Case Study Projects in an Undergraduate Process Control Course

B. Wayne Bequette[*] , Kevin D. Schott, Vinay Prasad, Venkatesh Natarajan and Ramesh R. Rao

Department of Chemical Engineering, Rensselaer Polytechnic Institute
Troy, NY 12180-3590

Keywords: Process Control, Case Studies, Simulation, Team Projects

Abstract

In this paper we present a case study approach to teaching undergraduate chemical process control. During the last half of a one-semester chemical process control course, the students work in three-person teams on a multivariable control project that they have selected from a choice of five processes. Each project is advised by a different member of an instructional team (instructor, course teaching assistant or a graduate student studying control). Each project includes 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. This approach provides a sense of an industrial control problem for the undergraduate student, 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.

1. Motivation

It has been argued in recent years that engineering students need more of the following in their undergraduate education

- Open-ended problems
- Team projects
- Written memos and reports and oral presentations
- Practical problems
- *Interactive learning*, rather than complete dissemination of course material by lecturing

We try and include these in our process control course. The focus of this paper is on a case study project which is performed during most of the latter half of the semester. In section 2 we provide some background on the Rensselaer curriculum, while the introductory process control material is covered in section 3. Section 4 reviews the various venues that we use for distributing course material. The thrust of this paper, a major case study control project, is presented in section 5. Future teaching efforts and a summary are provided in sections 6 and 7.

2. Background

The department of chemical engineering graduates roughly 80-90 BS ChE's, while the department of energy and environmental engineering graduates roughly 30 EnvE's each year. 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 ChE's and EnvE's.

Rensselaer Curriculum

A distinguishing characteristic of the Rensselaer curriculum (in addition to the fact that both chemical and environmental engineers 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 during the junior year is that students tend to take more of a process systems engineering viewpoint in their senior courses (reactor design, separations processes, process design, lab I and II)

Process Dynamics

The process dynamics course covers more material in more depth than the "front end" of a typical single-course in dynamics and control. A particular emphasis is given to numerical methods for the solution of algebraic and differential equations, with MATLAB as the numerical analysis package. State space models receive much attention. Also, phase-plane analysis and an introduction to nonlinear dynamics and chaos is provided. The textbook for this course is to be published by Prentice Hall (Bequette, 1998); see Bequette (1997) for more details about the course.

[*] Phone: (518)276-6683, Fax: (518)276-4030, Email: bequette@rpi.edu, WWW: http://www.rpi.edu/~bequeb

3. Introductory Material for Process Control

A major advantage to 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 this 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

We summarize each of the topics, including characteristic homework problems, in Appendix 1. The focus of this paper, control case studies, is presented in section 5.

What is not covered in this course

When we first taught this course we also introduced discrete control system design, and 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 readings course in advanced control, where we cover digital control and MPC.

4. Communication

Here we discuss the text used, lectures, computer labs, course homepage, and electronic newsgroup.

Text Material

The text used in this course is to be published by Prentice Hall (Bequette, 1999). A number of excellent process control textbooks are currently available, but each lacks some of the following features of our text:

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

Lectures

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 and motivate as much discussion as possible by using a "Phil Donahue" approach. There are three-50 minute lectures per week; a 50-minute recitation from 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, PC, VCR, computer/video projector and two overhead transparency projectors).

Computer Labs and Homework

Homework assignments are given weekly and solved in groups of three; typical assignments are discussed in Appendix 1. The students are expected to provide a one-page written memo summarizing the results of the assignment. Working in groups improves their interaction skills and enables more complex problems to be solved. 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 is for 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 30 workstations for three nights/week. The lab is staffed by the instructor or a TA.

Homepage

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. This is found by linking to Courses from the following URL:

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

Newsgroup

An electronic newsgroup is used to answer common questions, or to post notes about the lecture material. Rather than responding to many individual email 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).

Exams

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 this has been too big of a challenge to organize for 120 students, thus far.

5. Case Study Projects

In a typical semester, for the final course project we allow the students (in groups of 3) to select from at least five different case studies on multivariable control. A breadth of applications are covered, from biomedical to classical chemical processes; a list is provided in Appendix 2. Since the students are allowed to select from a wide-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 and place much more emphasis on it, as discussed next.

The Most Recent Incarnation of the Course (Spring 1997)

During the last half of the process control course, the students worked in three-person teams on a multivariable control project that they selected from a choice of five systems: (i) reactive ion etcher, (ii) drug infusion, (iii) rotary lime kiln, (iv) fluidized catalytic cracking unit (FCCU), and (v) anaerobic sludge digester. Control diagrams for each of these case studies are shown in Appendix 2.

Each project was advised by a different member of an instructional team:

Kevin Schott - Instructor (rotary lime kiln)
Vinay Prasad - Grad TA (FCCU)
Venkatesh Natarajan - Grad TA (anaerobic digester)
Ramesh Rao - Grad RA (drug infusion)
B. Wayne Bequette - Professor (reactive ion etcher)

The students were provided with a brief description of each project. They selected their own teams of three students, 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 provides a sense of an industrial control problem for the undergraduate student, 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.

We illustrate the case study by using the reactive ion etcher example; the control diagram is shown in Figure 1 and suggested references are in Appendix 2. Descriptions of all case studies can be obtained by linking to Educational Material at the instructor homepage (http://www.rpi.edu/~bequeb).

5.1 Literature review (1 week)

The students are provided 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.

5.2 Model Development (1 week)

A SIMULINK file, developed by the project advisor, is provided to each group. The open-loop diagram for the reactive ion etcher is shown in Fig. 2. The actual model for the etcher is shown, in *unmasked* form, in Fig. 3. Notice that constraints, time-delays, and noise are included.

To develop a model which will be used for control system design, the students perform open-loop step tests. Example results are shown in Fig. 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.

5.3 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 one). Groups provide a short written report describing their results. Here it is important that the project advisor catch obvious mistakes before the groups close both loops simultaneously.

5.4 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.

5.5 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 the previously written memo reports. Most groups also take the time to perform "full" multivariable control studies, such as static and/or dynamic decoupling.

5.6 Oral Presentation (1/2 week)
Each group prepares a fifteen minute oral presentation (+ 5 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 done using a web-crawler (Alta Vista or something similar). Approximately one-half of the literature reviews consisted of a rambling essay about motivation or previous work, with no specific citation to 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 had them evaluated and returned on Monday.

Comments from the undergraduate students have generally been favorable. The case studies give them the opportunity to "tie it all together" and 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 time from boss to smart co-worker to all-knowing judge and inquisitor.

6. 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/week. The recitation typically covers the assignment for that week or reviews an exam given recently. Students are also expected to participate in one computer laboratory session per week.

Studio or Workshop Learning
There is a move in the Rensselaer curriculum towards "studio" or "workshop" learning, where students meet twice/week for two hours per session, with a faculty member and 1 or 2 TA's. 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 TA can give "mini-lectures" as groups encounter common stumbling blocks, or to provide more background material.

Integration of Process Design and Control
Since the dynamics and control sequence is taught during the junior year, we have 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.

7. 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 TA's, graduate students and instructor all learn a lot from the approach.

References

Bequette, B.W. "An Undergraduate Course in Process Dynamics," *Comp. Chem. Eng.* **21**(Suppl), S261-S266 (1997).

Bequette, B. W. Process Dynamics: Modeling Analysis and Simulation, Prentice Hall, Upper Saddle River, NJ (1998).

Bequette, B. W. An Introduction to Model-based Control, Prentice Hall (in preparation for publication in 1999).

Appendix 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), 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 semester. 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. About this time of the semester the students 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.

Appendix 2. Control Case Studies

Mixing Tank (Tutorial example) Evaporator
Dowtherm Heater Solution copolymerization
Reactive Ion Etcher Fluidized cat. cracking unit
Drug Infusion System Wet grinding circuit
Rotary Lime Kiln Anaerobic Sludge Digester

References for Five Case Studies used in 1997

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

Badgwell, 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. Engng*., 19(1), 1-41 (1995).

Lee, H.H., Fundamentals of Microelectronics Processing, McGraw-Hill, New York (1990).

Sze, S.M., VLSI Technology, McGraw-Hill, New York (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., Elta, M., 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) 286-296 (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), 765-778 (1992).

Charos, G.N., Y. Arkun and R.A. Taylor, "Model Predictive Control of an Industrial Lime Kiln," *Tappi Journal*, 203-211 (February 1991).

Hovd, M. and S. Skogestad, "Procedure for Regulatory Control Structure Selection with Application to the FCC Process," *AIChE J.* 39(12), 1938-1953 (1993).

Alatiqi, I.M., A.A. Dadkhah, A.M. Akbar, M.F. Hamouda, “Comparison Between Dynamics and Control Performance of Mesophilic and Thermophilic Anaerobic Sludge Digesters,” *Chem. Eng. J.*, 55, B55-B66 (1994).

Figures

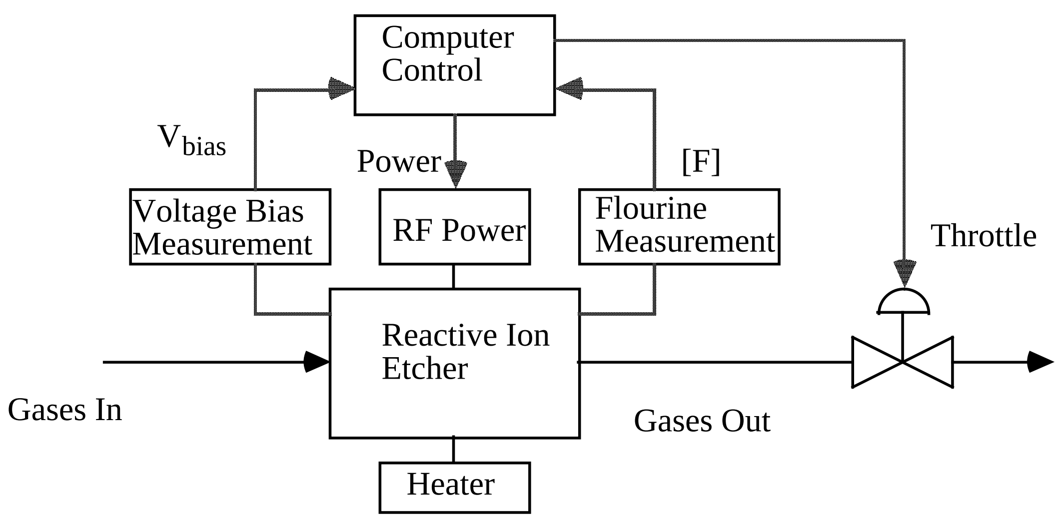


Fig. 1. Reactive Ion Etcher

Fig. 2. SIMULINK diagram for open-loop tests

Fig. 3. Etcher Unmasked.

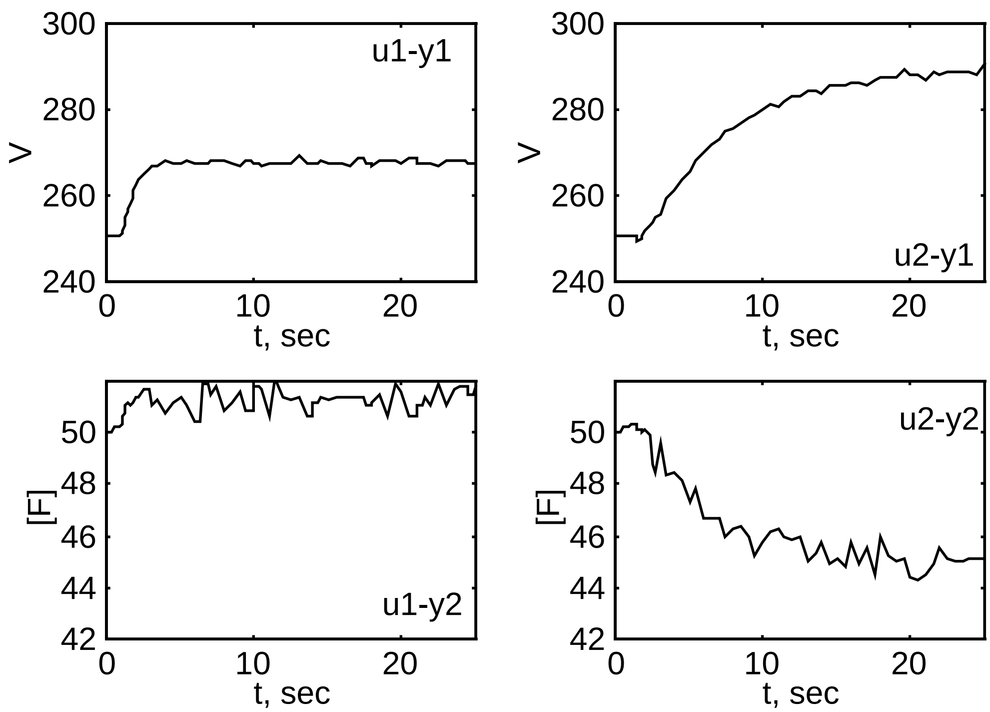
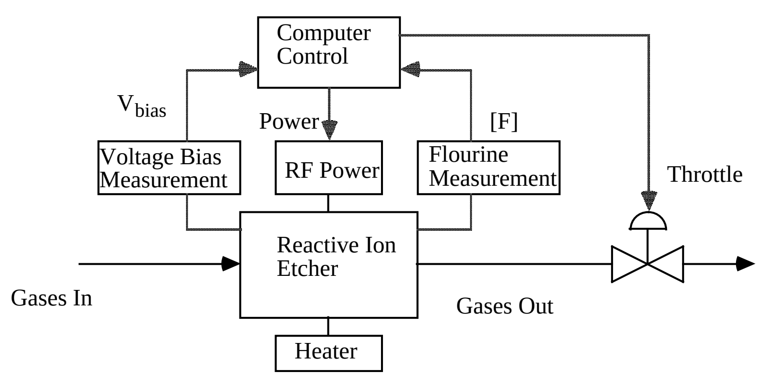
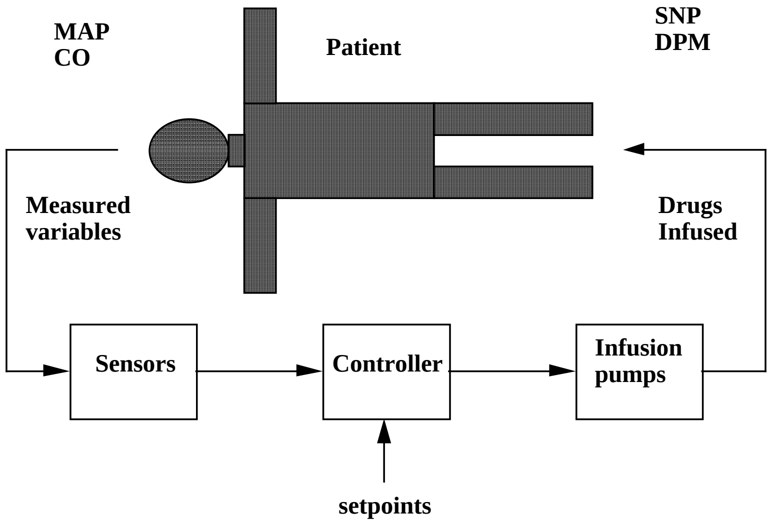


Fig. 4. Step Responses

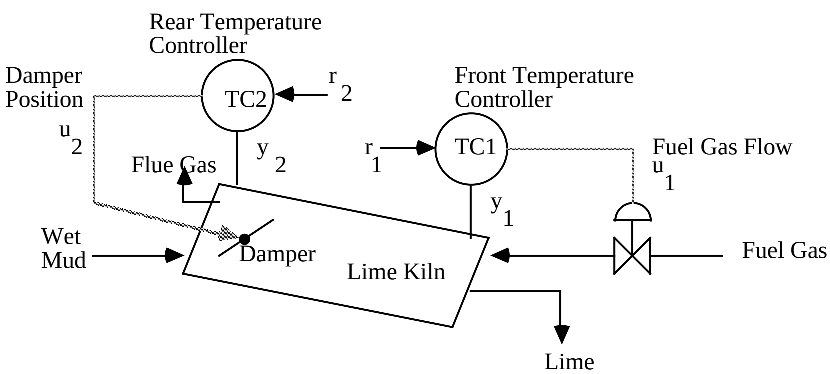
Case Study Instrumentation Diagrams



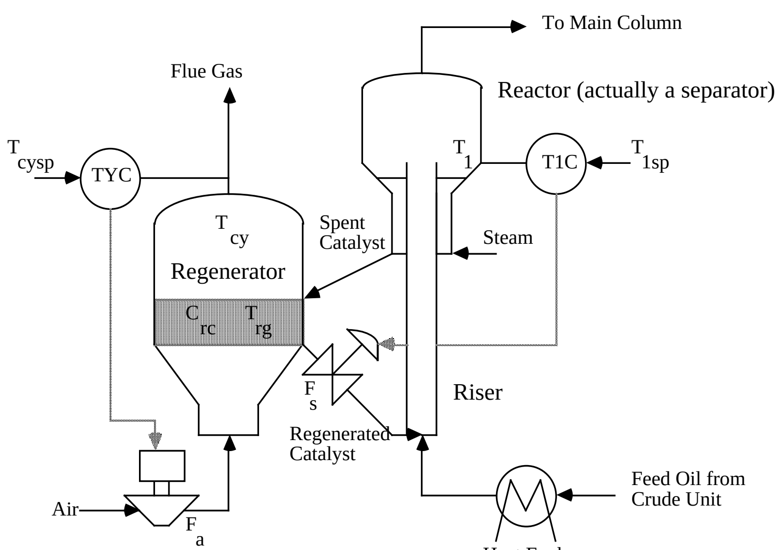
Reactive Ion Etcher



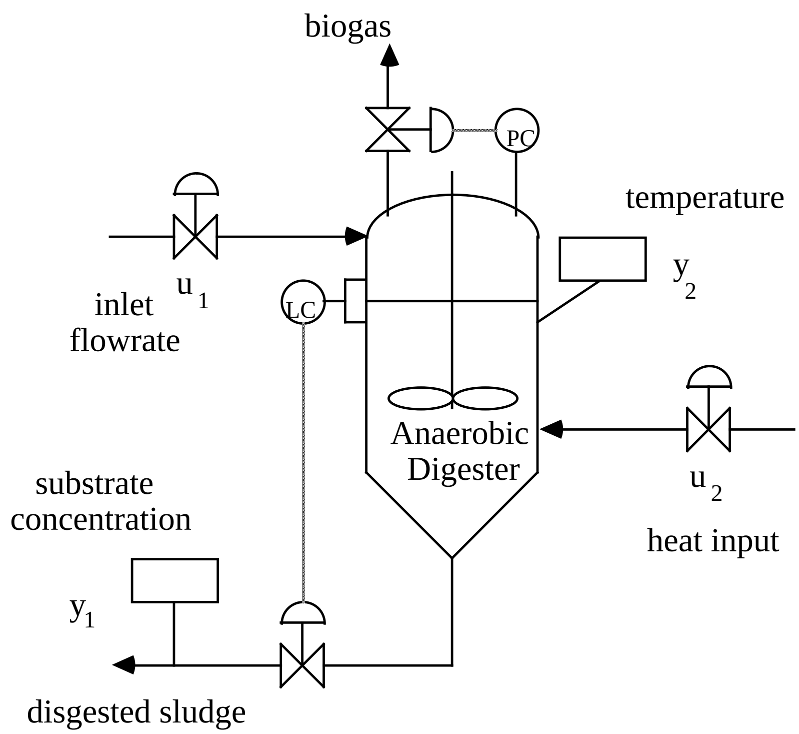
Drug Infusion Control



Rotary Lime Kiln



Fluidized Catalytic Cracking Unit (FCCU)



Anaerobic Sludge Digester