TEACHING PROCESS ANALYSIS

MOSES O. TADÉ, TERENCE N. SMITH
Curtin University of Technology
Perth 6001, Western Australia

***Moses O. Tadé** is a Senior Lecturer in Chemical Engineering at Curtin University of Technology. He obtained his BSc degree in 1980 from the University of Ife (now Obafemi Awolowo University) in Nigeria, and his MSc and PhD from Queen's University in Kingston, Canada (1982 and 1986, respectively). His current research interests are in process modeling and simulation, process optimization and control, and applied statistics.*

***Terence N. Smith** completed his BE degree at the University of Sydney in 1952. He worked at Bahrein Petroleum Company and Australian Oil Refining before joining the University of Adelaide in 1959. He obtained his PhD in 1965 and moved to Curtin University in 1982 to establish its Department of Chemical Engineering, which he heads. He has special interests in fluid mechanics, handling of fluids and solids, and mixing and separation of fluids and solids.*

The Chemical Engineering Department at Curtin University of Technology in Perth is about ten years old, and to date 175 students have graduated from our program. The department has excelled in its undergraduate Chemical Engineering Plant Design Project, having won the Student Design Award—an annual plant design competition among the nine Australian chemical engineering departments—for three consecutive years (1990-1992). Also, one of our students won this award in 1987, and another placed second in 1988.

The various components of the undergraduate curriculum have evolved over the years, and some of them are unique to our department. The purpose of this paper is to share our experience in the Process Analysis Units with the chemical engineering community. We will present a brief structure of the undergraduate curriculum, followed by a description of the contents of the three Process Analysis (PA) units. We will also discuss the instructional approach and the assessment procedure, and the use and integration of these units in the other units will be clearly indicated.

THE CURTIN UNIVERSITY PROGRAM

The chemical engineering degree program is a four-year course following the 12th grade of high school. About 95% of the students are in the mainstream program, and the success or completion rate is usually around 70%. The first-year intake averages about thirty-five students per year. The first and second years of the course establish a general foundation in engineering and science, with emphasis on chemistry and mathematics. Specialized units in handling of process materials, design of reactors, transfer of heat and energy, mixing and separation, and process control make up the mainstream of the senior years. A plant-design project concludes the course. It is also mandatory for our students to complete an industrial attachment for at least twelve weeks before graduation. This is usually undertaken after completion of the second and/or third year of the program.

The first-year students undertake a general program in common with other engineering students. Each engineering program differs by one or two units per semester to provide some variation to accommodate particular needs. For example, the chemical engineering program includes a full science-type chemistry component. The department does not have teaching contact with the first-year students. Teaching activities at this stage are usually coordinated by the Sub-Dean of Engineering.

Figure 1 shows a schematic of the chemical engineering course. The first-year units are shown in the two left-hand column boxes under YEAR 1, where the first column boxes show the seven first-semester units (*e.g.,* CHEM 115 to ENGLISH 150) and the second column boxes indicate the seven second-semester units (*e.g.,* CHEM 116 to WORKSHOP TECH 162). The units for the two semesters of YEAR 2 are shown in the next two column boxes, while those under YEAR 3 indicate the units for the two semesters of the third year. The fourth-year units are shown in the last two right-hand column boxes under YEAR 4, where the units for the first semester are SEP PROC 441 to CE PROJ 491, and those for the second semester are RESOURCE MAN 442 to DESIGN PROJ 442.

The vertical lines in two of the boxes for the first semester of YEAR 4 indicate that all the YEAR 1 to YEAR 3 (six semesters) units must be completed satisfactorily before SPECIAL TOPICS 441 and CE PROJ 491 can be done. Similarly, the vertical lines in the last two boxes of the second semester of YEAR 4 (the eighth and final semester of the CE program) indicate that all the first-semester units of YEAR 4 must be completed satisfactorily before PLANT DESIGN 442 and DESIGN PROJ 442 can be done.

Arrows are used in Figure 1 to indicate the prerequisite units for higher level units. For simplicity, only a few of these arrows are shown. For example, the arrows entering the box labeled PROC ANAL 342 indicate that PROC ANAL 242, MATH 272, and PROC ENG 242 are the prerequisites for this unit. Space limitation does not permit any further discussion of the complete prerequisite structure.

THE PROCESS ANALYSIS UNITS

The three Process Analysis units, PA 241, PA 242, and PA 342 are service units since some of the other units rely on them, as shown by the arrows in Figure 1. The contents of each of these units are summarized in Tables 1 and 2. The first author teaches all the three PA units. The second-year PA units (241 and 242) are 15 credit points each, with an allocated contact time of three hours per week over a fourteen-week semester, whereas PA 342 is 20 credit points with a four-hour contact time per week.

These units were originally incorporated in the curriculum in recognition of the growing importance of data modeling, numerical analysis, and optimization. The units support CE Project 491/492, Plant Design 442, Process Control 342/441, and Design Project 442, as shown in Figure 1. The rationale for locating these units in the second and third years of the program is to develop the ability of students in the analysis of chemical processes and plants before specialized chemical engineering units such as handling of process

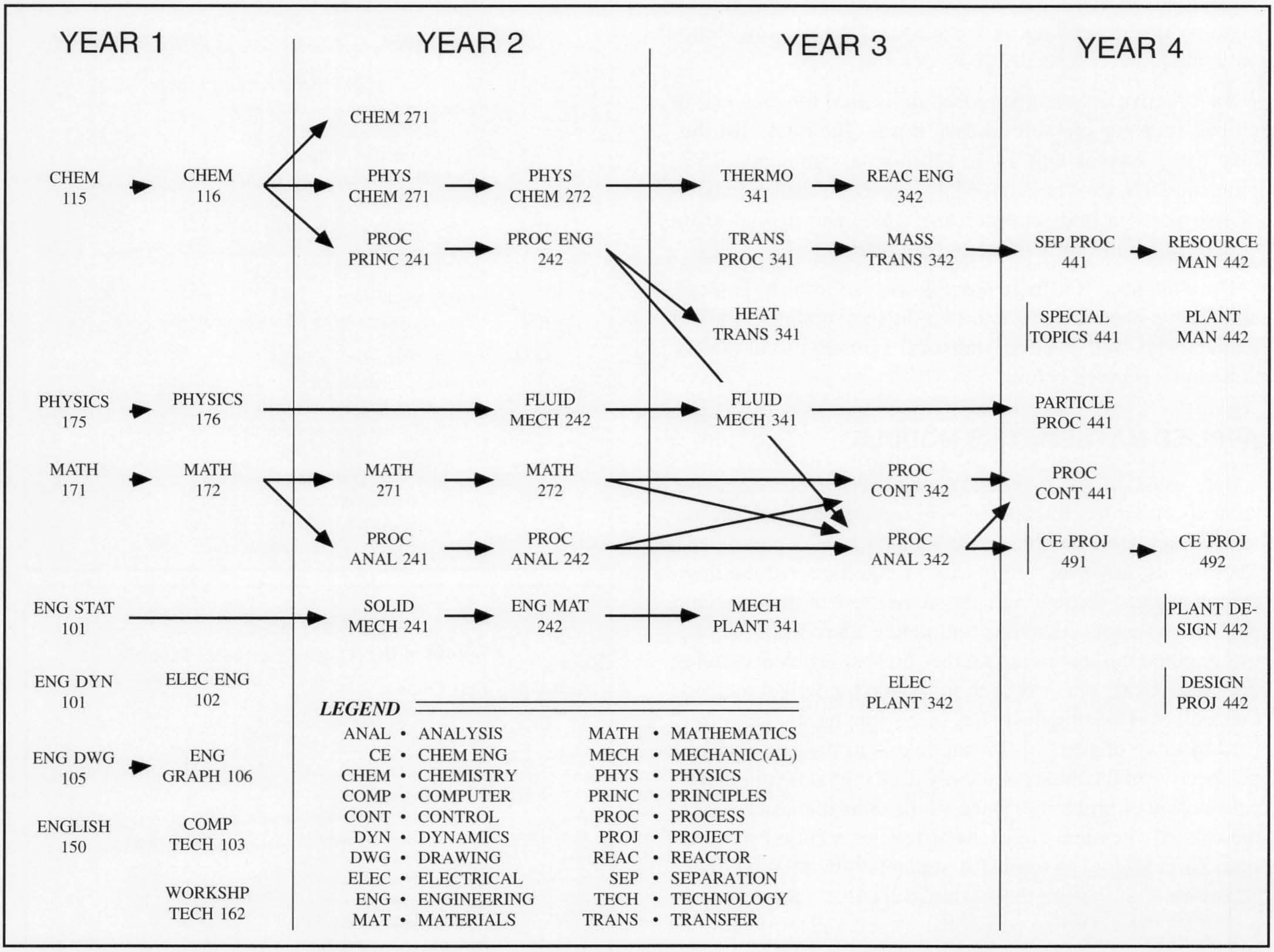

FIGURE 1. Chemical Engineering Course Schematic

materials, design of reactors, mass and heat transfer, etc., are covered. The tools for this analysis are applied mathematics and applied statistics. The components of these tools are introduced below. The content of each unit has been organized to avoid duplication of material in any of the other PA units. Since the same person teaches all three units, it is easy to consolidate and integrate the content of each unit from one level to the other, thereby ensuring that the prerequisite requirements are satisfied.

The instruction/teaching approach is a combination of lectures, tutorials, computer labs, projects, and case studies. The tutorials and projects are run in such a way as to ensure effective student participation in the various sections of the units during the semester. The tutorial problems are usually assigned a week ahead of discussion and a few students may be called to lead discussion of specific problems. Projects are carried out in groups of two or three students. The objective of the project is to integrate various sections of the unit in a given problem. Consultation times are provided outside of lecture periods to discuss various stages of the project. Times required for each project vary from four to eight weeks, depending on the scope of the project. Hence only one project is usually given per unit.

An effective assessment procedure is used for each unit to relieve students' pressure in final exam. The mark distribution for a typical unit is as follows: assignments, 15%; projects, 20%, examination, 65%. The examination consists of two parts: a mid-semester test, 15%, and a final exam which constitutes 50% of the overall mark.

The contents of the three process analysis units in Tables 1 and 2 have been divided into two distinct modules: applied mathematics and applied statistics. Further discussion of these units is given below.

APPLIED MATHEMATICS MODULE

It is usual in most chemical engineering curricula that students either teach themselves numerical methods or take units which are available in the mathematics department.[1] These units, however, are mostly oriented toward the theoretical aspects (proofs and theorems) rather than specific engineering applications. An alternative approach is for various engineering lecturers to either present problems having only analytical solutions or to introduce numerical methods themselves. This obviously has some drawbacks. Therefore, the objective of parts of this module is to present a unified perspective of the most commonly used methods for numerical solution of problems. Since all the units that teach fundamentals of chemical engineering require solution of equations, it is logical to teach the students how to solve these equations first, before they extensively learn about how to formulate them. During part of the second and third year, we strive to provide students with knowledge and experience in applying numerical methods efficiently. We also focus on the integration of the material with other concurrent units. The concepts of convergence, stability, and accuracy are emphasized with less theoretical detail at this level. The applied mathematics module is given in Table 1 and is made up of: Part I of PA 241; Parts I and II of PA 242; and Part II of PA 342.

Process Analysis 241, Part I

We begin this section with a brief introduction to personal computers. Three or four years ago, work in this section would have been curtailed in order to allow time for a formal introduction to MS-DOS (Microsoft[2]). But in the past two years about 60% of the students have had better exposure to using computers, and it is foreseen that this section of the

TABLE 1
Content of the Applied Mathematics Module

Unit Title	Unit Content
PA 241	*Part I: Computer Applications in CE* • Introduction to MS-DOS • Introduction to spreadsheet packages • FORTRAN programming language
PA 242	*Part I: Numerical Procedures for Problem Solving* • Linear and nonlinear equations • Matrix operations • Approximation of functions • Ordinary differential equations • Partial differential equations • Boundary value problems *Part II: Formulation and Solution of CE Problems Using* • Linear differential equations • Laplace transforms • Periodic functions and Fourier analysis
PA 342	*Part II: Optimization Techniques* • Problem formulation and basic concepts • Unconstrained optimization Single variable and multivariable systems • Constrained optimization Linear programming technique Lagrange multipliers Direct search methods Gradient projection approaches

TABLE 2
Content of the Applied Statistics Module

Unit Title	Unit Content
PA 241	*Part II: Applications to CE Problems in Context of* • Probability models • Frequency distribution • Variability of data • Statistical treatment and evaluation • Introduction to interactive statistical packages
PA 342	*Part I: Applied Statistics* • Analysis of variance • Correlation and regression analysis • Design of experiments

module may eventually be phased out. The section involves about three hours of lecture on the MS-DOS operating system together with two two-hour computer laboratories. We distributed an assignment covering various applications of MS-DOS during the first lecture to motivate and force students to pick up the salient features of this system and its associated editor. We do not cover the use of Macintosh machines since all our personal computers are IBM compatible.

A two-hour lecture is then given on the spreadsheet section. We discuss specific application of chemical engineering, *e.g.,* material and energy balances, fluid mechanics, heat transfer, statistical process control, etc. The lecture is complemented by a two-hour laboratory period where each student is allowed to explore the various utilities available on the spreadsheet package, Quattro (Borland[3]), which is licensed to the department. We encourage students to use any spreadsheet of their choice.

We devote about ten hours of lectures (two hours per week) to FORTRAN programming. The presentation covers the materials in Chapters 1 to 7 of Etter,[4] which is one of the recommended textbooks for this unit. We have restructured the presentation so as to avoid duplication of content which can be found from chapter to chapter. We emphasize the need to cultivate the habit of good program documentation and introduce the students to the LP77 FORTRAN compiler[5] during the third week of this section. We encourage them to start building their own subroutine library using the examples in Himmelblau,[6] Gerald and Wheatley,[7] and Press, et al.[8]

Process Analysis 242

We cover the material in Table 1 under PA 242 in the second semester of the second year. It is difficult to recommend a particular textbook for the material in Part I since most numerical analysis textbooks tend to be theoretical in nature (more so for second-year students). Therefore, the first author has written a partially completed set of notes which adapts the content of Gerald and Wheatley[7] and Riggs[1] in his lectures. The material is normally covered in about eighteen lectures (two hours per week for nine weeks). The rest of the allocated period is used for tutorials and computer related assignments.

The lectures begin with the solution of linear equations of the form, $Ax = b$. Our approach to teaching this section is similar to that described by Zygourakis[9] except that we do not stress the theoretical part (necessary for a first-year graduate chemical engineering unit) to as great an extent as he did. Students already have an appreciation of how these problems arise during the first semester on material and energy balances. We place emphasis on the computation of a solution, if it exists and briefly mention non-uniqueness issues without theoretical details.

We introduce the idea of iterative methods of solution for nonlinear equations by using specific examples. The use of polynomial expansions in finite difference approximations of derivatives, interpolation of function values, and integration of discrete valued functions are discussed. We stress the role of the Taylor series expansion in deriving finite difference approximations for first- and second-order derivatives, linear, quadratic, and cubic spline interpolations. We then cover the trapezoidal rule and Simpson's rule, and put stress on adaptive integration and the use of Romberg's integration in specific applications.

We discuss the solution of ordinary differential equations (ODE) and partial differential equations (PDE) for two classes of problems: initial value problems (IVP) and boundary value problems (BVP). More time is spent on the IVP class since these problems constitute a large class of chemical engineering problems. Methods that we cover include the Euler and Modified Euler methods, the Runge-Kutta methods, and the multistep methods (Milne's method and Adams-Moulton method). We discuss stability and accuracy considerations, using specific examples, as well as the various sources of errors and error propagation. The solution of n-coupled first-order ODEs using any of the above methods is described through a complete hand-calculation for two-coupled equations. This allows easy extension of the algorithms to the n-coupled system. We develop the numerical solutions of BVP using the finite difference approximations of the derivatives, with the focus mainly on one-dimensional, two-point BVPs. Only two methods are discussed: the shooting method and the finite difference method with the successive over-relaxation convergence procedure.

In Part II of PA 242 (Table 1), we reinforce the necessity for unsteady state material and energy balances and introduce additional elements of mathematical models, such as transport rate equations and reaction rate equations. We illustrate the effect of transportation lag on process out-

TABLE 3
Sample of Students' Experimental Design Projects, 1992

- Experimental Analysis of a Sedimentation Process
- Efficiency of Model Locomotives
- The PJS Challence: A 2^{5-1} Fractional Factorial Experiment in Bike Riding
- The Effect of Rig Settings and Wind Speed on Sailing Performance
- How to Get the Most Thrust from a Model Aero-Engine
- A 2^{6-2} Fractional Factorial Experiment for the Dyeing Process
- Bubble Maximization in Milkshakes
- The Factors Affecting the 3-Point Shot in Basketball
- Factors Affecting Sultana Moisture

puts and discuss examples to give the students an appreciation for how process models can be formulated. We cover Laplace transforms in the context of the third-year process control unit.

The emphasis throughout PA 242 is efficient computer implementation of the numerical procedures discussed. The students are forced to do this through assignments and projects. Various software packages are available to us on both PCs and the Vax mainframe; among them are the library programs, LINPACK, and Numerical Recipes. The collections of software in Riggs[1] and Gerald and Wheatley[7] have also been particularly useful. We encourage the students to write their own codes and to adapt any of the above software for their own software library.

Process Analysis 342, Part II

The final section in the applied mathematics module is Optimization Techniques (Part II of PA 342, Table 1), and it is taught during the second semester of the third year. The material is covered in about seven weeks of three one-hour lectures per week. An additional one hour per week is spent on tutorial related discussions. A good reference textbook which we have used selectively over the past three years is one by Edgar and Himmelblau.[10] About 60% of our examples and assignments are taken from this textbook.

We address the significance of problem formulation by using examples of different types of chemical engineering problems and feel that the examples give students an appreciation for the necessity of optimization. We emphasize the use of prior knowledge and experience in reducing the complexity of any given problem and discuss the hierarchy of optimization levels, from individual equipment design to management decision making. We then introduce the properties of objective functions and constraints as well as the necessary and sufficient conditions to ensure that an optimum is a minimum or a maximum. We also discuss the characteristics of the region of search. The rest of the lectures cover unconstrained and constrained optimization methods for single variable and multivariable systems.

THE APPLIED STATISTICS MODULE

The importance of the applied statistics module in chemical engineering education cannot be overemphasized. During the past decade, Western management has come to realize (due to the world-wide success of some Japanese industries) that their success is totally dependent on satisfying customers by constantly improving products and services (quality, cost, and reliability). According to Dyson,[11] the traditional approach of "design quality" (*i.e.,* to optimally target the features of a product to allow the customer to achieve maximum functionality) is now being augmented with "conformance quality" or product consistence (*i.e.,* minimizing variation about the optimum design targets of product features). Therefore, appropriate quality and statistical training is required to equip industrial personnel (and in particular, engineers) to focus on *conformance quality* as well as *design quality* throughout their careers. This is the motivation behind the applied statistics module in our undergraduate program.

Various statisticians (*e.g.,* Hogg, *et al.,*[12] and Bisgaard[13]) have written papers on "Teaching Statistics to Engineers," and the content of our applied statistics module and its presentation are adapted to some of their recommendations. The objectives of the module are:

- *Plan data collection, turn data into information, and achieve action.*
- *Apply the methods taught in real-life situations.*
- *Communicate statistical information in oral and written form.*
- *Use computer and graphical techniques.*
- *Plan, analyze, and interpret the results of experiments.*
- *Understand the scientific method.*

This module has been taught by the first author for the past three years. The medium of instruction during this period is: formal lectures on basic concepts (theoretical details are minimized and emphasis is on application); use of detailed examples, case studies, workshop, and laboratory experience (industrial practitioners are sometimes invited to give the case studies); use of suitable computer software; tutorials and assignments, as appropriate; requirements of the completion of a project, usually a design of an experiment and submission of a suitable report.

The applied statistics module is presented as parts of two units, as shown in Table 2. The first part is given over a five-week period during the first semester of the second year. The class meets about four hours a week for lectures, tutorials, and computer workshops. The second part is covered during the first five weeks of the second semester of the third year. Two hours per week are spent on lectures, one hour for tutorials, and another hour is reserved for students to discuss their projects which are usually started in the third week of the semester.

The detailed content of Part II of PA 241 (Table 2) is the same as that of modules A, B, and C of Section 6.3 of Hogg, *et al.,*[12] while the content of Part I of PA 342 (Table 2) is structured to follow the material in modules D and E of their proposed statistical course for engineering students.

We recommend a book by Walpole and Meyers[14] for some part of the above syllabus, and one by Box, *et al.,*[15] is used as a reference textbook. The first author also has a partially completed set of notes which is easier for the students to understand. We also emphasize the use of statistical software packages[16-18] for various sections of this module. Since these packages are easy to use, students spend less time writing codes for appropriate statistical formula and can concentrate on thorough problem formulation. The availability of these packages has also allowed solution of more complex problems. Space limitation does not permit more information on these packages here.

The most interesting part of the applied statistics module is the final project which the students do to complete the requirements for PA 342. This idea was adapted from Hunter[19] and Bisgaard.[13] During the third week of the semester, each student is required to team up with one or two other students and to design, conduct, and analyze an experiment of their own choice. A proposal to conduct the experiment is due within two weeks. The proposal consists of the objective of the experiment, its motivation, the response(s) and independent variables, the necessary resources, and the time required to carry out the experiment. A written report is due at the end of the semester. The projects help students to learn the practical aspects of experimental design and puts them in good stead to apply statistical techniques in their final-year thesis work. Table 3 gives a representative sample of the experiments conducted on experimental design by our students in 1992.

CONCLUDING REMARKS

Our process analysis units attempt to introduce students to the basics of numerical analysis, optimization techniques, and applied statistics which are significant in the education of a chemical engineer. We gear the teaching style and instructional medium toward effective student learning and participation in class activities. We use tutorials to facilitate student learning, assignments to force them to study, and projects to stretch their imagination. We use practical chemical engineering problems as examples in both tutorials and assignments, and we assign projects to integrate various sections of the material covered with other chemical engineering units. Emphasis throughout the units is on efficient computer implementation of popular numerical algorithms as well as use of available software packages and libraries. We encourage students to write their own codes for some of the assignments and projects. This is necessary because some of the library packages require user calling programs.

An effective assessment method is used so that performance does not rely mainly on a final examination. Student responses to the unit evaluation questionnaire indicate that they particularly like the project requirement for each of the process analysis units. These projects point out some of the real problems that a chemical engineer is required to solve, as well as integrating various sections of the units in problem solving. Among other things, students also learn to get along with other group members during the execution of the project, thus emphasizing that chemical engineering is rarely an individual profession.

The delivery of these units is considered a dynamic process where improvements are continually sought and made. In particular, more chemical engineering case studies and examples are introduced each year to enable students to appreciate the importance of these two modules in their careers well beyond graduation. Comments and suggestions from readers on case studies in these areas will be appreciated.

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REFERENCES

1. Riggs, J.B., *An Introduction to Numerical Methods for Chemical Engineers,* Texas Tech University Press, Lubbock, TX (1988)
2. Microsoft Corporation, *MS-DOS Version 3.3 Manuals,* Redmond, WA (1988)
3. Borland International, Inc. *Quattro Manuals,* Scotts Valley, CA (1990)
4. Etter, D.M., *Structured Fortran 77 for Engineers and Scientists,* 3rd ed., The Benjamin/Cummings Pub. Co., New York, NY (1990)
5. Lahey Computer Systems, Inc., *LP77 Compiler,* Incline Village, NV (1989)
6. Himmelblau, D.M., *Basic Principles and Calculations in Chemical Engineering,* 5th ed., Prentice-Hall, Inc., Englewood Cliffs, NJ (1989)
7. Gerald, C.F., and P.O. Wheatley, *Applied Numerical Analysis,* 4th ed., Addison-Wesley Publ. Co., New York, NY (1989)
8. Press, W., B. Flannery, S. Teukolsky, and W. Vetterling, *Numerical Recipes: The Art of Science of Computing,* Cambridge University Press, New York, NY (1986)
9. Zygourakis, K., "Linear Algebra for Chemical Engineers," *Chem. Eng. Ed.,* **18**, 176 (1984)
10. Edgar, T.F., and D.M. Himmelblau, *Optimization of Chemical Processes,* McGraw-Hill Book Co., New York, NY (1988)
11. Dyson, L.A., Industrial Statistics and Quality Training for Engineering Students, Alcoa of Australia Ltd., Private Communications, March (1990)
12. Hogg, R.V., *et al.,* "Statistical Education for Engineers: An Initial Task Force Report," *The Amer. Statistician,* **39**, 169 (1985)
13. Bisgaard, S., "Teaching Statistics to Engineers," *The Amer. Statistician,* **45**, 274 (1991)
14. Walpole, R.E., and R.H. Myers, *Probability and Statistics for Engineers and Scientists,* 4th ed., Macmillan Pub. Co., New York, NY (1989)
15. Box, G.E.P., W.G. Hunter, and J.S. Hunter, *Statistics for Experimenters: An Introduction to Design, Data Analysis, and Model Building,* Wiley & Sons, New York, NY (1978)
16. Lincoln Systems Corporation, *ISP User Guide,* Westford, MA (1987)
17. SAS Institute, Inc., *SAS User's Guide: Basics Version 5 Edition,* Cary, NC (1985)
18. Joiner Associates, Inc., *JASS Manual, Version 2.1,* Madison WI (1986)
19. Hunter, W.G., "Some Ideas About Teaching Design of Experiments, and 2^5 Examples of Experiments Conducted by Students," *The Amer. Statistician,* **31**, 12 (1977) ❐