CASE STUDY PROJECTS IN AN UNDERGRADUATE PROCESS CONTROL COURSE

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In recent years, there has been an on-going argument that engineering students need more open-ended problems, more team projects, more written memos, reports, and oral presentations, more practical problems, and more interactive learning (rather than complete dissemination of course material by lecturing) in their undergraduate education.

At Rensselaer Polytechnic Institute we try to include all these factors in our process control course. The focus of this paper is on a case study project performed during the latter half of the semester. We will cover not only the project, but also a background description of the Rensselaer curriculum, the introductory material for the project, the venues used for distributing course material, future teaching efforts, and a summary.

BACKGROUND

There are roughly 80-90 BS degrees granted in chemical engineering at Renssealer each year, while there are approximately 30 environmental BS degrees granted. A number of courses in the curriculum (material and energy balances, dynamic systems, chemical process control, unit operations laboratory I and II) are taught to both the chemical and the environmental students.

A distinguishing characteristic of the Rensselaer curriculum (in addition to the fact that both chemical and environmental engineering take many of the same courses) is that we have had separate courses in dynamics and control for over a decade. Another is that the dynamics and control courses are taught during the junior year. One advantage of teaching these courses at that time is that students tend to take more of a process-systems engineering viewpoint in the senior courses (reactor design, separations processes, process design, lab I and II).

The process dynamics course covers more material in more depth than the "front end" of a typical single course in dynamics and control. Particular emphasis is given to numerical methods for the solution of algebraic and differential equations, with MATLAB as the numerical analysis pack-

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age. State space models receive much attention. Also, phase-plane analysis and an introduction to nonlinear dynamics and chaos is provided. A textbook for this course has been published by Prentice Hall.[1,2]

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INTRODUCTORY MATERIAL FOR PROCESS CONTROL

A major advantage of the two-course sequence in process dynamics and control is the proper coverage that can be given to the topic of process control. Process control is taught in the spring of the junior year, immediately after the students have taken process dynamics. After a concise review of modeling and dynamics, we are able to leap into important issues of control-system design. The topics covered in the course are

- Motivation
- Review of process modeling for control
- Introduction to feedback control
- Direct synthesis and open-loop "control"
- Internal model control (IMC)
- IMC-based PID control
- Introduction to frequency response
- Frequency response for control-system design
- Control using multiple measurements
- Implementation issues
- Decentralized control
- Multivariable control
- Case-study problems in multivariable control

Each of the topics, including characteristic homework problems, is summarized in Table 1.

When we first taught this course, we also introduced discrete control-system design, and in some years we included model-predictive control (MPC). Our philosophy now is to cover less material, but to provide more depth. Since our course is taught during the junior year, students often select a senior project in control or take a reading course in ad-

TABLE 1
Process Control Course Topics

Motivation and Introduction to Control *Fairly standard material on economic, safety, and environmental incentives is presented. Simple examples, such as "taking a shower" and surge drum level control are discussed extensively in the lectures. Issues include objectives, measurements, manipulated inputs, disturbance inputs, continuous vs. batch (and semi-batch) and feedforward/feedback. As a homework problem, the students select a favorite activity and analyze it in detail from a control perspective.*

Review of Process Modeling for Control *This section is much shorter than in a standard course since the students completed a dynamic-systems course during the previous semeter. Both fundamental and input/output models (obtained by step tests) are reviewed. An example homework problem is to develop a nonlinear model for a series of gas surge drums. The students form a state-space model via linearization, find transfer functions, and simulate the open-loop system using SIMULINK.*

Classical Feedback Control (PID) *The concept of PID control (in various forms) is presented, and the effect of the tuning parameters is discussed and illustrated by example. Traditional methods such as Cohen-Coon and closed-loop Ziegler-Nichols are covered. A typical homework assignment is a continuation of the previous modeling and simulation assignment (gas drums, for example), again using SIMULINK for closed-loop simulation. The students are encouraged to explore the robustness of their control-system designs.*

Direct Synthesis and Open-Loop "Control" *One issue stressed in this section is that, because of inherent performance limitations (right-half-plane zeros, time-delays), one cannot arbitrarily select any desired closed-loop response and yield a physically realizable (or internally stable) controller. We show how the open-loop control system design approach evolves to the internal model control structure when one accounts for disturbances and model uncertainty.*

Internal Model Control (IMC) *The IMC procedure is a major focus of the course and distinguishes the course text from other undergraduate texts. Factorization of the model, inversion of the "invertible" portion of the model to form the ideal controller, addition of a filter for realizability, and tuning for robustness are all covered.*

IMC-Based PID Control *We show how to rearrange the IMC structure to the standard feedback structure, often resulting in a PID algorithm. The design procedure for open-loop unstable systems is also detailed. The control of a biochemical reactor at an open-loop unstable point is used as a homework problem.*

Frequency Response for Control-System Design *One of the main motivations for covering frequency response is that gain-margin and phase-margin concepts lead to a better understanding of robust control-system tuning. A typical homework problem involves steam drum level control.*

Control Using Multiple Measurements *Here we introduce feedforward and cascade-control design. Again, steam drum level control is often used for the homework problem. At this point in the semester, the students usually have a week with a lighter load because of student government elections. During this week we normally take a tour of the campus boiler house, pointing out the various control loops; it is clear to the students that an operator would not be able to operate the boilerhouse without feedback control.*

Implementation Issues *Important practical issues, such as variable scaling, proportional gain, installed valve characteristics, are covered in this section of the course.*

Decentralized Control *The relative gain array is introduced as a tool to help select variable pairings for decentralized multivariable control structures; distillation control problems of various sizes are used as illustrative examples. Students implement these techniques in their case studies.*

Multivariable Control *There is little time to provide detailed treatment for full multivariable control design. Usually, static and dynamic decoupling are covered; sometimes, multivariable IMC is also covered.*

vanced control where we cover digital control and MPC.

COMMUNICATION

A number of excellent process-control textbooks are currently available, but each lacks some of the features of the soon-to-be-published text,[3] such as

- In-depth coverage of the IMC procedure
- Connections between open-loop design and IMC
- IMC design for open-loop unstable systems
- Focus on MATLAB and SIMULINK

The course enrollment is typically large (roughly 120 students), which somewhat limits the type of faculty/student interaction that can occur in lectures, although we try to motivate as much discussion as possible by using a "Phil Donahue" approach. There are three 50-minute lectures per week, a 50-minute recitation by a teaching assistant, and a weekly computer lab for solving homework problems. Lectures contain a mix of analytical derivations and simulation results (the lecture hall is equipped with a workstation, a PC, a VCR, a computer/video projector, and two overhead transparency projectors).

Homework assignments are given weekly and are solved in groups of three; typical assignments are discussed in Table 1. The students are expected to provide a one-page written memo summarizing the results of the assignment. Working in groups improves the students' interaction skills and enables more complex problems to be solved, and providing a written memo improves their communication skills. The homework assignments constitute 30% of the course grade. We place a high weighting on the homework assignments because we feel that students learn more about dynamics and control through interactive simulations (combined with analytical solutions) than analytical solutions alone.

MATLAB is the software package used for numerical analysis and simulation. The students have been introduced to MATLAB in the process-dynamics course, and it is sometimes used in the chemical engineering thermodynamics course. One of our first assignments directs the student to complete a tutorial review of MATLAB.

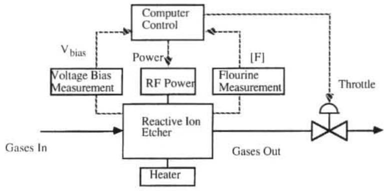
Rensselaer has an extensive network of roughly 500 workstations (IBM RS6000 and Sun SparcStations), with a site license for MATLAB/SIMULINK (as well as many other packages). We reserve a computer lab with thirty workstations for three nights a week. The lab is staffed by the instructor or a teaching assistant.

The course homepage is used as an additional venue for distributing material. Summaries of lecture notes, practice problems for exams, and tutorial modules in hypertext form, are made available on the course homepage. It can be found by linking to "Courses" from

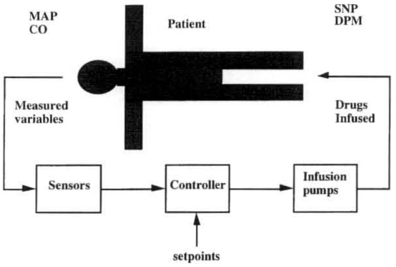
http://www.rpi.edu/~bequeb

TABLE 2
Control Case Sudies

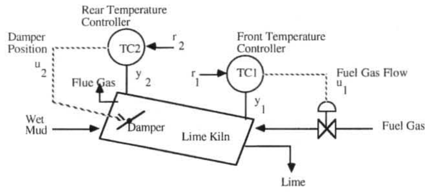
- **Mixing Tank (tutorial example)**
- **Dowtherm Heater**
- **Reactive Ion Etcher**
- **Drug Infusion System**
- **Rotary Lime Kilm**
- **Evaporator**
- **Solution Copolymerization**
- **Fluidized Catalytic Cracking Unit**
- **Wet Grinding Circuit**
- **Anaerobic Sludge Digester**



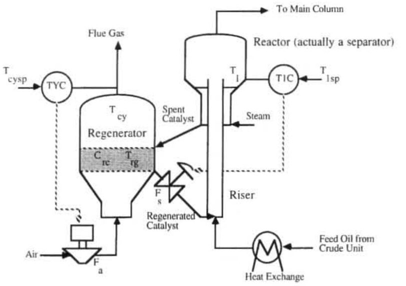
Reactive Ion Etcher



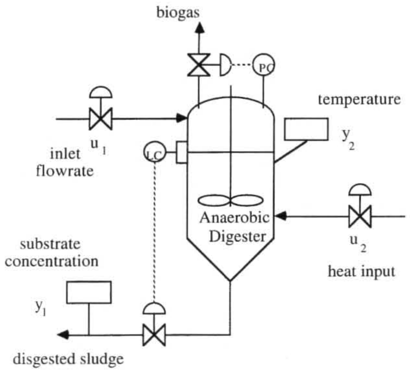
Drug Infusion Control



Rotary Lime Kiln



Fluidized Catalytic Cracking Unit (FCCU)



Anaerobic Sludge Digester

__Figure 1.__ Case study instrumentation diagrams.

The projects are more open-ended than typical undergraduate assignments, provide more experience working in a group environment, and further develop written and oral presentation skills. . . . The case studies give [the students] the opportunity to "tie it all together" and to understand each component of a control-system design project.

An electronic newsgroup is used to answer common questions or to post notes about the lecture material. Rather than responding to many individual e-mail questions, a single posting to the newsgroup saves faculty and TA time. Also, it gives the students the capability of posing questions that can be answered by other students (this feature is not used as often as we would like).

The written examinations are fairly standard. Three one-hour exams (45% of the course grade) and a three-hour comprehensive final exam (25% of the course grade) are required. It would be nice to give some exams on the computer, but thus far it has been too big of a challenge to organize for 120 students.

TABLE 3
References for Five 1997 Case Studies

General references for reactive ion etcher (suggested to the students)

- Bagwell, T.A., T. Breedijk, S.G. Bushman, S.W. Butler, S. Chatterjee, T.F. Edgar, A.J. Toprac, and I. Trachtenberg, "Modeling and Control of Microelectronics Materials Processing," *Comp. Chem. Eng.*, **19**(1), 1 (1995)
- Lee, H.H. *Fundamentals of Microelectronics Processing*, McGraw-Hill, New York, NY (1990)
- Sze, S.M., *VLSI Technology*, McGraw-Hill, New York, NY (1988)
- Wolf, S., and R.N. Tauber, *Silicon Processing for the VLSI Era*, Lattice Press, Sunset Beach, CA (1986)

The model we use is modified from

- Rashap, B.A., M. Elta, H. Etemad, J.P. Fournier, J.S. Freudenberg, M.D. Giles, J.W. Grizzle, P.T. Kabamba, P.P. Khargonekar, S. Lafortune, J.R. Moyne, D. Teneketzis, and F.L. Terry, "Control of Semiconductor Manufacturing Equipment: Real-Time Feedback Control of a Reactive Ion Etcher," *IEEE Trans. Semicond. Manuf.*, **8**(3), 286 (1995)

Models for drug infusion, lime kiln, FCCU, and an anerobic digester are presented in

- Yu, C.L., R.J. Roy, H. Kaufman, and B.W. Bequette, "Multiple-Model Adaptive Predictive Control of Mean Arterial Pressure and Cardiac Output," *IEEE Trans. Biomed. Eng.*, **39**(8), 765 (1992)
- Charos, G.N., Y. Arkun, and R.A. Taylor, "Model Predictive Control of an Industrial Lime Kiln," *Tappi J.*, 203, February (1991)
- Hovd, M., and S. Skogestad, "Procedure for Regulatory Control Structure Selection with Application to the FCC Process," *AIChE J.*, **39**(12), 1938 (1993)
- Alatiqi, I.M., A.A. Dadkhah, A.M. Akbar, and M.F. Hamouda, "Comparison Between Dynamics and Control Performance of Mesophilic and Thermophilic Anaerobic Sludge Digesters," *Chem. Eng. J.*, **55**, B55 (1994)

CASE STUDY PROJECTS

In a typical semester, for the final course project we allow the students (in groups of three) to select from at least five different case studies on multivariable control. A breadth of applications are covered, from biomedical to classical chemical processes (see Table 2). Since the students are allowed to select from a variety of problems, they are more motivated and able to attach physical significance to the problem they study. During the most recent offering of the course, we decided to revise the case-study concept, placing more emphasis on it.

During the last half of the (spring 1997) process control course, the students worked in three-person teams on multivariable control projects that they selected from a choice of five systems: reactive ion etcher; drug infusion; rotary lime kiln; fluidized catalytic cracking unit (FCCU); and anaerobic sludge digester. Control diagrams for each of these case studies are shown in Figure 1. Each project was advised by a different member of an instructional team.

The students were given a brief description of each project. They selected their own teams of three students each and chose a project (project advisors were not designated until after the groups were selected). Each project included many phases typically associated with a control design project: literature review, model development and process identification, control structure selection and controller tuning for SISO systems, multiple SISO loop tuning, and decoupling. This approach gives the undergraduate student a sense of what an industrial control problem involves, including working in a project-team environment with a project advisor. It also gives the graduate students and teaching assistants experience in advising and teaching and reinforces many control-system concepts.

To illustrate the case study, we will use the reactive ion etcher example. The control diagram is shown in Figure 1 and suggested references are in Table 3. Descriptions of all case studies can be obtained by linking to "Educational Material" at the homepage found at

http://www.rpi.edu/~bequeb.)

◐ *Literature Review (1 week)*

Students are given a brief description, with control instrumentation diagrams, for each of the projects. They form groups of three and perform a concise literature review to provide background material on the unit operation of interest and the industry where this process is dominant. They write a concise memo, which is evaluated by the project advisor.

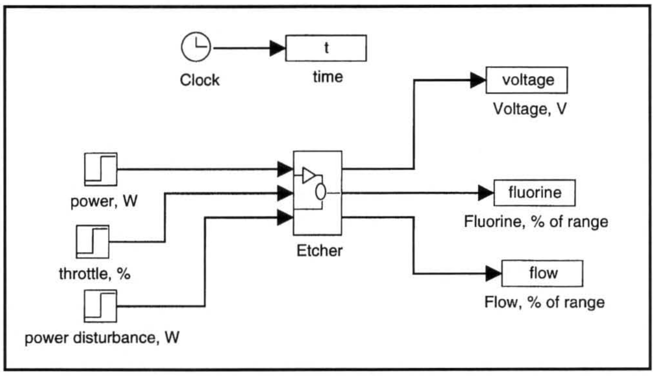


Figure 2. *SIMULINK diagram for open-loop tests.*

◐ ***Model Development*** (1 week)

A SIMULINK file, developed by the project advisor, is provided for each group. The open-loop diagram for the reactive ion etcher is shown in Figure 2. The actual model for the etcher is shown, in *unmasked* form, in Figure 3. Notice that constraints, time-delays, and noise are included. To develop a model that will be used for control system design, the students perform open-loop step tests. Example results are shown in Figure 4.

The groups provide a short memo (with plots and transfer functions attached), summarizing the modeling results. The advisor evaluates the memo and makes suggestions for additional modeling studies, if necessary.

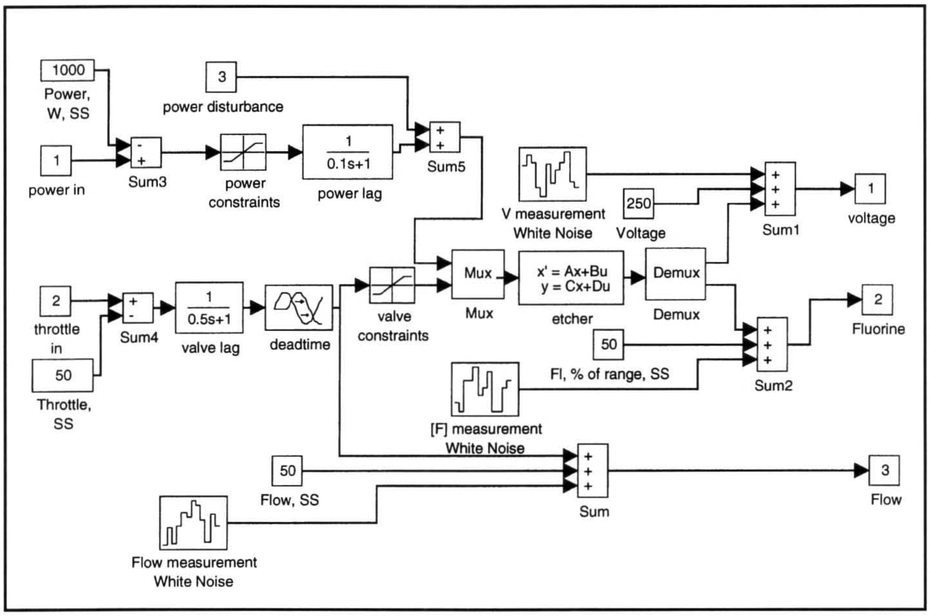


Figure 3. *Etcher unmasked.*

◐ ***SISO Controller Design (1 week)***

In this phase, the groups perform independent SISO control design, usually pairing the loops based on physical considerations. They use one or more of the techniques covered in the course (IMC-based PID is the most popular choice). The groups prepare a short written report describing their results. It is important here that the project advisor catch obvious mistakes before the groups close both loops simultaneously.

◐ ***MV-SISO Controller Design (1 week)***

Here the groups use the relative gain array (RGA) to gain insight about variable pairing and how independently designed loops need to be retuned when both loops are closed. Failure sensitivity is considered very important in this phase; if one loop fails (is opened or saturates), the other loop should not go unstable. Advisor comments on the memo report assist the groups in preparing the final written report.

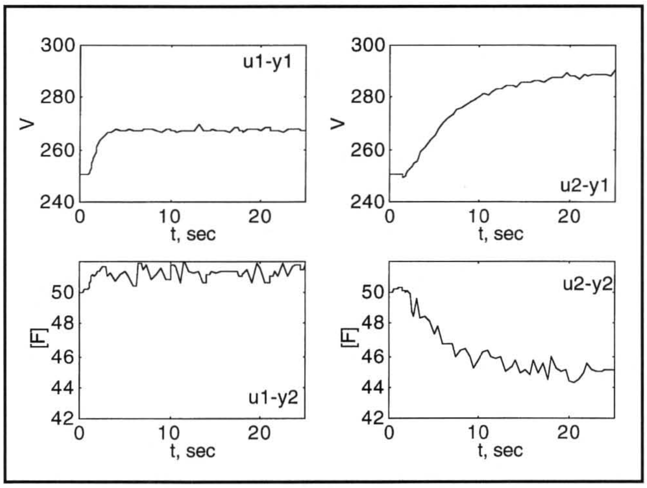


Figure 4. *Step responses.*

◐ ***Final Written Report (1 week)***

This is a formal written report with the structure of a typical technical paper. Much of the material can be gathered (with some rewriting) from previously written memo reports. Most groups also take the time to perform "full" multivariable control studies, such as static and/or dynamic decoupling.

◐ ***Oral Presentation (1/2 week)***

Each group prepares a fifteen-minute oral presentation (plus five minutes for questions) that is evaluated by the project advisor and at least one other evaluator. This gives the students a chance to enhance their oral presentation skills. Also, it is much easier for the project advisor to see what the students really learned from the experience and to provide immediate feedback.

GENERAL COMMENTS

We found that many students have no idea how to perform a literature review. Often, an internet search was conducted using a web-crawler (Alta Vista or a similar program). Approximately one-half of the literature reviews consisted of a rambling essay about motivation or previous work, with no specific citations of the literature. We asked a number of groups to revise their literature review.

Clearly, our case studies in multivariable control require a lot of effort and coordination of all members of the instructional team. It is important to have a robust simulation set-up for the students to perform their initial identification tests. It is also important to provide rapid feedback. Groups generally turned in their memo reports on Friday, and we usually evaluated them and returned them to the students on Monday.

Comments from the undergraduate students have generally been favorable. The case studies give them the opportunity to "tie it all together" and to understand each component of a control-system design project. It should also be noted that the role of the case-study advisors shifts during the projects, ranging at various times from boss to intelligent co-worker to all-knowing judge and inquisitor.

FUTURE TEACHING EFFORTS

Currently, the control course has been taught in a fairly traditional lecture/recitation/computer-lab format, with three lectures and one recitation per week. The recitation typically covers the assignment for that week or reviews a recent exam. Students are also expected to participate in one computer laboratory session per week.

There is a move in the Rensselaer curriculum toward "studio" or "workshop" learning, where students meet twice a week for two-hour sessions with a faculty member and one or two teaching assistants. The idea is for the students to learn interactively by solving problems rather than by passively listening to lectures. Rensselaer is currently renovating or constructing a large number of classrooms to fit the studio format, with student workstations (not just computers) where students can interact and solve problems in groups. The instructor or teaching assistant can give "mini-lectures" as groups encounter common stumbling blocks or can provide more background material as needed.

Since the dynamics and control sequence is taught during the junior year, it offers an excellent opportunity to consider process control implications in the process-design course. We plan to do this as process-flowsheeting packages begin to have dynamic extensions that are relatively easy to use.

SUMMARY

We have presented an approach to using case-study projects in a process control course. The projects are more open-ended than typical undergraduate assignments, provide more experience working in a group environment, and further develop written and oral presentation skills. In addition to the learning experience for the undergraduates, we have found that the teaching assistants, the graduate students, and the instructor also learn from the approach.

REFERENCES

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2. Bequette, B.W., *Process Dynamics: Modeling Analysis and Simulation,* Prentice Hall, Upper Saddle River, NJ (1998)
3. Bequette, B.W., *An Introduction to Model-Based Control,* Prentice Hall (in press, 1999) ❐

BOOK REVIEW: *Mathematical Methods*

Continued from page 189

takes a fairly classical approach, and the authors dig into first-order partial differential equations in Chapter 6 with relish. They offer a particularly thorough treatment of the subject replete with examples of waves, shocks, and weak solutions. This is obviously a favorite topic of the authors, and many chemical engineers dealing with packed bed or chromatographic separations will find meaty bones to chew on in Chapter 6.

Fourier and Hankel transforms are covered in Chapter 7, but the applications to the vibrating circular membrane and semi-infinite strips and cylinders are not particularly stimulating for the chemical engineer. The applications of Laplace transforms in Chapter 8 are probably of greater relevance to chemical engineers.

Although the references at the end of each chapter are not extensive, they are well thought out and direct the interested reader to more comprehensive treatments of the subjects. The variety of mathematical tools useful to chemical engineers is reasonably well covered, and the authors point out that they felt it necessary to exclude complex variables, statistics, and numerical methods. It would have been reasonable to include a short summary of similarity analysis because similarity solutions are so often encountered in fluid mechanics and heat and mass transport processes. An instructor may wish to supplement the book with examples of similarity analysis.

Some of the chapters are beyond the abilities of many undergraduates, but chemical engineering graduate students would profit greatly by working through the entire nine chapters. I plan to use this text in my graduate course in mathematical methods applied to chemical engineering, replacing Hildebrand's widely used book *Advanced Calculus for Applications,* because it is necessary to supplement Hildebrand's book with chemical engineering applications. Varma and Morbidelli do this well and at a cost that is reasonable.

One finds that the book has been carefully proofread, for it is difficult to find typographical errors. The figures are simple and uncluttered, and they are entirely adequate to illustrate the relevant mathematics. There is a good set of problems at the end of each chapter, and many chemical engineering applications are incorporated in these problems.

The rigor and sophistication of this book go well beyond the few competing texts that claim to be advanced mathematics for chemical engineers, and I can add my humble imprimatur to those of Professors Amundson and Aris who encouraged the authors to write this book. ❐