A SYSTEMS APPROACH

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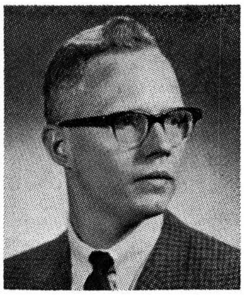
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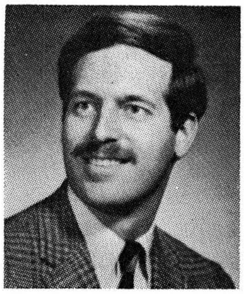
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Chemical Engineering Laboratories have proved traditionally less "cookbook" than other engineering laboratories, but they have tended to suffer none the less from becoming stereotyped as to their objectives and the types of experiments run. Mostly laboratories have been used to complement traditional textbook material by attempting to illustrate the application of theory to experiment. In the course of a major curriculum revision at Drexel we had the unique opportunity, and the strong support of our administration, of NSF and of industry, to make a break with the past and to develop a new approach to chemical engineering laboratories.

We have changed the objective of the laboratory from one of complementing lectures to one of supplementing them. We believe that the students in their junior and senior years are sufficiently mature to apply principles already learned to the analysis of laboratory data and to forge beyond what they had received in class to develop new ideas so as to deepen that analysis. We feel that if the student understands that he has certain specific responsibilities in the course to educate himself, laboratories might be approached with more curiosity and enthusiasm than in the past. Our goals were to develop a laboratory which would require the students to (1) study and apply principles not taught in class as well as to use those previously learned; (2) analyze problems such as might arise in pilot plant studies, i.e., a realistic engineering situation, (3) be challenged sufficiently that the experience would be enjoyed rather than endured.

From our early discussions evolved the idea of having the student approach chemical engineering from a systems viewpoint. This was consistent with an earlier decision to introduce to the elementary stoichiometry course use of flow sheets as teaching tools. We want students to learn early that material and energy balances around units are related to other sections of a process flow sheet. Consequently, it was logical to design a laboratory in which units could be run as an integrated system or as small subsystems, and thus provide an opportunity for students to study the interrelationships. With such a system both dynamic and steady-state studies are possible. We felt that the student would be able to progress from running individual units to running combinations of units to eventually running the entire line. The line not only had to meet our educational objectives but also had to remain within the constraints of our budget.

THE LABORATORY FLOW SHEET

What evolved for our first processing system is the flow sheet of Figure 1. This is an inorganic processing line in which a mixture of soluble and insoluble salts is separated and the products refined in units under automatic control.

The mixture is fed from an automatically controlled, vibrated feed-hopper to a mixing tank where it is slurried. The mixing tank is provided with density, level, and temperature controllers. The tank contents are mixed by means of a side-entering agitator. This is the one feature of the subsystem which is not under automatic control. Agitation rate, however, can be manually varied. The water for the mixer comes from two heat exchangers which are automatically controlled.

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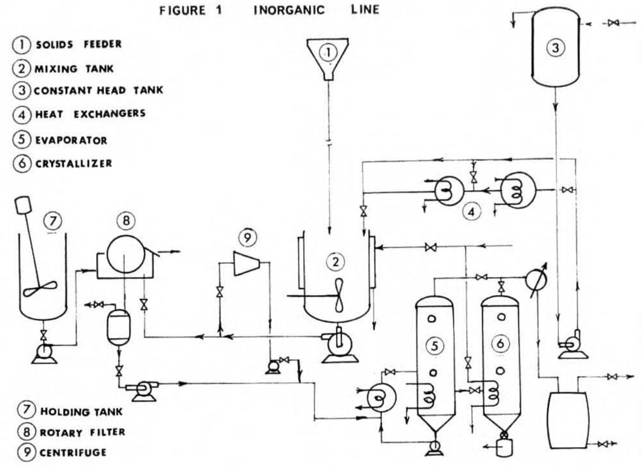
FIGURE 1 INORGANIC LINE



The slurry can be pumped to either a rotary vacuum filter, or to a continuous centrifuge, or it can be fed to an intermediate holding tank for future processing. The rotary filter is designed for washing of the insoluble cake as well as for removal of filtrate. The solid cake can be manually transferred to either a tray drier or to a fluidized bed drier. The cake may be pretreated before drying if the students decide that such treatment is necessary. The filtrate or centrifugate can be pumped either to intermediate storage or directly to a double effect evaporator. The first effect is for concentrating the solution and the second effect is an evaporator-crystallizer. Both effects have temperature, level, flow, and pressure control. As crystals of the salt build up within the conical bottom of the crystallizer they can be manually dropped into a salt catch for later removal and drying.

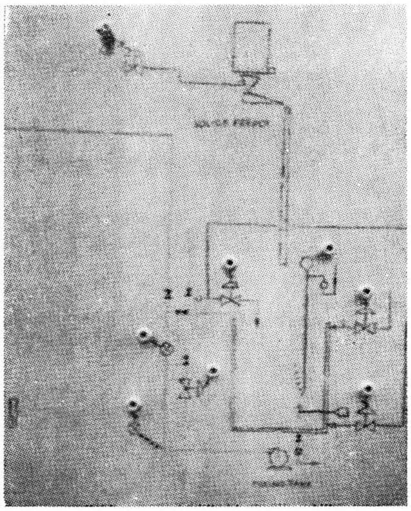


Figure 2. Graphic Panel View

We have, for reasons of economy as well as for educational value, designed the panel board (Figure 2) for maximum flexibility in the use of equipment. Sensing elements can be plugged into any of several controllers, which in turn can be connected through flexible tubing to stations on the graphic panel which represent — and are connected to — the final control element. Recording equipment for temperatures, flows, levels, pressures, etc. is at the right of the panel board; controllers at the left. Our control elements are mostly pneumatic. In addition there is a magnetic flow meter in the line, some thermocouple elements, and some electrical to pneumatic conversion units. We also have available, when dynamics experiments dictate their use, either a two channel or a six channel oscillograph for more detailed study of transients.

Figure 3 illustrates how flexibility was attained in the instrument installation for the Inorganic Line. The equipment sketched is the jacketed mixing tank. In the processing scheme, it is the unit where the solids are introduced, the soluble salt is dissolved, and the insoluble one is slurried. The equipment of Figure 3 is used in the intermediate laboratory course for heat transfer experiments. It is piped to permit hot water, steam, or cold water to enter the jacket and to use either hot or cold water as the processed fluid. A filled-bulb temperature transmitter is installed in the pumped recycle line and diaphragm motor control valves are installed in the jacket inlet water and steam lines.

The level control instruments are useful for steady-state experiments on heat transfer (during the second laboratory course) and for studying the dynamics of level control (during the third course). A bubbling-type level transmitter is employed as the source of the level signal for control, and control valves are installed in both inlet and outlet process fluid lines. The control valves can be used in flow control studies of liquid to and from the tank. (Flow transmitters are not shown in Figure 3.)

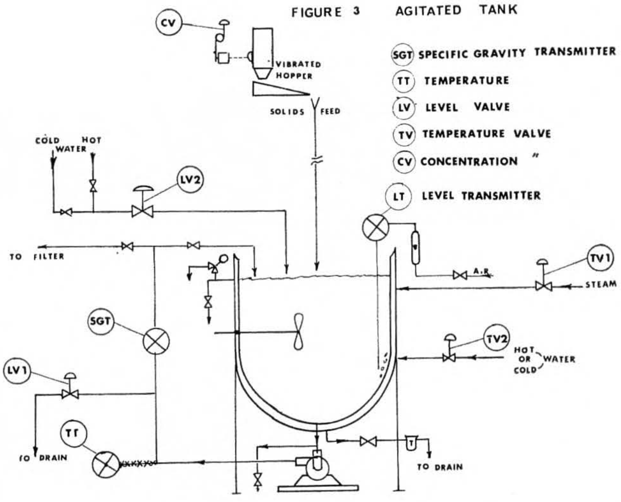


FIGURE 3 AGITATED TANK

OPERATION OF THE LABORATORY COURSES

We realized that students would not be able to operate and analyze the overall system unless they first had some understanding of its subsystems. Consequently, the first lab in the three term sequence is devoted to experiments which develop skill in manipulation of equipment and analysis of data. Students learn how to use measuring equipment, how to safely operate pumps, heat exchangers, mixers, etc. There are a few bench scale transport experiments interspersed with an introduction to larger scale experimentation on the equipment in the line, e.g. conduction in rods, determination of diffusivities.

During the second laboratory, students investigate both the dynamic and steady-state behavior of individual processing units. Use is made of the instrumentation and control equipment so that the students learn of the interactions of the controls and the process.

With the wide variation possible in experiments, no two student groups need be asked to study the same phenomenon. As a consequence, the lab has more of the character of small scale research projects, forcing the students to rely more on themselves than they would in a conventional setting. They gain confidence in their ability to analyze and solve new problems. Control of a double-effect evaporator, and interrelationship of variables such as level control and throughput have real meaning to them so that when they advance to the final laboratory in the last term of their senior year, the students are ready to meet the more challenging problems presented there.

Since one purpose of the final laboratory course is to involve the student in a relatively large scale project which requires some ingenuity and originality on his part, we have avoided establishing a specific set of experiments. Rather we have some interrelated units of processing equipment and their associated instruments for study. The student has the responsibility to specify the control loop or loops he will study. He then is expected to analyze the various components of the control loop to obtain the appropriate differential and algebraic equations, to linearize the equations if necessary, to predict, using linear control theory, the transient behavior of the equipment under control, and to prove his model and mathematics by experimentation on the equipment. He is expected to have a full understanding of the control hardware involved including valves, sensing elements, and controllers.

As an example a group might be asked to determine the system control characteristics for the water preheat exchanger operating under proportional control. The group would be expected to prepare an experimental plan, a mathematical model, and to decide what measurements were needed to test their model. They must explain any discrepancies between their idealized description and their experimental results.

Every effort has been made to keep instrument application flexible so the equipment could be run in a variety of ways. Initially the student may not wish to operate under closed-loop control at all. In that case, control loops need not be closed and sensing instruments, transmitters, and recorders are still available for steady-state measurements. Certainly the availability of these instruments makes steady-state operation easier. It has proved, for example, especially useful to have level control instruments available for operating the rotary filter and the evaporator. The level of drum submergence in the rotary filter is an important parameter in the equipment opera-

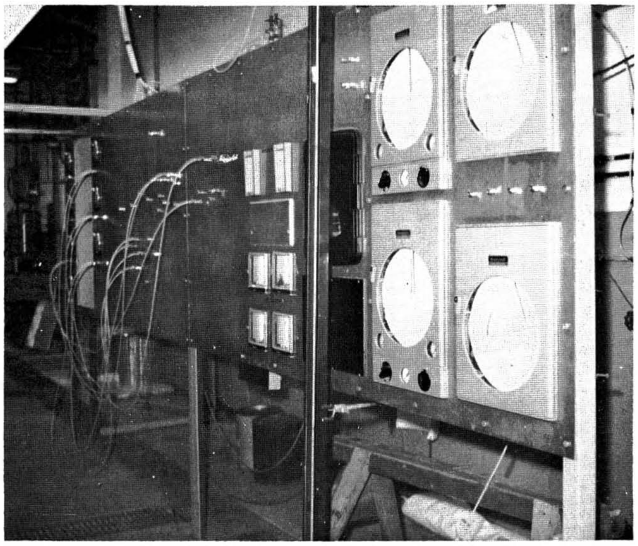


Figure 4. Panel Board View

tion and it is difficult to maintain it fixed without the controls. In the evaporator level is only a secondary variable, but matching inlet flow to evaporation rate is essential for accurate mass and energy balances to be performed. The equipment responds so slowly that manual rate adjustment cannot be relied upon; effects of changes can be observed only after long times. To use the controls in these cases, the students need have only a minimal understanding of the hardware and no real knowledge of theory.

From the study of single units the student groups progress to operation of linked units. They quickly discover, for two or more pieces of equipment to be operated in sequence, that control devices are essential. There are too many interrelated variables to be adjusted for the students to obtain steady-state in a reasonable time without the aid of instruments. Suppose that the filter and evaporator are to be operated in series so that the filtrate, which contains a soluble salt, is to be fed to the evaporator-crystallizer where the salt will be removed. In steady-state, the filtrate production rate has to match the evaporation rate and all levels will be constant. The students have three or more variables to manipulate; typically, slurry rate to the filter, filtrate feed rate to the evaporator, and the evaporator steam valve position. Achieving steady-state in this situation without controls would be very difficult and time consuming.

Most groups also do steady-state analyses of their processing units in order to obtain necessary data and understanding for running the processing line.

Once the students have reached the point where they are able to handle the operation and analysis of two units in sequence, meshing of their projects begins. One group, for example, may have been collecting operating information on the feeding of mixed salts to the slurrying tank (data such as feed rates, specific gravity, agitation requirements, pumping, etc), Another group would have been collecting information on the rotary filter, its efficiency, cake moisture, residual solubles, drum immersion, filtrate rate, drum speed, etc. A third would have been studying the influence of level, flow rate, vacuum level, temperature difference, steam rate, etc. on evaporator operation. From the data obtained from two or three weeks of experimentation and analysis, the individual groups would have determined feasible operating limits for the unit which was their responsibility. The student groups then meet with each other and decide on the operating details for running the entire line to manufacture product.

It is worth noting here some special features of the mixture of salts which are both the raw material and the products of our processing line. The insoluble is calcium carbonate, chosen because it has good filtering characteristics, is relatively non-abrasive, and is cheap. The soluble salt is sodium sulfate, chosen on the basis of its relatively low corrosive effects on the equipment and its low price. It has the added educational benefit, however, of forming a series of hydrates which complicate its handling when removing it from the crystallizer. In our system the crystallizer is operated around 90°F which, the student soon finds out by consulting the phase diagram, results in anhydrous sodium sulfate as product. However, if the product is not immediately centrifuged upon removal from the salt catch and dried, the mother liquor provides enough water for decahydrate to form as the temperature lowers. The result is a very hard lump that can only be broken by a hammer.

It requires about one week of joint operation before the groups learn how to coordinate the operation of the individual process units so as to make product. The line has been run for several hours at steady-state. Once the salt catch fills it is very difficult to remove product without severe upset to the system so that steady operation is limited by this factor. Perturbations of feed flow rate, steam flow, level in the evaporator have all been carried out and the response of the system determined. The large capacitance of the equipment relative to the upsets imposed showed the processing line to be very stable.

Since our senior classes tend to be large (40-50 students), we allow some groups with the inclination to do so to study complex control problems rather than to run the line. This is possible because of the flexibility built into our instrumentation scheme. We deliberately purchased some additional control equipment whose main function was to make available automatic control loops beyond those needed simply to study the equipment. The heat exchangers, for example, have such capacity.

While the groups studying advanced control problems may not be operating more than a subsystem of the processing line, they are constantly aware that their experimentation is being done on operating equipment and in that sense they are making a contribution to a better understanding of how the line operates and how that operation might be improved.

DESCRIPTION OF CONTROL EQUIPMENT

All of the installed instruments either generate or are operated by 3-15 psi pneumatic signals. The leads from transmitters and to control valves are all brought to a panel board where a schematic of the equipment is drawn. A photograph of a portion of this panel board is attached as Figure 4. Connection can be made to any of the instruments at the front of the panel board through quick-disconnect pneumatic fittings.

The transmitter outputs are, in addition, connected permanently to strip chart recorders mounted in the panel board. A continuous record of the transmitted signals is thus available to students for their analysis. Some channels on the recorders are left free for students to trace intermediate signals in control loop, such as valve position.

As the equipment confronts the students, there are no completed control loops (e.g., as indicated by the schematic of Figure 3,), Controllers are installed so that adjustment of proportional band, reset rate, or derivative time can be made from the front of the panel. Several manufacturers are represented. All the controllers have indicating control stations and all have a 3-15 psi signal. Each, therefore, is compatible with each instrument installed with the equipment. Access to the controller receiver and to its output signal is available at the front of the panel board through quick-disconnect fittings.

The student is able to complete the control loop he wishes to study by connecting, at the front of the panel board, the appropriate transmitter output to the specific controller desired and by connecting the controller output to the control valve that is to be manipulated. Any controller may be used in any control loop; any transmitter may be employed in manipulating any valve.

STUDENT RESPONSE

The response of our students even in the early stages when the line had to be made operable has been gratifying. The first classes, whose task it was to make things work, had the attitude that they were pioneers in a new approach to chemical engineering and worked long hours to carry out their assignments, to find out what the difficulties were, and to make suggestions on how to correct them. The next group of students who ran the line as individual units were enthusiastic about their laboratory work. They approached it with an enthusiasm not seen in a more routine course. They did the job and they are doing the job of digging out those things they have not been taught but which they need to know.

In general the students are finding the laboratory a real learning experience and not just a routine chore to be endured and gotten out of the way with a minimum amount of effort. Those students who have run the system as a complete line have had a sense of accomplishment that usually most students do not get from chemical engineering or any other undergraduate laboratory. They have had the opportunity, the excitement, and the satisfaction of running a purposeful operating system and of learning how the parts of it interact, and how they can make a product. The students look upon the lab as a challenge to be met instead of an affliction to be suffered.

PROBLEMS

Of course, we had some problems which arose during the design, construction and debugging phases of the laboratory, as well as some which have appeared with operations. For example, during design many changes were made in the flow sheet in order to match our ideas with our budget.

Another problem which caused some concern was to minimize hold-up in pipelines and to have pipe runs as short as possible consistent with the scale equipment available to us (50 to 100 gallons) and still have a realistic system. Another constraint is having enough space between equipment units for students to move and do their jobs safely. The spacing is largely controlled by the floor plan of a building already erected. We were able to overcome these difficulties without significant sacrifice to the educational concepts.

During the initial phase some final control elements had to be relocated because system response was too slow. Some minor piping changes had to be made in order to accomodate flow rate and pumping requirements.

CONCLUSIONS

- A systems approach to laboratory can be made to work successfully even under the constraints of curriculum limitations and available time.
- Student acceptance has been excellent and the levels of learning high.
- The cost in faculty time has been great but the benefit to the undergraduate student has been worth it.
- As a consequence of this faculty investment in time and the student enthusiasm for the concept, overall student morale within the department has improved.
- Response from both visiting educators and industrial people has been universally favorable.

The results have encouraged us to complete and to improve our original concept for an organic processing line. The students will study different interacting operations including those involved with chemical reactors and kinetics.

We believe that the students participating in Drexel's laboratory will graduate with a firm appreciation of the problems of running an entire processing system. We especially feel that those students who go into design and research will have benefitted by knowing something about systems problems and the interactions of subsystems with each other and with the men who must run them.

ACKNOWLEDGMENTS

The plan for the laboratory was an outgrowth of the philosophy of Dr. Charles E. Huckaba who was at the time department chairman. With his basic ideas, enthusiasm and assistance the support of the National Science Foundation and of the Institute administration was enlisted in the project.

ChE curriculum

CHEMICAL ENGINEERING EDUCATION IN WESTERN EUROPE

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Charles Barron received his chemical engineering education at Clemson University and the University of Virginia. He taught at Tulane University for five years, and he spent the academic year, 1967-68, as a Fulbright-Hays lecturer at the Catholic University of Louvain, Belgium. The following year he joined the faculty of the University of Virginia. His research interests are in the area of homogeneous catalysis and chemical reactor analysis.

In thinking of curricular reform, which seems to be a never-ending chore, it is worth attending to trends that arise and evolve in circle other than our own. With this in mind an attempt will be made to discern directions in which chemical engineering education in western Europe is moving. Many ideas on this subject were presented and discussed at a meeting held in Churchill College, University of Cambridge, early in July, 1968, under the sponsorship of The European Federation of Chemical Engineers. Several of the key points presented at that meeting will be cited, and implications and conclusions will be drawn as they are relevant to the educational