# BETTER INTEGRATION OF PROCESS DESIGN / CONTROL PRINCIPLES IN ENGINEERING LABS

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## ABSTRACT

Where is the best place to teach basic principles of process control, data reconciliation, nonequilibrium analysis of multistage processes, statistical design of experiments, design of alarms and interlocks for a process, and hazard analysis? Maybe you can get some of it across in the classroom, but we contend that you can probably do it better in the labs. While many Engineering programs are reducing active lab experiences, with the help of veteran industrial practitioners and a partnership with data acquisition / control companies (Emerson Process Management, Honeywell IAC, and National Instruments), we've expanded ours. The labs are now more representative of the upper level curriculum, both reinforcing and in some ways anticipating several topics. For example, we use a ternary distillation experiment to teach fundamentals of a nonequilibrium transport package (ChemSep 5®), a polymerization / separation experiment to introduce students to alarm / interlock logic, and pH neutralization, heat exchanger train and the previously mentioned experiments both for introducing process control concepts and for more advanced topics such as dynamic modeling of processes and online composition control. We are even giving students valuable exposure to topics that, while important, are discussed cursorily (if at all) in typical classes – e.g., two-phase flow and tracer analysis in a combined packed bed / fluidized bed / nonideal reactor experiment, and crystallization in a newly designed experiment for salicylic acid (intermediate in production of aspirin) purification. Of course, by combining some standalone process simulation with the experimentation, the students also learn the use of process simulators (e.g., ASPEN®, HYSYS®) better and faster.

The capabilities and ease of use of modern data acquisition/control systems, the advent of paperless labs, and the familiarity of students with Excel as a notebook platform now give us the opportunity to make labs less an exercise in drudgery and more the locus of active learning for the entire department. We'll discuss how this has been accomplished at LSU over the last seven years, and specify what worked and what didn't. We'll also discuss some of the advantages / disadvantages from a typical department's perspective of all three of our data acquisition/control systems (Emerson Process Management's Delta V®; National Instruments' Labview® and Honeywell IAC's TPS®; their characteristics span the space of all such systems currently available.

## INTRODUCTION

The LSU Chemical Engineering Department is Louisiana's largest. Achievements of the department include: (i) annual production of more than 70 B.S. recipients; (ii) ranking among the nation's top 20 chemical engineering departments in undergraduate enrollment and degrees. The chemical / energy / plastics / paper / food processing industries, which employ our students, are the state's and region's largest. Seven years ago ABET and the College Industrial Advisory Committee asked for significant laboratory modernization. A plan was developed to renovate lab facilities used by our Juniors and Seniors. We re-engineered experiments from manual to computerized data acquisition and control, added new experiments to supplement the curriculum, and scrapped obsolete ones. The breadth of experiments was expanded to include polymer science, nonlinear control, environmental analysis and remediation, and biochemical engineering, all of increasing importance in our curriculum. Our new facilities are also used as teaching tools in courses such as Unit Operations (required, 4 hours credit), Process Control (required, 3 hours), and Senior Projects (optional, 3 hours). Of course, the chief uses of lab equipment are in the labs themselves. All our students take both a Junior and a Senior lab.

As part of this modernization we added two large distributed control systems (DCS), a Honeywell TPS with two Universal and two Global Universal Stations and an Emerson Process Management Delta V system with four control stations. These systems control the following experiments: Packed Column Distillation and Nonlinear Control (Honeywell); Tray Distillation, Catalytic Reactor and Polymerization Reactor / Separator (Emerson). We recently were also awarded a grant from the state to add a Biological Crystallization experiment to either the Honeywell or an existing National Instrument system. This third (NI) system controls the following experiments: Heat Exchanger Train; Permeameter (Packed Bed Transport) / Nonideal Reactor; Two Tank Dynamics; Adsorption; Evaporator; Tray Dryer; Simple Heat Exchanger. Finally, we have significantly upgraded our analytical facilities, with more emphasis on online analysis / control, and have rendered the entire department wireless-capable in order to better allow students to retrieve data from control systems and instruments to their laptops.

Our vision of the ChE curriculum of the future is one grounded in the fundamentals, but with far greater emphasis on dynamics, simulation, control and optimization as enabling technologies. This vision largely coincides with the view of the Chemical industry itself (Technology Vision 2020, ACS, 1996), which foresees the primary “engineering” enabling technology not as nanotechnology or biotechnology but as manufacturing and process improvements based on the integration of process control and optimization, the implementation of production planning, scheduling and optimization tools, the design of “smart” processes making use of advanced control schemes, and the improvement of manufacturing process flexibility. Vision 2020 further notes that the software tools to enable these developments either already exist or are rapidly being developed; it is implementation that is lacking. Can anyone doubt that industry expects new engineers to spearhead such implementation? Some academic leaders of our profession have come to similar conclusions (e.g., Luyben et al., 1999; Edgar, 2003), and have noted that the concepts of process dynamics and control find increasing application across almost all manufacturing industries (e.g., electronics, pharmaceuticals).

## PROCESS CONTROL IN THE LABS

An example of the type of new experiment brought on line as part of this program is shown in Figure 1. This is the batch polymerization / separation unit; we polymerize dimethylsiloxanes anionically (a ring-opening polymerization). The low boilers are removed by stripping, and the catalyst by filtration. It is based on a similar unit designed by Dow Corning for Michigan Tech (Barna et al., 1995), but we downsized and simplified it considerably (Dooley et al., 2002). The experiment is used to teach fundamentals of polymerization, batch control, sequencing, control system design, and design of alarm / interlock systems. In fact, students did much of the configuration of the control system and the batch sequencing design as part of their lab assignments. The Emerson Delta V system is programmed using a familiar VBA-type interface; expression and other help facilities eliminate the need to understand programming details, so we can focus on the control. An example interface for programming sequential logic is shown in Figure 2. It is made up of "action" blocks (commands addressing devices or controllers) and "transitions" (logic statements to be satisfied prior to moving to the next block). The sequence in Fig. 2 was written and tested by students as part of Senior Lab, for partial startup of our batch polymerization system. The assignment specified that they develop and test a sequence to meet certain goals (execution in less than 30 min., vacuum / leak test included, hold vacuum below 80 mm Hg for at least 5 min, etc.). Delta V Simulate can fulfill the same functions using the same programming, but for a virtual rather than actual process. An example control module showing the extensive assistance provided in various templates is shown in Figure 3. A typical process control assignment: examine two possible alternatives – (1) gain scheduling of the reactor heating control loop; (2) feedforward control of reactor temperature based on actual heater temperature. The assigned goal was to minimize heating cycle times with <5 K overshoot of desired reactor temperature.

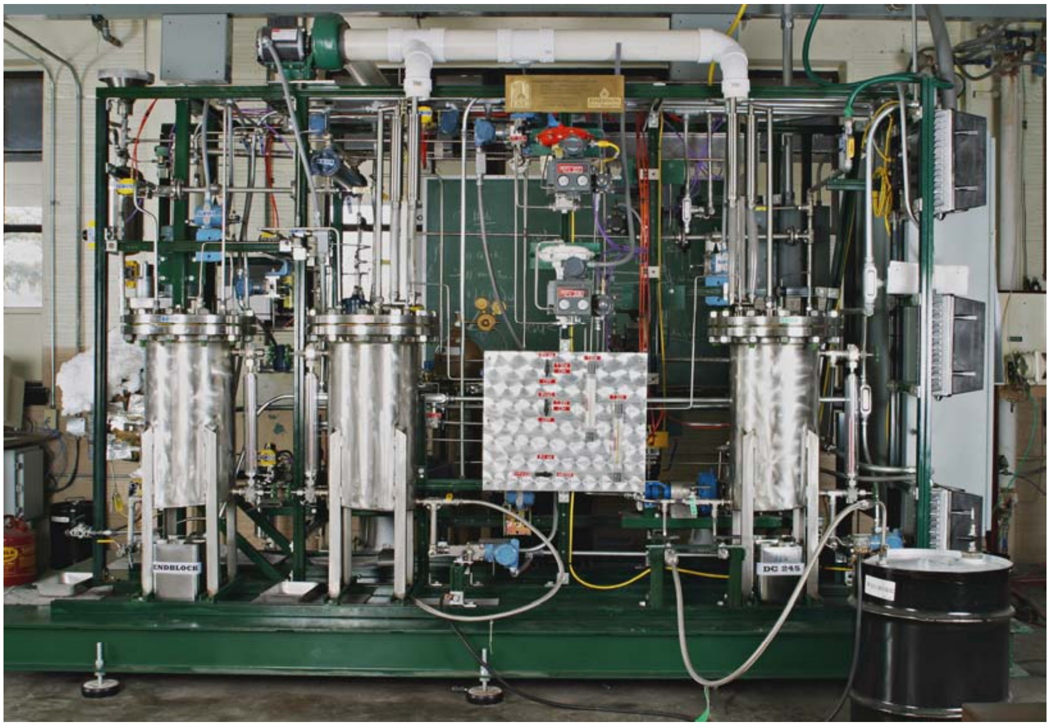


**Figure 1.** Polymerization reaction / separation unit.

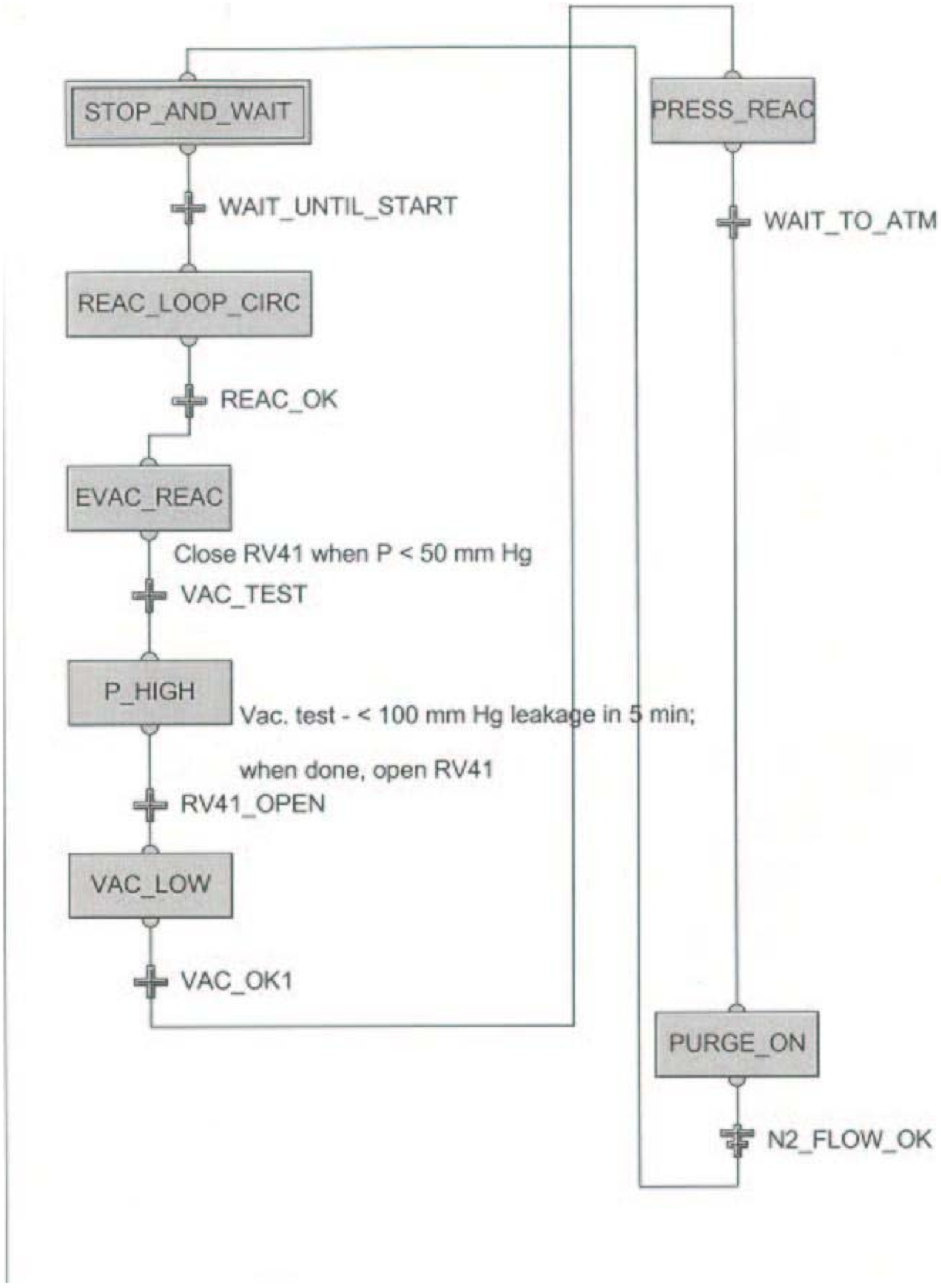
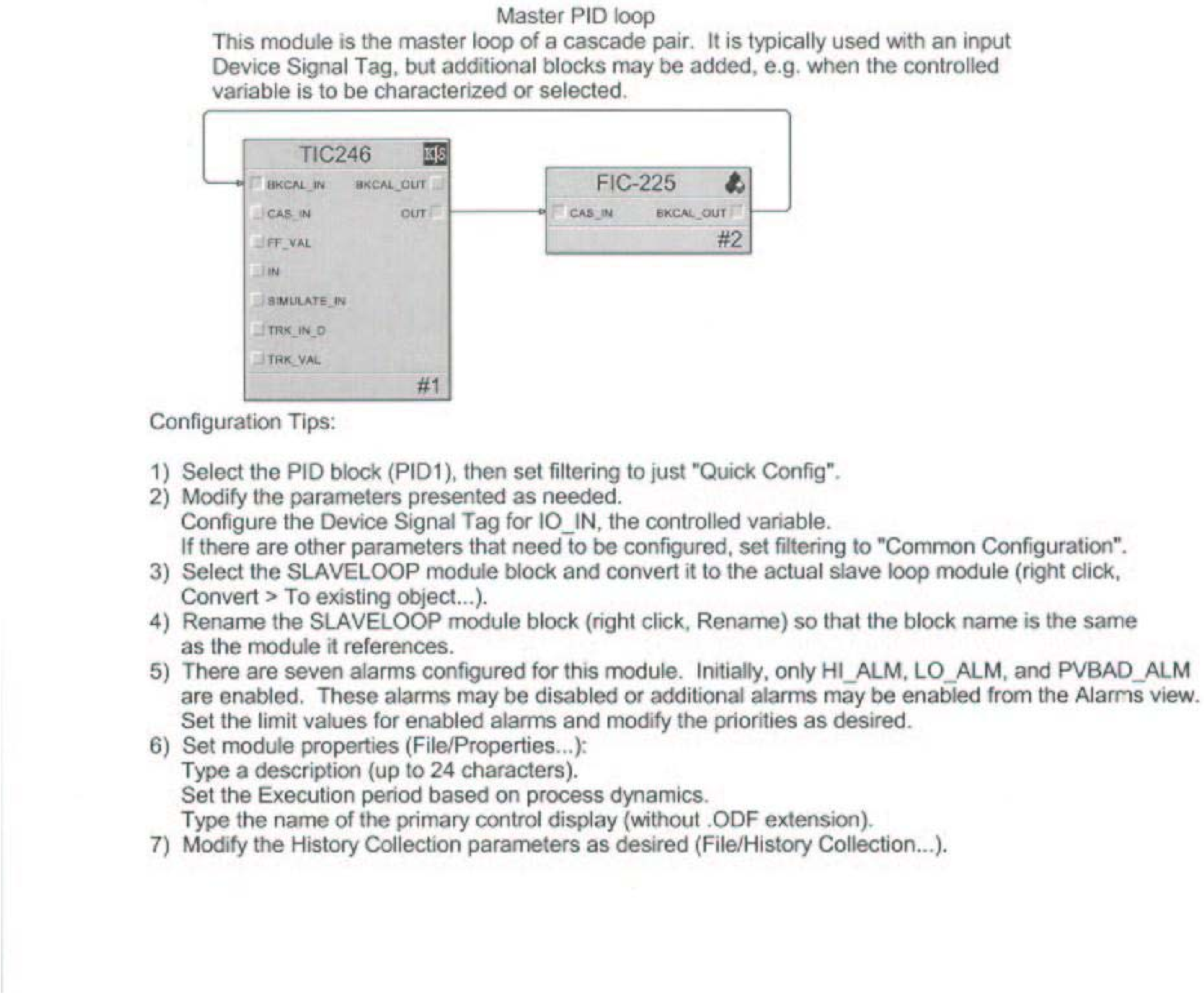


**Figure 2.** Sequence for inerting / purging polymerization unit.



Master PID loop

This module is the master loop of a cascade pair. It is typically used with an input Device Signal Tag, but additional blocks may be added, e.g. when the controlled variable is to be characterized or selected.

Configuration Tips:

1) Select the PID block (PID1), then set filtering to just "Quick Config".
2) Modify the parameters presented as needed.
   Configure the Device Signal Tag for IO_IN, the controlled variable.
   If there are other parameters that need to be configured, set filtering to "Common Configuration".
3) Select the SLAVELOOP module block and convert it to the actual slave loop module (right click, Convert > To existing object...).
4) Rename the SLAVELOOP module block (right click, Rename) so that the block name is the same as the module it references.
5) There are seven alarms configured for this module. Initially, only HI_ALM, LO_ALM, and PVBAD_ALM are enabled. These alarms may be disabled or additional alarms may be enabled from the Alarms view. Set the limit values for enabled alarms and modify the priorities as desired.
6) Set module properties (File/Properties...):
   Type a description (up to 24 characters).
   Set the Execution period based on process dynamics.
   Type the name of the primary control display (without .ODF extension).
7) Modify the History Collection parameters as desired (File/History Collection...).

**Figure 3.** Control module for a cascade loop. Note extensive online support.

With three major control systems, a long-range goal is to introduce students to control / process dynamics using actual industrial teaching tools, in several courses rather than just the formal "Process Control" class taken in Senior year. Our partnerships with Emerson Process Management (EPM), Honeywell IAC and National Instruments are making this possible. To further our goal, we also wrote and received (in 2003) an NSF Grant for Developmental Research entitled "Reforming the Chemical Engineering Curriculum: Manufacturing/Process Dynamics/Process Control Emphasis". As part of the grant, we evaluated control simulation software (EPM Delta V Simulate™ and Control Station Inc.'s Control Station™, both similar to Wonderware's InControl™ and InBatch™ products) that can be used as teaching tools in the classroom. Such software exchanges data with both process simulators and control systems via OPC. Advanced control functions such as model-predictive control, neural nets, fuzzy logic control, and advanced tuning algorithms are included. Other new software makes it possible to apply an expert system to diagnose control loops which are performing poorly, or which in their current configuration waste material or energy ("Inspection" algorithms). Therefore one can study not only routine control problems such as load changes, but also major process upsets, startups, abnormal situations, etc.

Some of the lab experiments are controlled using the Honeywell Local Control Network R630 software; therefore the students experience the differences between the platforms of two of the largest instrumentation and control software suppliers in the U.S. (Honeywell IAC and Emerson Process Management). The Honeywell LAN communications software (APNODE 211) allows for data transfers to typical applications such as EXCEL or MATHCAD. There is also a new WEBGUS program which embeds active X controls within Internet Explorer to enable both data transfer and remote access to the control displays (EPM provides similar software). In summary, the era of open communications between industrial control software and the classroom is now here and we wish to become a part of it.

As shown above, the problems based on these control packages are open-ended; students are encouraged to explore possible solutions using both the packages and lab testing. The role of the instructors is to assist them in initial understanding of the equipment and the packages, and to explain the potential differences between the simulations and reality. The instructors also provide incomplete simulation modules of the basic features of the virtual or actual plant to give the students a starting point. The incomplete module approach conforms to the collected wisdom of many departments using such simulators (a survey is in Dahm et al., 2002). Recent engineering experience has shown that a problem-based, "lab"-type environment is the best in which to first encounter both process simulation packages (e.g., Wankat, 2002, which also includes student surveys) and, by inference, the process control simulation packages. The multiyear teaching experiences in process simulator packages documented by Wankat showed that 95% of responding students felt that a lab-type was superior to a lecture-type environment for rapid assimilation of basic simulator functions. Similar findings hold in the teaching of process control itself; one study reports that >80% of responding students felt that a hands-on, self-directed learning class with the appropriate computer packages is superior to the traditional lecture class (Young et al., 2001). Finally, our previous Chair conducted exit interviews with graduating seniors over 5 years, and virtually all those who had experience in manufacturing facilities, either as co-op students or as summer interns, commented that enhanced practical education in process dynamics and control is necessary.

As part of this effort, the Process Control class itself is evolving to focus more on computer control and the use of control tools rather than just classical theory. Some of the classical theory can be covered in a Junior-level class incorporating process dynamics and simulation, some in the labs themselves. However, some of the theory should probably be relegated to the trash heap, as recommended by experts in the field (for discussion of these points, see Smith, 2000; Young et al., 2001; Edgar, 2003).

## A NEW LABORATORY EXPERIMENT RESPONDING TO A CHANGED CURRICULUM – BIOCHEMICAL CRYSTALLIZATION

We recently designed an experiment to expose our students to one of the most common separation techniques, crystallization. It is the primary step in, e.g., chiral separations (Wibowo et al., 2004), purification of antibiotics (Genck, 2004), separation of amino acids from precursors (Takamatsu and Ryu, 1988), and many other pharmaceutical (Wang and Berglund, 2000; Kim et al., 2003), food additive (Hussain et al., 2001; Gron et al., 2003) and agrochemical (Lewiner et al., 2002) purifications. The control of crystal morphology and size distribution is critical to overall process economics, as these factors determine the costs of downstream processing operations such as drying, filtration, and recycle of uncrystallized product. Solid / liquid processes such as crystallization are found in over 90% of production in fine chemicals and pharmaceuticals (Genck, 2004).

The new experimental apparatus enables study of all facets of crystallization: (a) effects of key parameters such as supersaturation and cooling/heating rates on morphology and crystal size distribution; (b) on-line control of crystallization processes. The system is designed to handle different types of crystallizations, including cooling, evaporative, pH swing and chemical modification. The key to control here is the analysis of solids content and crystal morphology / size distribution (Barrett, 2003).

Assembly / construction was performed by our shop personnel (the P&ID is shown in Figure 4). Many of the larger equipment items (LC, particle counter, circulating bath heater) was donated. An online fiber-optic spectrometer (Ocean Optics PC2000) can also be used to estimate solids content by turbidity, comparing to the offline particle counter.

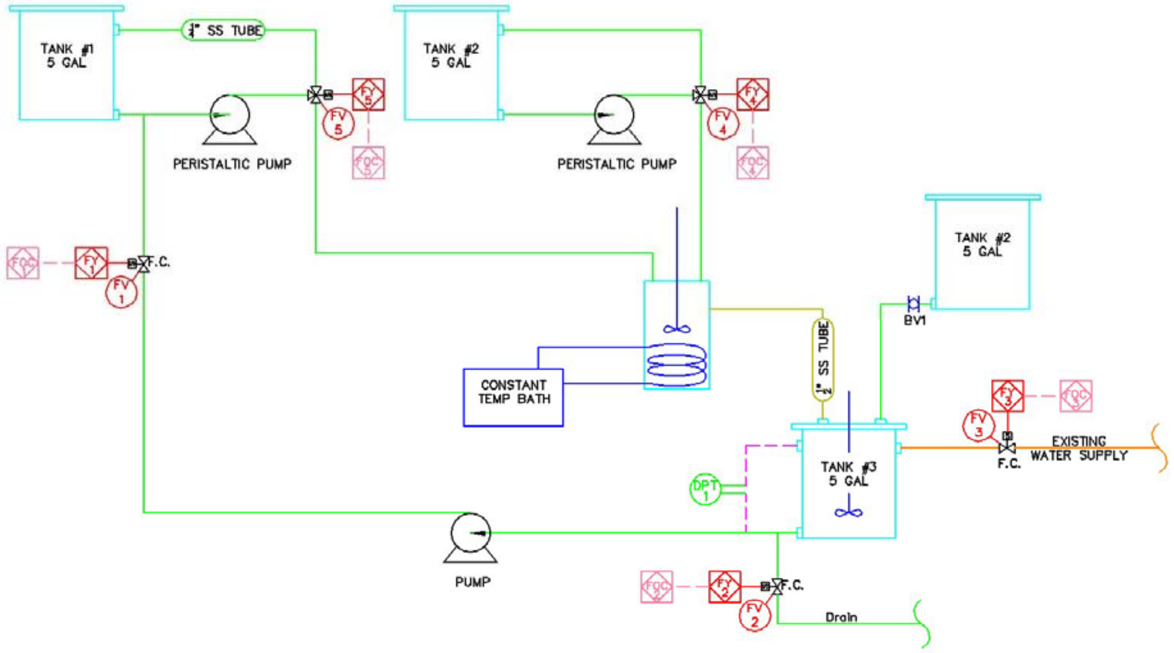


**Figure 4.** P&ID, biochemical crystallization experiment

An initial experiment is the control of a salicylic acid (component of aspirin) crystallization (Franck et al., 1988). This "chemical" crystallization has many facets in common with crystallizations of other biologicals such L-ornithine-L-aspartate (LOLA), used to treat chronic liver failure (Kim et al., 2003). However, whereas the precursor L-ornithine hydrochloride costs >$300/kg and is difficult to recycle, we can buy sodium salicylate for $50/kg, and the salicylic acid can be reused by rinsing out the byproduct sodium sulfate and then reacting with dilute NaOH solution in the product slurry tank, followed by recycle. We are testing the system now.

## NEW ANALYTICAL FACILITIES RESPONDING TO A CHANGED CURRICULUM

We have had considerable success using low-cost fiber optic PC or USB spectrometers (e.g., from Ocean Optics). An example analysis is the quantification of potassium iodide or red food color tracers in characterizing transport in packed beds (our "Permeameter" experiment). The probes for the spectrometers are online, connected using standard low pressure fittings (Cajon VCR-type). Students measure the response to pulse or step inputs for both non-adsorbing and adsorbing tracers, and study the partitioning of tracers between a trapped immiscible (paraffinic) phase and the flowing aqueous phase. In this manner we can simulate transport of subsurface environmental pollutants.

A new portable gas analyzer (H-P Micro3000) was recently acquired; the goal was to improve our capabilities in online analysis. The new Micro GC is multifunctional, with four channels for the separation and quantification of air, other permanent gases, volatiles, and semivolatile nonpolar liquids. It is portable, requiring only a small helium cylinder and weighing only 25 lbs. (16x48x42 cm). The analysis speed is much greater than our existing GCs, <2 min/sample. This allows integration of the GC into the Emerson process control system for, e.g., composition control of a distillation column.

The HP-3000 is also useful for continuous emissions monitoring (CEM) of combustion gases. Therefore it can be used to analyze and troubleshoot gas turbines and recip engines in power plants. This is an area of great importance in Engineering, given the increasingly stringent regulations on fossil fuel combustion and power generation. Carl Knopf of LSU ChE has been working with LSU's Office of Energy Services to involve ChE students in LSU's new cogeneration facility. We plan to incorporate future emissions studies of the cogeneration facility into our UG laboratory courses as part of a collaboration between LSU ChE and the Office of Energy Services. The emissions study would constitute a new "real-world" experiment for our undergraduates, at minimal cost.

We are integrating the portable GC into a portable CEM system of our own design and construction. In addition to the GC, this requires electrochemical NO, $NO_2$ and $SO_2$ analyzers, and a sampling system (pump, traps, tubing). The GC itself can quantify all typical emissions components except $SO_2$, $NO_2$ and NO. While it is possible to buy specialized GC detectors to analyze these gases also, electrochemical diffusion transmitters are far cheaper than the detectors (by a factor of >3), give faster results (response times <30 s) and have adequate resolutions (<0.1 ppm). There are almost no interferences from other gases to these transmitters, except some higher hydrocarbons, which are easily removed by an activated carbon trap in the line to the transmitters (Berezkin and Drugov, 1991). Sensor lives in continuous operation are >2 years. As they will be in continuous operation only when in use at the Power Plant, their actual life will be much longer. The sensor signals are transmitted to the computer through its serial port using existing serial conversion modules and software. A pump is used to suck the sample from the process line into the line containing all 3 transmitters. The exhaust lines from both the GC and the transmitters are combined and routed to three small traps, alumina, 13X mol sieve and sodium bicarbonate, which will remove all hydrocarbons, CO, $NO_x$ and $SO_x$ (Berezkin and Drugov, 1991). No pollutants will be discharged.

CEM of gas turbines and recip engines requires sophisticated GCs and other analyzers due to the low levels of pollutants (CO, hydrocarbons, $NO_x$ and $SO_2$) involved, and because their levels are highly correlated with other factors, such as excess air, or water content (Fokema and Ying, 2001). Many new $NO_x$ and $SO_x$ removal technologies, such as two-stage catalytic combustion of exhaust gases, are being researched and tested on power generation facilities. A mobile system of the type described here would allow our students to be on the cutting edge of such testing, and possibly also aid LSU's Office of Energy Services in troubleshooting emissions control facilities.

## CONCLUSION

In our talk several more examples of lab / class integration will be presented, including how we help teach the use of process simulators (HYSYS and CHEMSEP) using existing separation experiments, more on process control using the Honeywell system, and how data reconciliation can be incorporated into the labs. We have learned many lessons during the course of our efforts; hopefully these may be of value to other departments also struggling to keep their laboratory classes relevant. Some of the most important lessons are:

- renovate lab and shop at same time;
- upgrade training of lab coordinator;
- get network administrator more involved in the labs – many of the jobs are computer-admin related;
- split industry contacts - the bankers, the loaners (expertise) and the junkers (used equipment) - all contacts can help with something;
- use the students themselves to commission / debug new experiments as part of their learning experience;
- simulation as taught in senior-level courses and the ChE labs experience can (and must) complement one another.

## REFERENCES

ACS, "Technology Vision 2020: the U.S. Chemical Industry," http://www.ccrhq.org/vision/index.html. American Chemical Society, Washington, 1996.

P. Barrett, *Chem. Eng. Prog.*, August 2003, 26-32.

Barna, B.A.; Caspary, D.W.; Crowl, D.A.; Herlovich, J.A., Jr.; Pintar, A.J.; Rogers, T.N., *Safety in Chemical Engineering Design*, Center for Chemical Process Safety, AIChE, New York, 1995.

V.G. Berezkin and Y.S. Drugov, "Gas Chromatography in Air Pollution Analysis," Elsevier, Amsterdam, 1991, chapters 5 and 6.

K.D. Dahm, Hesketh, R.P.; Savelski, M.J., *Chem. Eng. Educ.*, Summer 2002, 192-198.

Dooley, K.M.; Thompson, K.E.; Rodriguez, V.P., "Lab Experiments Integrating Process Control, Transport Phenomena, and Reactor Design," presented at AIChE Annual Meeting, Indianapolis, November, 2002.

Edgar, T.F., *Computers and Chemical Engineering News*, Spring, 2003, http://www.che.utexas.edu/cache/newsletters/spring2003_curriculum.pdf .

M.D. Fokema and J.Y. Ying, *Catal. Revs. – Sci. Eng.* , 43, 1-29 (2001).

R. Franck, R. David, J. Villermaux and J.P. Klein, *Chem. Eng. Sci.*, 43, 69-77 (1988).

W.J. Genck, *Chem. Eng. Prog.*, Oct. 2004, 26-32.

H. Gron, A. Borissova and K.J. Roberts, *Ind. Eng. Chem. Res.*, 42, 198-206 (2003).

K. Hussain, G. Thorsen and D. Malthe-Sorenssen, *Chem. Eng. Sci.*, 56, 2295-2304 (2001).

Y. Kim, S. Haam, Y.G. Shul, W.-S. Kim, J.K. Jung, H.-C. Eun and K.-K. Koo, *Ind. Eng. Chem. Res.*, 42, 883-889 (2003).

F. Lewiner, G. Fevotte, J.P. Klein and F. Puel, *Ind. Eng. Chem. Res.*, 41, 1321-1328 (2002).

W.L. Luyben, W.L.; B.D. Tyreus, and M.L. Luyben, *PlantWide Process Control*, McGraw-Hill, New York (1999).

Smith, C.L., *Chem. Eng. Progr.*, Aug. 2000, 19-29.

S. Takamatsu and D.D.Y. Ryu, *Biotechnol. Bioeng.*, 32, 184-191 (1988).

F. Wang and K.A. Berglund, *Ind. Eng. Chem. Res.*, 39, 2101-2104 (2000).

C. Wibowo, L. O'Young and K.M. Ng, *Chem. Eng. Prog.*, Jan. 2004, pp. 30-39.

P.C. Wankat, *Computers and Chemical Engineering News,* Spring 2002, http://www.che.utexas.edu/cache/newsletters/spring2002_integrating.pdf

B. Young,; D. Mahoney, ; W. Svrcek, *Computers and Chemical Engineering News*, Fall, 2001, http://www.che.utexas.edu/cache/newsletters/fall2001_educating.pdf