A Course In . . .

PROCESS DYNAMICS AND CONTROL

An Experience to Bridge the Gap Between Theory and Industrial Practice

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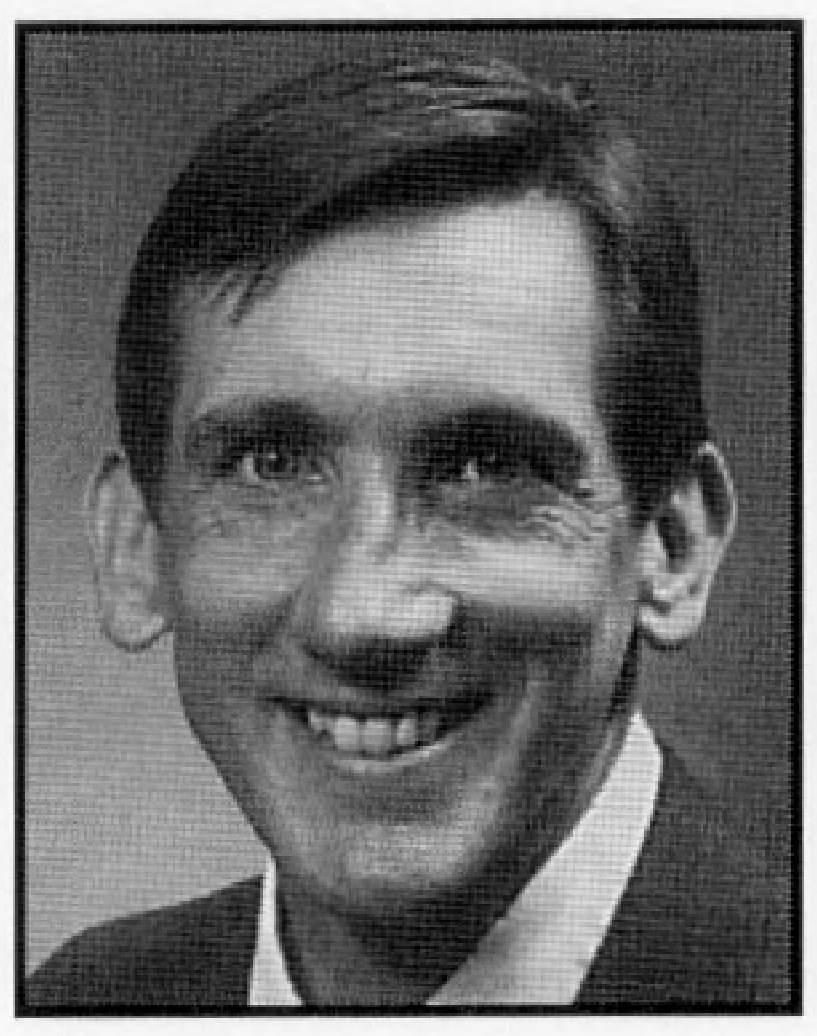
► I'm the professor.

► *And we're the students . . . together we'd like to tell you about a graduate course in process dynamics and control that emphasizes the application of fundamentals to industrial practice.*

There is only so much experience that can be crammed into a three-credit course . . .

It was worth five credits!

. . . and every professor must choose the subject matter that best balances what he or she can provide with what the students need. Most of our MS and PhD students enter industrial practice where 90% of the loops use conventional control techniques, where the KISS principle guides engineering, and where employers value those who can "make-it-happen" within the commercial environment. Industry needs people who can practice the theory, and this course attempts to do just that.



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__J. Joseph Anderson__ received his BS and MS degrees in Chemical Engineering from Oklahoma State University and is presently working toward his PhD at Texas Tech University. His current research focuses on distillation control systems, and he has a strong interest in computer applications in chemical engineering.

Students implement, tune, and explore the issues associated with control in MIMO systems on a realistically noisy, nonstationary, nonlinear simulator of a chemical process.

Realistically noisy? The feed flow and composition ranged ±50% of their nominal values over a several hour period. Setting up PI controls for such a wide control span was difficult, to say the least.

With this experience, the concepts and issues that justify the subject matter of subsequent control courses and laboratories are unambiguously a part of the student's experience. They understand the fundamentals, analyze the relevant issues, make the right design choices, and implement the design.

My first goal for graduate education was to gain the knowledge that would make me successful as a process control engineer. Analyzing something for an ideal situation doesn't help industry. Practicality and applicability is what I sought.

A NONSTANDARD CLASSROOM APPROACH

Learn by doing is the approach used. There are no tests or home assignments—only eight projects.

Having no homework or tests was a refreshing idea at the beginning of the semester, but those "only eight" projects took quite a bit of time.

The projects progress from understanding the process simulator, to analyzing the dynamic responses, to adding primitive controls, to finally implementing an integrated control system and to reconsidering the process design.

Projects were much like laboratory exercises. We got a maximum grade of B if the control technique was implemented, demonstrated by simulation, and explained in the report. To obtain an A, we were expected to explore the relative merits of alternative techniques and to use simulation experiments to confirm their theoretical analyses.

Since the major objective of the course is to make people functional as control engineers, I want every student to get at least a B. To make this happen, discussions with the professor,

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the teaching assistant, and with each other are encouraged to help students debug their routines and to overcome conceptual errors. And, except for late submissions, any project with a grade of C or less can be resubmitted for a maximum grade of B.

PROCESS DESCRIPTION

The process is a two-component adiabatic flash (see Figure 1). The objective is to control liquid composition; necessarily, liquid level must also be controlled. The simulator proceeds in five stages. Stage I is the adiabatic flash at the inlet valve and is dependent on the tank pressure as well as the inlet composition and temperature. Flashed vapor enters the tank vapor space, Stage II, where ideal, well-mixed dynamic energy and material balances determine the tank vapor space pressure, composition, and temperature. Unflashed liquid similarly mixes with the tank liquid in Stage III. Evaporation and condensation at the tank liquid-vapor interface and heat transfer between the tank walls and liquid contents are included. The vapor exit rate, Stage IV, depends on the valve characteristic, stem position, and the downstream pressure. The vapor exit rate influences tank pressure, which in turn influences the results in Stage I. The liquid exit rate, Stage V, similarly depends on the valve characteristic, stem position, and the hydrostatic head.

Both the vapor and liquid valves include the dynamic responses to their pneumatic systems. The vapor valve is air-to-close and the liquid valve is air-to-open. The liquid composition analyzer suffers from a considerable lag. Environmental influences are simulated by ARMA drifts on the inlet flow rate, feed temperature, feed composition, downstream vapor pressure, and downstream liquid pressure. Further, Gaussian distributed noise is added to all measurements. The components and the process conditions used are fictitious, but are an adequate representation of a real process.

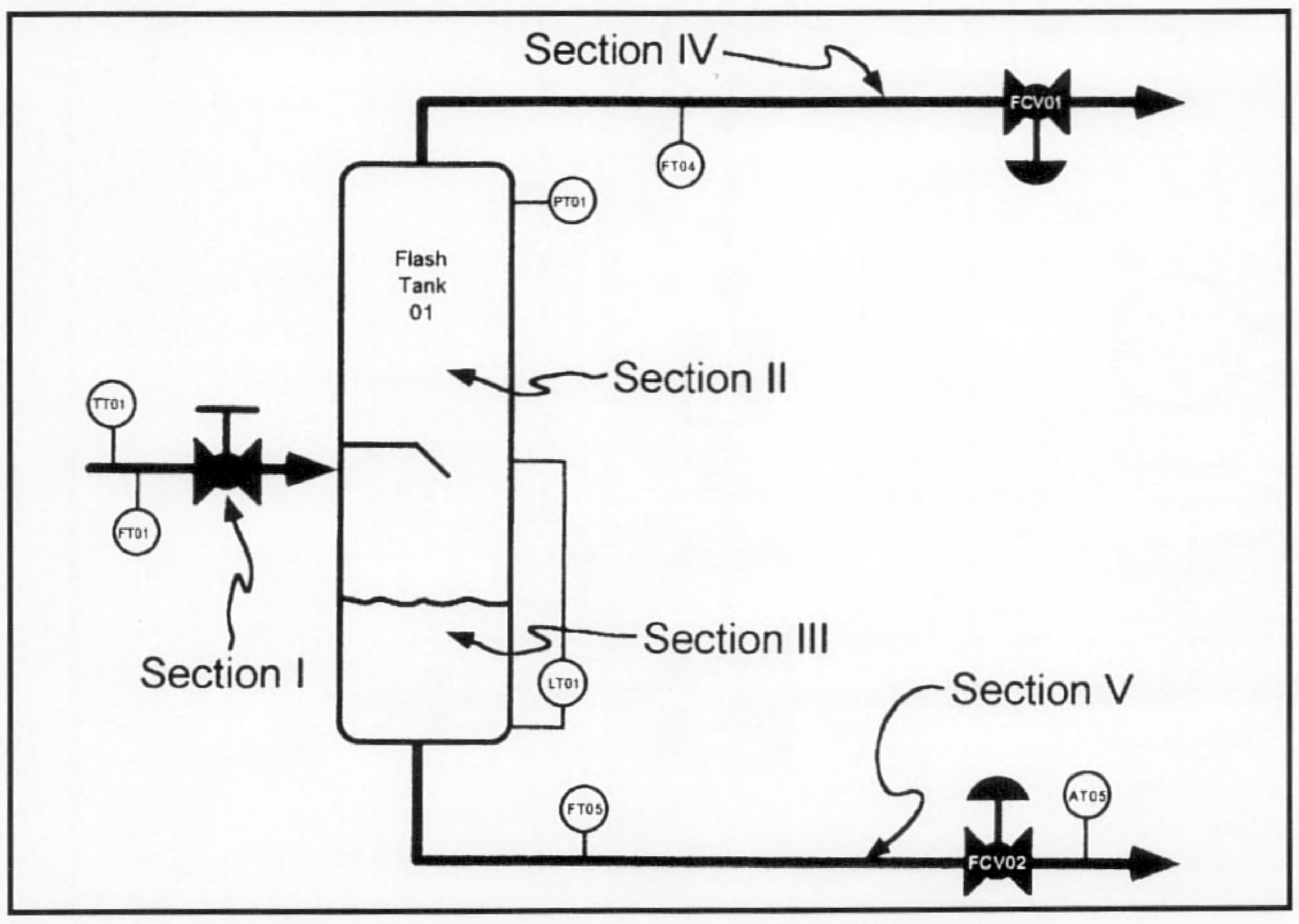


Figure 1. *Schematic of the flash tank.*

The experience I got from simulating valve lags, noise, and drifts really made this work fun. It was a learning experience that I shall apply to my distillation column research.

The process automatically shuts down and plays the "Death March" from Chopin's *Saul* if any of the three constraints are hit: high tank pressure, low liquid level, or high liquid level. The high tank pressure constraint is necessary for safe operation of the flash tank, the low liquid level constraint is necessary to prevent the gas from getting into the liquid product, and the high liquid level constraint is necessary to prevent the liquid from covering the flashing inlet.

The simulator was programmed in Microsoft Quick BASIC for several reasons. It provides a convenient mechanism for operator-initiated keyboard entries to toggle between controller modes CAS/AUTO/MAN, to adjust tuning coefficients, and to switch environmental influences ON/OFF. The keyboard feature also allows one to make setpoint changes in the controlled variables and step/ramp disturbances in the feed flow rate, feed temperature, and feed composition. The simulator also provides a real-time strip chart and displays the process status on the screen. The simulator source code, EXE file, and detailed description are available by sending a blank 3.5" diskette to the corresponding author of this article (RRR).

While others abandoned ship and programmed in FORTRAN, the Quick BASIC source code made interaction with this simulation fun, except when the level jumped to 0.8 meters and shut the system down and everyone else heard my computer laugh the "Death March" at me.

The best part of the program was the graphical interface. We could watch the system as it worked. Interactive monitoring of the level, pressure, and composition helped us understand the Laplace transform descriptions of those behaviors.

STUDENT PROJECTS

The report on each project must demonstrate the student's understanding of the technique and the results of the implementation.

For project I, we added various so-called "small" features to the deterministic simulator (to force familiarity with it) and modeled several dynamic responses with customary empirical fits to the appropriate, simple transfer functions. Nonlinear behavior and shutdown imposed limits on operator freedom became obvious to us.

For project II, we added noise, disturbances, signal conversion and transmission features, control device dynamics, and modification of the process model. The confounding effects of non-stationary process *behavior and difficulty of manual control were experienced—much to our chagrin but to the professor's amusement.*

Imagine—they even pay me to participate in such fun!

Imagine—we even paid to participate in "such fun."

In project III, a primitive PID control scheme from LT to LRC to FCV02 and from AT to ARC to FCV01 was implemented, with bumpless transfer features for changes from MAN to AUTO or back. The controllers were tuned and found to work satisfactorily most of the time, but we found that sometimes disturbances caused integral windup and consequential loss of control, triggering automatic shutdowns. We added goodness of control measures such as ISE and cumulative valve travel to evaluate the control system responses.

Project IV required the use of internal reset feedback to prevent windup. We demonstrated that this modification works as desired with "bad drifts."

Cascading LT to LRC to FRC to FCV02 and AT to ARC to PRC to FCV01 was the objective of project V. Here, external reset feedback was used to prevent windup and output tracking was added for bumpless transfer. ISE was used to quantify the benefits of cascade control.

In project VI, ratio and feedforward additions were implemented, requiring minor changes to the reset feedback signals. We actually found feedforward control to be of very little benefit for our case with cascade and ratio functioning, and so removed it. But we kept the cascade and the ratio features in place.

In project VII, a one-way decoupler was added to alleviate the interaction between the composition and the level loops, and this was also found to be inconsequential. But the override of the composition controller by a high-pressure limit prevented occasional shutdowns caused by the high-tank-pressure constraint.

Finally, project VIII required the addition of a supervisory optimizer to determine the composition setpoint that maximized the net product value.

In each of the projects IV through VII, the students also had to submit an annotated P&ID. Figure 2 typifies one author's (JJA) work. Enjoy. I required the students to put cartoon balloons on the P&IDs so they would be able to characterize the function of the elements and the signal "conversations."

In order to obtain an "A" grade, the students had to experience additional control technology. Typical criteria are listed in Table 1.

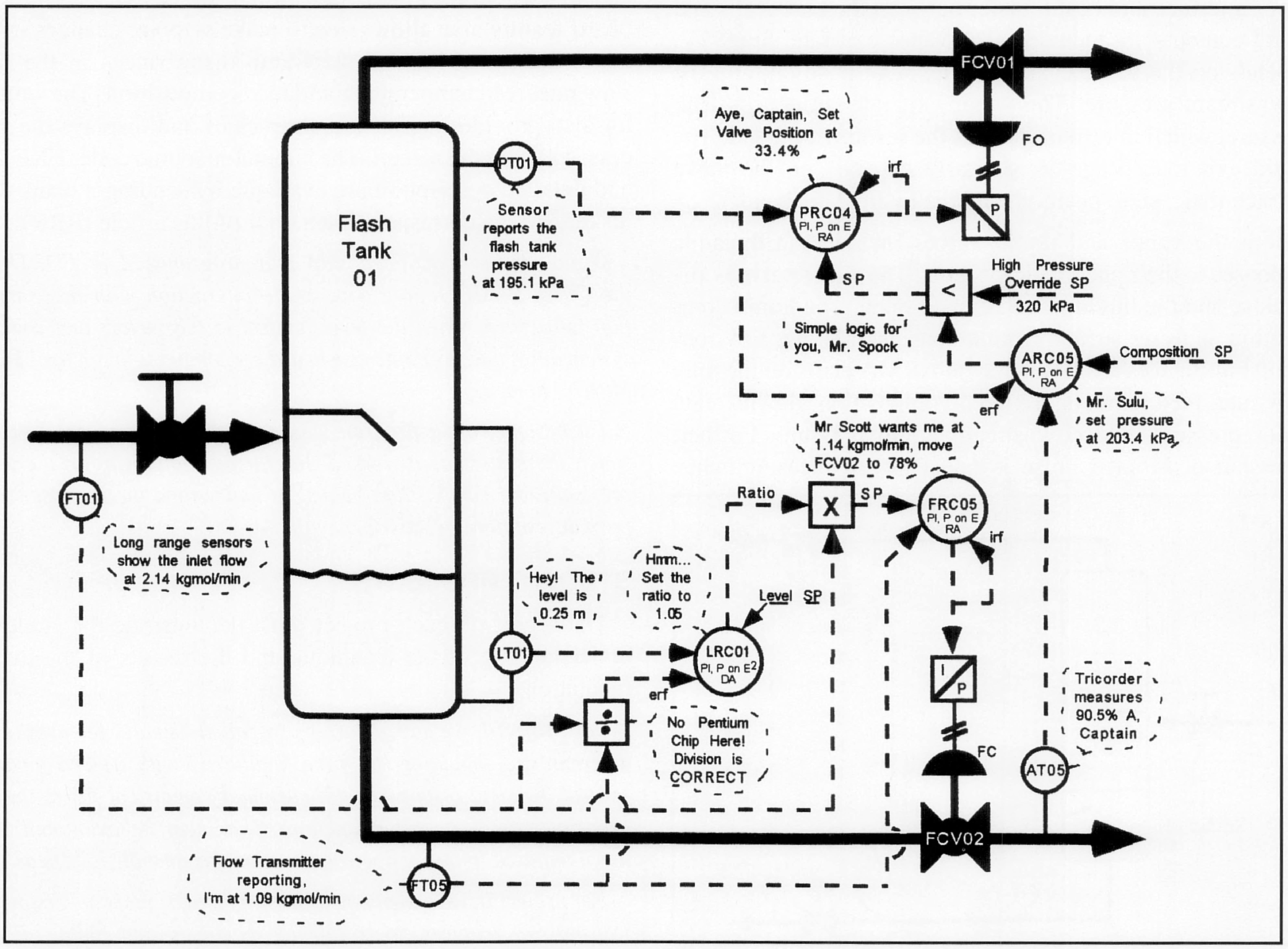


Figure 2. Annotated P&ID (typical)

ILLUSTRATION

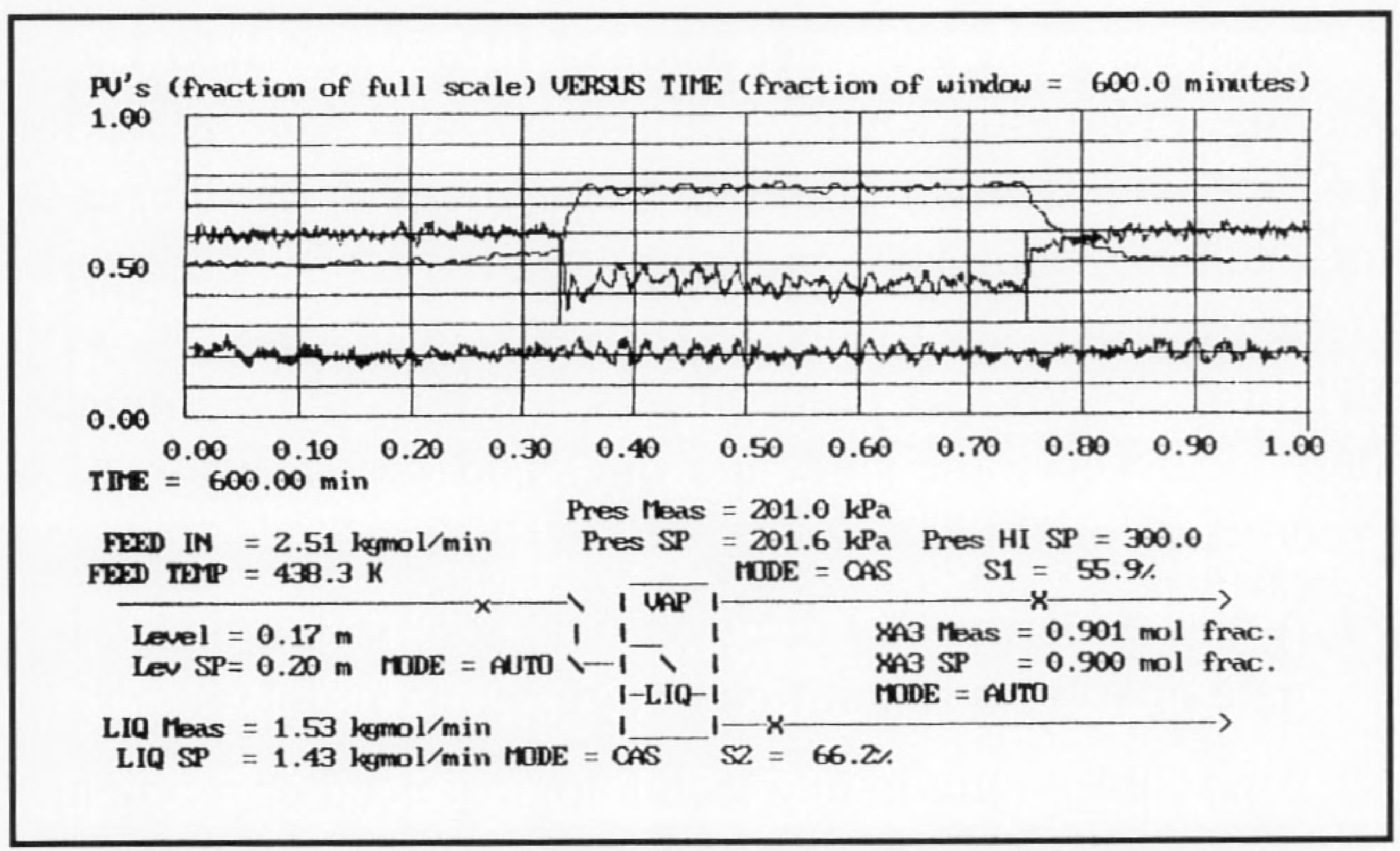
As an illustration of the results, Figure 3 is the screen print of the display for project VII (cascade+ratio+override shown in Figure 2). The "wrap-around" strip chart shows the past ten hours of simulated process and controller response. At about 210 minutes, events caused the analyzer controller to ask for a high-pressure setpoint, and the pressure override took effect. At around 450 minutes, events changed—the override was no longer necessary and control was immediately resumed with no windup.

EVALUATION OF THE CLASS AND TEACHING METHODS

Because the course content is progressively structured, and because projects make us fully experience the techniques, we feel that we are capable of applying advanced control in the real world. Further, the course covered a wide gamut of topics in process control practice. The projects are thought provoking, and more often than not entail coming up with independent and clever solutions.

TABLE 1
Typical Additional Criteria to Obtain an "A" Grade

- Explore the influence of ARMA coefficients
- Compare methods to obtain model coefficients
- Test if the filtered signal noise reduction matched analytical expectations.
- Develop a procedure to fit SOPDT models
- Compare standard tuning recipes to heuristic methods
- Investigate the benefits of statistically-based filters.
- Compare theoretical and actual propagation of variance through the P, I, and D terms.
- Compare theoretical and actual limits of controlled-system stability.
- Compare different anti-windup methods.
- Investigate controller modifications (gain scheduling, elel, P-on-X).
- Implement tertiary cascade control strategies.
- Investigate the effect of process equipment sizing on goodness of control.
- Add high- and low-level override controllers.
- Compare linear valves with equal-percentage valves.
- Calculate RGA elements for a variety of MV/CV choices.
- Implement a method for automatic identification of steady state.



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TIME =  600.00 min
                                   Pres Meas = 201.0 kPa
 FEED IN   = 2.51 kgmol/min         Pres SP   = 201.6 kPa  Pres HI SP = 300.0
FEED TEMP = 438.3 K                            MODE = CAS       S1 =  55.9%
  Level  = 0.17 m
  Lev SP= 0.20 m  MODE = AUTO                          XA3 Meas = 0.901 mol frac.
                                                       XA3 SP   = 0.900 mol frac.
                                                       MODE = AUTO
 LIQ Meas  = 1.53 kgmol/min
  LIQ SP   = 1.43 kgmol/min MODE = CAS     S2 =  66.2%
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Figure 3. *Interactive screen display of the system.*

SUGGESTIONS FOR FURTHER IMPROVEMENT

Additions can easily be made to the relatively simple process simulator. The liquid and vapor heat capacities can be made temperature dependent and the feed could be multicomponent. Incorporating an in-tank or feed heating/cooling device can facilitate more flexibility in controlling liquid composition. The process behavior can easily be changed by changing the feed constituents, inlet flow range, tank size, and valve characteristics. But too much rigor may mask the control aspects for non-ChEs who may take the course.

Having less disturbing disturbances, especially in the feed rate, would be the biggest improvement. The "relatively simple" flash tank definitely represents a nonlinear problem. It appears simple from the outside, but is deceptively difficult to control.

CONCLUSIONS

From the perspectives of the professor, the teaching assistant, and the students, it is collectively felt that this approach is an excellent method for training people to implement advanced control strategies and to be prepared for subsequent courses in control theory and model-based controllers.

ACKNOWLEDGMENT

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NOMENCLATURE

ARC	Analysis Recording Controller
ARMA	Autoregressive Moving Average
AT	Analyzer Transmitter
AUTO	Automatic
CAS	Cascade
CV	Controlled Variable
FCV01	Flow Control Valve #1
FCV02	Flow Control Valve #2
FRC	Flow Recording Controller
ISE	Integral of Squared Error
KISS	Keep It Simple, Stupid
LRC	Level Recording Controller
LT	Level Transmitter
MAN	Manual
MIMO	Multiple-Input Multiple-Output
MV	Manipulated Variable
P&ID	Piping and Instrument Diagram
P-on-X	Proportional-on-Measurement
PID	Proportional Integral and Derivative
PRC	Pressure Recording Controller
RGA	Relative Gain Array
SOPDT	Second Order Plus Dead Time ❐