE 1
Outline of Topics: Fall Lecture Course

	Lecture Hours
• Introduction to process synthesis	3
• Flowsheet simulation using ASPEN PLUS	11
• Synthesis of separation trains	2
• Thermodynamic efficiency and lost work	5
• Heat and power integration	4
• Heat exchanger design	2
• Capital cost estimation	1
• Profitability analysis	6
• Selection of design projects (for spring project course)	2
TOTAL	36

> ***As a result of a recent ABET decision to provide flexibility in design instruction, many curricula can be expected to shift emphasis toward a more comprehensive design experience at the senior level. A senior-level two-course sequence has been offered . . .for many years at Penn***

We next review the concepts of thermodynamic availability according to Chapter 1 of an excellent monograph titled *Availability (Exergy) Analysis: A Self-Instruction Manual,*[3] and follow that by covering thermodynamic efficiency and lost-work analysis using another excellent monograph, *Thermodynamic Efficiency of Chemical Processes.*[4] The latter concentrates on refrigeration cycles (which most students do not study in their thermodynamics courses) as well as distillation. The principal sources of lost work are identified, and the students design a refrigerator that significantly reduces the sources of lost work.

This leads naturally into the synthesis of networks of heat exchangers, as well as heat and power integration. First, we discuss the methods that minimize the use of external utilities, including the temperature-interval method[5] and the graphical approach for identifying the "pinch" temperatures. We solve a problem using the TARGET II program,[6] and then cover the methods of stream-matching (beginning at the pinch temperatures) as recommended by Linnhoff and Hindmarsh.[7] Finally, the heat loops are broken and we examine the effect of heat being exchanged across the pinch temperatures. Here also the students design a network of heat exchangers.

Since in the synthesis of a process the analysis of individual units often involves approximations (*e.g.,* an overall heat-transfer coefficient), for costly units it is important to check the approximations by developing a more rigorous model. We demonstrate this procedure for the design of a shell-and-tube heat exchanger for which the heat transfer resistances and pressure drops are adjusted through the details of the tube bundle and the baffle spacing. Chapter 14 of *Plant Design and Economics for Chemical Engineers*[8] provides excellent coverage of the design procedures, and these procedures are used by the students to design a multi-pass heat exchanger.

Throughout the course there is a need to estimate capital and operating costs, in addition to the simpler measures of profitability such as venture profit and "annualized" cost. Detailed cost and profitability calculations, however, are postponed until the topics on process synthesis have been completed, approximately two-thirds into the semester. At this point, we cover the factored methods of capital cost estimation, using Chapter 5 of *A Guide to Chemical Engineering Process Design and Economics.*[9] The students are also introduced to the implementation of these methods in

ASPEN PLUS. Then the students learn the principles of venture analysis through a four-lecture sequence by Adjunct Professor R. M. Busche. They estimate the fixed capital investment and a cost sheet for a fermentation flowsheet, and compute the cash flows as well as the net present value and the internal return on investment. Dr. Busche also introduces his CASH'92 spreadsheet program, which the students may use to carry out similar calculations for their spring-semester design projects.

The fall lecture course concludes with scheduling of the senior design projects and the presentation of instructions for executing the projects during the following spring. The nature of the design projects and the format of the spring course are discussed in the next sections.

We do not require the students to purchase a textbook for the lecture course since there is no existing text that follows the sequence in which process synthesis and flowsheet simulation are intertwined. Although a text by Douglas, *The Conceptual Design of Chemical Processes,*[10] is excellent in its presentation of a hierarchical design strategy using many heuristics, it does not readily accommodate the sequence in Table 1. The heuristics are helpful, however, and are shared with the students throughout the fall semester.

SUBJECTS FOR DESIGN PROJECTS

During the fall semester we invite industrial consultants to suggest ideas for projects that can be undertaken in the spring semester. Interested faculty members and the students themselves occasionally suggest projects. The processes are expected to be timely, challenging, and offer a reasonable likelihood that the final design will be economically attractive. We remind the project originators that student motivation and faculty enthusiasm are directly related to the feasibility and potential impact of the final designs. Potential problems should be workable by seniors without unduly gross assumptions, good sources of data should exist for the reaction kinetics and thermophysical and transport properties, and pertinent references should be provided. In a recent project involving the reactive distillation of mixtures with many azeotropes, ARCO provided the thermophysical property data for the ASPEN PLUS simulator. With the approval of the course organizers, the students signed a nondisclosure agreement not to share the data with others.

After a process of winnowing, we prepare an approved list of projects which includes one or two more than the required number. In making a selection, each team rates each project on the list as a first-through-fourth choice, and whenever possible, we then give the team its first or second choice. If none of its choices are available, the team is simply assigned a topic by the professor in charge of the course. The pedagogical justification behind this practice is that junior engineers in industry do not have the luxury of picking jobs; they are simply assigned jobs as the jobs come up, and will be expected to do the best they can with the assignments they are given.

The design projects reflect the current interests of the people who suggest them. In some cases the projects do not involve the design of a chemical plant (*e.g.,* the design of a heat-exchange system for a fast-breeder nuclear reactor, or of a heart-lung machine). Such projects demand assistance from consultants with specific experience in the pertinent field, and obviously such problems cannot be assigned unless consultants with that specific experience can be found.

Every design problem incorporates a requirement that environmental and safety issues be taken into account. We take note of all possible waste materials and investigate the means and cost of their disposal. We are placing increased emphasis on the cost of energy, on designs which avoid or minimize handling of hazardous chemicals, and on protection against processing accidents. We note that increasingly, projects are directly related to environmental issues; *e.g.,* the design of a tetrahydrofuran plant to achieve "zero emissions," the reduction of NOX in boiler-stack discharges, and the partial recovery of the carbon content of CO_2 from power-plant off-gases.

Table 2 lists some project titles from 1960 through 1993—the time-dependent interest in space exploration, nuclear-power generation, medical technology, ecology, and improved energy efficiency, as well as a variety of chemical or

TABLE 2

Selected Design-Project Subjects Through the Years*

<1970	Liquid-Metal Heat Exchanger: Fast Breeder Nuclear Reactor
<1970	Recovery of Minerals from a Lunar Station
<1970	Design of a Heart-Lung Machine
<1970	Recovery of Solar Energy by Hot-Water Solar Panels
1979	Conversion of Methanol to Gasoline in a Fluid Bed Reactor
1981	Manufacture of MTBE Anti-Knock Additive
1982	Pressure-Swing Adsorption for Separation of Air
1983	Heat Pump for Ethane-Ethylene Split
1984	Heat and Power Integration for Manufacture of Propylene Oxide
1985	Scleroglucan Biopolymer for Enhanced Oil Recovery
1985	Helium Recovery from Natural Gas
1986	Cogeneration Flue Gas Cleanup
1987	Groundwater Cleanup and Organics Incineration
1988	Thermally-Stable Amylase Enzymes
1989	Gas Processing for Ethane Recovery
1990	Ammonia Purification by Refrigeration and Membrane Processing
1991	Zero Emissions from a Tetrahydrofuran Plant
1992	Itaconic Acid by Fermentation
1992	Ultra-High Purity Oxygen Manufacture
1993	MTBE Manufacture

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* *See "Process Design Projects at Penn: 100 Problem Statements," available from W.D. Seider.*

petrochemical processes, is immediately evident. We have compiled a report, "Process Design Projects at Penn: 100 Problem Statements," in which over one hundred project descriptions (each about one page in length) presented to our seniors over a period of twelve years are included. This report is available from the authors, as are many of the design reports.

INDUSTRIAL CONSULTANTS

No chemical engineering department has on staff experts in every aspect of plant design. The progenitors of the plant design course at Penn, the late Professor Melvin C. Molstad and A. Norman Hixson, both had ample industrial experience before and during their academic careers, but it was obvious to them that the students' efforts would be greatly enhanced by exposure to other engineers in addition to the Penn faculty. Since the Delaware Valley is home to many companies in the chemical processing industries and to the consulting engineers, contractors, and equipment vendors who serve them, we have been able to secure the volunteer services of a body of experienced and competent engineers to serve as a source of vicarious experience for the students.

Each consultant usually spends two to four hours during one afternoon per week on alternate weeks throughout the spring semester. Over the length of the semester, every consultant meets with several of the design groups three or four times. They provide specific answers to those students who know enough to ask meaningful questions, and offer guidance and suggestions to those whose progress leaves something to be desired. They are particularly effective in providing advice on the best choice of processing equipment (*e.g.,* in selecting from among vacuum filters, centrifuges, and hydroclones), materials of construction, plant capacities, and start-up strategies. In the past five years, our department has added an adjunct professor, Dr. Arnold Kivnick, a retired engineer who served for over thirty years as one of the consultants. His job is to be available as a resident consultant for two days each week during the spring semester.

TABLE 3
Industrial Consultants (1993)

Years Served	*Consultant • Company*
3	Dr. Rakesh Agrawal • *Air Products and Chemicals*
12	Dr. E. Robert Becker • *Environex, Inc.*
1	Dr. David D. Brengel* • *Air Products and Chemicals*
10	Dr. Robert M. Busche • *BIO-EN-GENE-ER Associates*
15	Mr. Leonard A. Fabiano • *ARCO Chemical Co.*
4	Dr. Brian E. Farrell* • *Air Products and Chemicals*
10	Mr. F. Miles Julian • *E.I. DuPont de Nemours*
5	Dr. Grant G. Karsner* • *Mobil Research and Development*
2	Dr. Frank Kelly* • *Mobil Research and Development*
15	Dr. Donald J. Klocke* • *Mobil Research and Development*
15	Dr. Jack McWilliams* • *Mobil Research and Development*
4	Dr. Mark R. Pillarella* • *Air Products and Chemicals*
13	Dr. William B. Retallick • *Consultant*
1	Dr. Henry M. Sandler • *Consultant*
2	Mr. Andrew Savo* • *Rohm and Haas*
15	Mr. Peter Schmeidler • *Rohm and Haas*

* *University of Pennsylvania alumnus*

Over the years, the relationship between the consultants and the students has developed to a point where the students feel free, within reasonable limits, to call upon the consultants when the need arises outside of scheduled sessions. The students have learned that equally competent people, with different experiences, often reach disparate opinions on the basis of the same information. They have also learned how competent people reach conclusions even in the face of inconsistent data or when insufficient information is available.

A faculty advisor is assigned to each design team. Even though his or her experience in the specific area of the team's problem may be limited, all of the faculty members have worked as advisors at one time or another, with several of them serving almost every year. They bring their own expertise to the project and provide continuity and general supervision throughout the term. Further, they use their knowledge of the interests and strengths of their colleagues, both inside the department and elsewhere in the University, to direct the students to sources of information and advice best suited to their needs. As a result of having advised design teams, *all* of our faculty have a better appreciation of the important prerequisites that need to be covered in their own courses.

An indirect objective of the course is to teach the need for information networks in the development of projects, how to set up and be part of such a network, and how to persevere in the face of indifference or non-cooperation from potential sources of information. Experienced design engineers are well aware of the assistance that sales representatives from equipment and material vendors can provide, and they usually know which colleagues have expertise in areas of importance to the project and are not shy about consulting them. For the seniors, who have worked individually for most of their academic lives, this course aims to provide a taste of professional *teamwork.* Cooperation among students, faculty, consultants, and sales representatives, who are all motivated only by the need to solve a design problem (within reasonable limits to the time available and the sensitivity of the often proprietary technical information sought), helps to build camaraderie between the students and other members of their chosen profession, while at the same time giving the students a sense of the value of their own efforts.

We are gratified that several former Penn students, some of whom received graduate degrees elsewhere, now serve as consultants in our department. Table 3 lists the current consultants, the companies which contribute their services, and the number of years they have been involved in the course.

Penn is, of course, fortunate to be located in an area where the process industries are very active. There are other schools of chemical engineering located near major industrial centers that could enjoy a similar advantage. Also, schools located in areas served by a local section of the AIChE should be able to get help of this kind. Even if only one consultant from outside academic circles is available, it should provide a worthwhile broadening of exposure for the undergraduate engineering students.

EFFECTS OF THE SIMULATOR ON THE PLANT DESIGN COURSE

In bygone years, each plant design project led to *one design* that satisfied the problem statement. The development and availability of design simulators and the computer spreadsheet have considerably changed that scenario. They have so accelerated the design process that it is now reasonable to require the design teams to choose from among two or more alternative designs (with the need to study all of them and to justify their choice) and to optimize the design ultimately chosen with respect to energy utilization and choice of operating conditions. In some cases, the simulator has enabled the students to arrive at more effective processes, designs that would not have been possible otherwise, with much improved profitability. Recent cases have been the reactive distillation of azeotropic mixtures and the recovery of krypton and xenon from air in thermally-coupled distillation towers.

There is a tendency, however, for students in the 1990s to depend entirely on the simulator, sometimes without understanding exactly what it is doing. We urge students to perform manually crucial parts of the design study; this may provide approximate results which serve as initial estimates for the simulator calculations. Occasionally, especially in fractionation calculations, the simulations take so long to converge that manual approximations (such as McCabe-Thiele plots based on key binaries, or the sketching of residue-curve maps and simple distillation boundaries) can rapidly provide useful insight into the problem, permitting the simulator to achieve more rapid convergence. More often, the manual procedures increase the students' awareness of the process details (*e.g.,* whether more distillation trays are needed above the feed tray or below or where phase changes are occurring). Once convergence has been achieved, a legitimate use of the simulator is to study the effects of adding trays at various locations, or of changing the reflux ratios.

THE INFORMATION NETWORK

Throughout much of their prior course work, the students' textbooks presented new concepts through examples and homework exercises, but in the design lecture course we use individual chapters from several books to present the concepts in the sequence shown in Table 1. Although this helps accustom students to working with diverse sources of information, it does not involve them in the actual gathering of information from the vast literature.

To address this need, at the beginning of the spring project course the students learn to access such well-known sources as the *Kirk-Othmer Encyclopedia of Chemical Technology* and the *Encyclopedia of Chemical Processing*, edited by McKetta and Cunningham. Even more important, our librarian introduces them to the electronic media and available data bases, such as the *Science Citation Index,* the *Engineering Index,* and *Chemical Abstracts.* The students are given examples of search procedures and are introduced to sources of assistance in the library system. They also learn that library resources at other universities can be searched through electronic mail, and interlibrary loans can be used to obtain sources that are not available locally. This relative ease of information access has a major impact on the quality of the designs.

THE WRITTEN REPORT

Since one objective of the course is to introduce students to some of the profession's requirements, the design report must be prepared as if it were written for an industrial supervisor (for transmittal to his superiors) by a junior engineer assigned to study a potential project. The required form is a typical industrial report, beginning with the letter of transmittal. The usual sections are required: abstract, introduction, process flowsheet (including a material balance block), process description, unit descriptions, energy balance, specification sheets, equipment cost summary, fixed capital summary, economic analysis, conclusions, and recommendations. A specific requirement is that the report be so organized that a conscientious industrial supervisor can check the design of any particular item of equipment, from its functions in the unit descriptions to its details in the specification sheets and its purchase price in the equipment cost summary to the detailed design calculations (in the form of Xerox copies of reasonably legible calculation sheets) in the Appendix.

Preparing the report takes a great deal of time, so we encourage students to start writing the descriptive portions while the design computations are still under way. The report adjudged best in the class is awarded the Molstad prize (a non-negligible cash award) and is often submitted for the prestigious Zeisberg Award, administered by the Delaware Valley Section of the AIChE, in competition with other area schools.

THE ORAL PRESENTATION

A lucky junior engineer may get the opportunity to attend the meeting where his or her work and ideas are presented to the decision-makers among his or her employers, but it is rare that he or she is required to make the presentation in person. The experience of making an oral presentation has been part of the plant-design course at Penn since its inception. Each team must present its report to an audience of classmates and as many of the faculty and consultants as can attend. All team members must participate in the oral presentation, and each team is allotted about forty minutes for the presentation, including five or ten minutes for questions from the audience. To set the appropriate atmosphere, the students attend in clothes suitable for a business meeting. The presentation covers all the salient factors of the design, including the pertinent chemistry, design problems and their solutions, equipment costs, and project economics. We encourage the use of audio-visual aids, including transparencies and slides, with suitable projectors and, more recently, computer-screen projectors.

The oral presentations are weighted in the student's grade and in the considerations for the Molstad prize. All faculty members and consultants present at the sessions contribute to the evaluations.

CONCLUSIONS

The plant design course is regarded, by students and faculty alike, as the culmination of the seniors' efforts. Since the BS degree is still considered the professional degree in engineering, this course is designed and conducted so that the students use much of what they have learned during their years of study. With few exceptions, the students will put more concerted effort into the design, the written report, and the oral presentation than they have into any other single event up until that time. It is considered a kind of final exam, not in a particular course offering but for the whole chemical engineering undergraduate curriculum. In recognition of that fact, the department customarily invites the members of the graduating class, along with as many of the faculty and consultants as can be present, to have lunch together during the midday break in the presentations, to celebrate the students' success and hard-won maturity.

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Three Symbols in Search of a Location

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Four mathematical symbols (∞, ∞, ∞, ≠) recently visited my office. I was surprised that they would do this as I had considerable reservations that they might become lost in the piles of papers, journal articles, and assorted correspondence that provides a marvelous camouflage for any horizontal surface. While they were small, they assured me that they could represent themselves quite well and pleaded with me to restore them to their proper locations in a previous publication.[1]

Seeing these symbols so left out in the cold, I had nothing but great compassion for their needs. I assured them that I would do all in my power to see that they would be placed where they belong. This note serves to fulfill my part of the bargain.

The first ∞ symbol belongs on the fourth line from the bottom of the left-hand column of page 65 following the words *“. . . a value of - .”*. The second ∞ symbol belongs at the end of the first line at the top of the right-hand column of the same page following the words, *“. . . this limit is not - .”*. The third ∞ will find a home at the beginning of line 14 on page 66 following “ . . . $\underline{V} \rightarrow$,”. The ≠ symbol belongs in the second line of the answer between the α symbol and the 0 symbol on page 66. I trust that all readers will recognize the suffering these symbols have been asked to bear and share in my joy in seeing them placed in their proper locations.

REFERENCE

1. Brainard, Alan J., “Beware the Use of an Ideal Gas,” *Chem. Eng. Ed.*, **28**(1), 62 (1994)

Editorial note: *We apologize to Professor Brainard and to any of our readers who may have been confused by the voids left by the inexplicable disappearance of the symbols, so good-humoredly identified above. Having now cornered the responsible computer culprit we will endeavor to keep a tighter rein on the little fellas in the future!*