

TEACHING PROCESS SYNTHESIS --

The Integration of Plant Design and Senior Laboratory

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THE CURRENT ATTEMPT at Vanderbilt University is to organize our undergraduate chemical engineering curriculum around process synthesis and design, rather than around transport phenomena or the traditional unit operations sequence. The students acquire a firm foundation in the engineering sciences of mechanics, thermodynamics, and the transport and electrical phenomena, but the emphasis in the ChE core courses is on design, beginning with flow sheet generation in the sophomore "stoichiometry" course and culminating in the senior plant design project. Such an approach requires a careful effort to develop problems and case studies, but we feel that the effort is justified by a closer approximation to modern ChE practice.

Until recently, the laboratory courses have not contributed directly to this curriculum. They have tended to emphasize the understanding of physical principles, report writing, team work, and the development of planning and reasoning abilities, but they have done so through a series of self-contained experiments which were all too often unrealistically well defined.

Nevertheless, a second-semester senior develops a curious enthusiasm for his ChE laboratory work. He sniffs the air, realizes what may be expected of him in a few months, and begins to approach his laboratory work in mature and productive fashion.

We saw an opportunity to combine the phenomenon of senior lab motivation with our design emphasis. It seemed particularly appropriate to seek the close involvement of industry. This paper describes our first serious attempt to combine laboratory work, industrial contact, and "plant design" into one five-semester hour course. We assigned, with the help of chemical engineers and chemists in local practice, a semester-long process design for which data might be unavailable. The students had to decide what information to obtain in the laboratory, perform the appropriate experiments, complete their process design, and report to their industrial and faculty advisors. Because many other schools are moving toward a design-oriented curriculum, we felt that our experience might supply some insight into the advantages and disadvantages of an integrated laboratory-design approach.

COURSE OBJECTIVES

WHEN THE COMBINED course was in the planning stages, we identified five objectives:

First, we hoped that the students could gain some confidence in their ability as engineers. In order for this objective to be realized, we would have to pick a difficult project with a good chance of successful completion. If the class could complete such an assignment, they would justifiably feel a sense of accomplishment and pride. It was important that the assignment not be totally artificial, but be as realistic as possible.

Second, we wanted the students to see the real

The integration of plant design and lab was so successful that we see no reason to return to our old system . . . We enthusiastically recommend the joint lab design approach. If you try it, you might consider four points which we feel to be of paramount importance. The cooperation of an accessible industry is essential; a suitable problem must be chosen; a great deal of advance planning is necessary; consider your equipment constraints in advance planning is necessary. Consider your equipment constraints in advance.

utility of engineering experimentation. Instead of requiring the students to spend one afternoon a week verifying physical laws or measuring properties, they would be expected to resort to laboratory work only when the data required for the plant design could not be obtained from alternate sources. They would have to decide what information was needed. They would have to design the experiments.

Our third goal involved the development of the managerial skills required to efficiently carry out a long, complex project. It is important for young



engineers to learn how to organize and communicate among themselves.

Next, we hoped that the lab would help give a physical feel for the plant design project. Most of us, when assigned an engineering job, have at least seen the materials and processes with which we are asked to work. This is rarely the case in a senior design project.

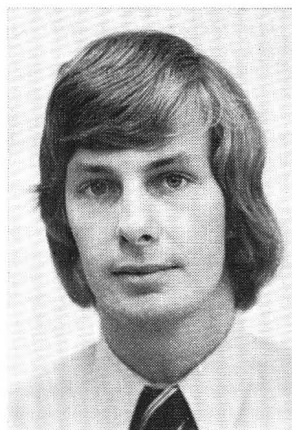
Finally, we hope to develop contact between the students and practicing chemists and chemical engineers, contact based on technical matters of joint interest. Seniors want this contact; too often they get it only in job recruitment situations.

THE PROBLEM

THE PROBLEM WAS PRESENTED to the students at the first plant design session and during the first lab period in the following form:

“Design a plant to produce 100 million pounds of polyester melt from the raw materials DMT and ethylene glycol. The plant is to be located on a 1000 acre spread on the Cumberland River near Nashville, Tennessee.”

The process to be used was basically that of the DuPont Old Hickory Plant. This facility produces Dacron (polyethylene terephthalate) from nitric



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C. C. Woltz was the student project leader. He is now a graduate student in chemical engineering at Vanderbilt. (Left above)

T. M. Godbold, instructor for the Plant Design course, received his B.S. and M.S. from the University of South Carolina and his Ph.D. from North Carolina State University. He has industrial experience with DuPont and Celanese and has been a consultant for several companies. His areas of interest include process control and diffusional operations. (Right above)

acid, xylene, methanol, and ethylene glycol. Paraxylene and nitric acid react to form terephthalic acid which is then combined with methanol to form dimethyl terephthalate (DMT). The DMT is fed to transesterification reactors where it is combined with ethylene glycol to form methanol and ester monomer (bis-hydroxyethyl terephthalate, or BHET). The monomer is polymerized under vacuum, yielding ethylene glycol for recycle; the resulting highly viscous polyester melt is spun and packaged.

Some initial ground rules were stated:

- The entire ChE faculty will answer all questions to which they know the answers and will supply any factual information to which they have ready access. The students were encouraged to make use of all of the faculty as consultants.
- The DuPont staff will help and answer questions within proprietary limitations.
- Any of the ChE lab and computer facilities may be used at any time, subject to our safety rules.
- The library and the patent files should be used as extensively as time allows. Don't take data in the lab if you can find it (and trust it) elsewhere.
- Data and information discovered by anyone will be made available to the class as a whole.

- Each student must design his own plant, although students may work together until all laboratory data required are obtained.

The class was given a supply of raw DMT by DuPont. The firm also supplied a small quantity of recrystallized BHET for quality comparisons and determination of physical properties.

The ChE Program supplied antifreeze from which the class could obtain ethylene glycol if they so chose.

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From this point until the end of the semester the class was on its own in the design and lab project, receiving only occasional unrequested advice from the faculty.

CLASS MEETINGS

THE PLANT DESIGN PORTION was offered for three semester credit hours. In the first third of the course (while the lab was getting started), the students reviewed and practiced equipment sizing and design decisions on several case studies. Although the class had had a course in Engineering Economy, methods of economic analysis and optimization were briefly reviewed and expanded to meet the anticipated needs of the Plant Design. The primary texts for this course were Perry's Handbook [1] and Peters and Timmerhaus [2]. During the latter half of the semester, the class did not meet formally, but students were strongly encouraged to meet with the design professor once a week to discuss design problems and report their progress. This weekly meeting provided an opportunity to discuss design and lab progress as well as exchange information.

The Laboratory portion met once a week from 8 a.m. to noon. All lab work was devoted to the design project. Each session began with coffee, donuts, and a report meeting, after which the students would begin experiments, library research, or planning. It was often necessary to work additional hours outside of this period. The

students had obtained much of the physical property data that they needed about six weeks before the end of the semester. The overall process flow sheet was fixed by discussion at this time and the students began sizing equipment for their design. Laboratory data on the kinetics for the process was completed about three weeks before the end of the semester. At that time, the lab stopped meeting formally.

CHAOS AND ORDER

THE FIRST TWO LAB meetings were, predictably, mixtures of order and chaos. The problem was laid before the class, a temporary discussion chairman was appointed, and the group was left on their own to lay plans.

After an hour or so, the group decided to go to the laboratory and get started (they planned to measure the melting point of DMT). At this point the laboratory instructor established an apparently arbitrary rule:

- Even though this is a lab course, no one may go to the lab for the first two weeks.

(Note that intervention was essential at this point—left entirely to their own devices in the initial planning stages, the class might well have embarked on a course which would surely have led to failure in the end.) The students were thus forced back on the track, and they finally got around to posing such questions as “what do we need to know in order to design this plant?” and “How can we find the information we require?” The discussion proceeded relatively smoothly through the next four hours. The instructors did not participate, except to supply factual information as requested, but did assign a new discussion leader every forty minutes. By the end of the day, after much backing and filling, it had been decided that the following information would be sought:

- Kinetic and thermodynamic equilibrium data for the reaction of DMT and ethylene glycol over a range of different temperatures, initial concentrations, and catalyst concentrations.
- Kinetic data for the polymerization step.
- Information on the nature of polymerizers and stirring mechanisms.
- Information on possible catalysts for the DMT/glycol reaction so that a suitable catalyst might be selected.
- Physical properties (viscosity, melting and boiling points, thermal conductivity, specific gravity) and thermodynamic data (heats of fusion, vaporization, solution, and reaction) for all components and mixtures involved.

- Heat transfer coefficients for the process streams.
- Methods for analyzing the samples from reactor experiments.
- Phase equilibrium data for the glycol-methanol-DMT system.
- Costs of raw materials, utilities, transportation, etc.
- Information on appropriate safety precautions against burns, fires, and dust explosions (these and other hazards were identified at the outset by the instructors and by the industrial advisors).

The class split into three groups, each group taking responsibility for obtaining some of the data in the above list. The Kinetics group was responsible for identifying and gathering all information necessary for the specification and design of the transesterification reactor. The Separations group took responsibility for all laboratory separations (e.g., separating ethylene glycol from antifreeze) and for obtaining information relevant to the process separations. The third group was responsible for obtaining all physical properties which might be needed to estimate heat-transfer coefficients and friction factors. They were also charged with devising laboratory analytical procedures and with analyzing samples generated by the other two groups. This third group was called FHA (flow, heat transfer, and analysis) group.

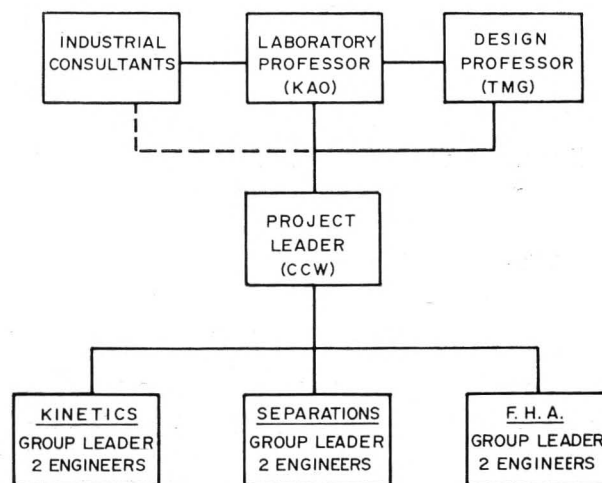
The lab instructor picked a team leader for each group based on past performance and on performance during the initial discussion period. One student was charged with the responsibility of coordinating the three groups, acting as liaison between students and faculty, and setting up a timetable to insure that all data would be obtained before the end of the semester.

The organizational structure is shown in Figure 1.

REPORTING SYSTEM

EFFECTIVE COMMUNICATION was particularly important in this project. It was es-

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COURSE ORGANIZATION

Figure 1.

sential, for example, that the necessary experimental equipment and supplies for a week's work be set up beforehand. The project and group leaders had to anticipate their needs and communicate them to the lab instructor and shop technician. Since each student had to design his own plant in the end, it was essential that he understand where the data were coming from and learn how the other groups were solving their problems.

To accommodate these communications needs, a reporting system was set up. Once a week, each group member would submit a short written report of last week's results and this week's plans to his group leader, who would read them, add a cover report of his own, and pass them on to the student project leader. The project leader met with the lab professor each Friday afternoon to discuss reports and problems and to compare progress to the timetable. Group leaders and group members were often asked to attend these Friday meetings.

In addition to the written reports, short oral reports were given by representatives of each group at the beginning of each lab period.

LABORATORY WORK

Kinetics Group

Based on a preliminary library investigation and on a limited acquaintance with the DuPont process, the Kinetics group identified three

variables upon which production rate might depend and set ranges over which they would take data on the reaction of DMT and glycol to form BHET. These ranges were:

Reactor temperature: 180-200° C

Manganese acetate catalyst

concentration: 175-275 ppm

Reactor feed mole ratio:

4:1 to 6:1 mole glycol/mole DMT

Time was not available to investigate the effect of pressure and different catalysts.

It was necessary for the instructors to guide the group away from a proposed semi-infinite series of univariant experiments. To avoid excessive experimentation, the group chose to plan their work using an incomplete factorial method.

The reaction was carried out in two electrically-heated, stirred, batch reactors at constant pressure. The concentration of BHET as a function of time was determined by condensing the methanol and measuring its volume as it was evolved. The reactor system was quite complicated and plagued with problems such as non-isothermal operation, loss of methanol and boil over of ethylene glycol. The students also got bogged down a few times in the kinetic analysis of their data.

The kinetics group finally obtained thirteen sets of smooth concentration-time data. Their library search, meanwhile, had turned up one appropriate study of the kinetics of their reaction [3]. The reaction rate equation proposed in the reference, however, was found inadequate for conversion levels above 85%; it was necessary for the students to fit their own rate expression. They proposed a model involving a monosubstituted intermediate. The model was found to fit the data quite well, even at high conversions. A computer program was written to integrate the set of differential equations. Given molar feed ratio, catalyst concentration, reactor temperature, and physical properties, the program predicted per cent conversion and rate of BHET production. It was invaluable in later repetitive attempts to seek optimal plant design.

An energy balance around the reactor revealed that the heat of the transesterification step was approximately 115 Kcal/mole DMT. This value along with the kinetics computer programs and some qualitative information on similar reactors as found in the literature, was all that the students felt was needed to design the ester exchange reactor.

Since the necessary equipment was unavailable, the polymerization reaction could not be studied in the laboratory. Fortunately, the students found a paper [4] and a patent [5] with the essential information.

Separations Group

This group had no difficulty obtaining the

ethylene glycol from antifreeze, and they rather quickly located vapor-liquid equilibrium data for the methanol-glycol system [6]. A series of glassware experiments revealed that the presence of DMT should have little effect on the design calculations for the separation of methanol and glycol. Since their work was finished early, the Separations group spent the rest of the semester helping the other two groups.

FHA Group

The most important task of this group was to obtain enough information to enable the class to size the heat exchange equipment and pipes and pumps. They realized from the start that the job was most efficiently accomplished not by designing and building special devices for measuring heat-transfer coefficients, friction factors, etc., but instead to measure or find physical properties (particularly for mixtures) and use presently design correlations.

The physical properties of the glycol were easy to find, the properties of molten DMT a bit less so. It was necessary to measure many of the properties of BHET and almost all of the properties of glycol/DMT/BHET mixtures over the relevant temperature and concentration ranges as specified by the Kinetics group. Melting points, densities, heat capacities, and viscosities were measured. Interesting experimental problems resulted from the relatively high (250° C) temperature involved.

All three groups were successful in obtaining

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the data needed in the design project before the end of the term. The data, along with useful correlations found in the literature, were compiled by the group leaders and distributed to the class.

FINAL REPORTS

EACH STUDENT SUBMITTED a formal, written design report at the end of the semester. Although some ideas (and all raw data) were common to the reports, the students did not

work together on equipment design. They were allowed to discuss their ideas on data requirements and the overall process flow sheet. When it was agreed that all the essential data were available, each student worked independently.

Both the lab and the design courses culminated in a seminar presented jointly to representatives from DuPont and to the Vanderbilt ChE faculty and students. Class representatives spoke for five minutes each on aspects of the laboratory or plant design; the talks were arranged so that the presentation would proceed smoothly and logically from problem statement and organization through experimentation and design to economic evaluation and optimization. The formal presentation was followed by an informal luncheon discussion between the student participants and their industrial advisors.

EVALUATION

THE JOINT PROJECT WAS successful from the standpoints of students, industry, and faculty. The two courses complimented each other appropriately, and all of our objectives were met, at least to some degree. The students were able to see the results of a finished piece of work. They did well; they performed in a mature, professional fashion. They demonstrated a strong sense of accomplishment and pride after their oral presentation to industry. Our goals were accomplished with a minimum of artificial rules, imitation engineering or pressure and guidance from the faculty. There were problems:

- Students from one group had a difficult time fully understanding what was being done in the other groups, or occasionally even by a different member of their own group. In order to gather data as rapidly as possible, specialization was the order of the day. For instance, one student would analyze samples for a month while another group would run the reactor. While this may be efficient it is not a desirable situation since the man analyzing the samples would not have a good feel for the kinetics.
- Although our industrial consultants were always ready to help, the students failed to take full advantage of the situation; student industry interaction could have been better.
- The weekly reports were often poor; insufficient feedback was provided.

FUTURE PLANS

THE INTEGRATION OF plant design and laboratory was so successful that we see no reason to return to our old system.

We are working on a new project for next year, again involving local industry. This time, we will arrange for the student groups to visit

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the plant regularly and discuss their problems with the practicing engineers and scientists. The final report will be presented at the plant site.

Financial support from industry seems in the offing.

REQUIREMENTS FOR SUCCESS

WE ENTHUSIASTICALLY recommend the joint lab design approach. If you try it, you might consider four points which we feel to be of paramount importance:

- The cooperation of an accessible industry is essential. The company should be willing to help provide ideas, materials, and (within proprietary limits) information.
- A suitable problem must be chosen. If it is too old, all the necessary information will be readily available in the literature. If it is too new, it may be too "secret."
- A great deal of advance planning is necessary. The faculty members in charge must familiarize themselves with the process and with its problems. They must develop a feel for the feasibility of the assignment.
- Consider your equipment constraints in advance. The project is unlikely to succeed if the students have to wait for orders, shipments, and deliveries.

ACKNOWLEDGMENTS

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Much of the equipment used in this project was provided by the Olin Foundation.

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