ChE *curriculum*

A PROJECT-BASED, SPIRAL CURRICULUM FOR INTRODUCTORY COURSES IN ChE

*Part 2. Implementation**

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This series of papers reports the development, delivery, and assessment of a project-based, spiral curriculum for the first sequence of courses in chemical engineering. The program is a significant restructuring of the traditional chemical engineering curriculum. Traditionally, a compartmentalized course sequence designed to build a conceptual foundation is taught during the sophomore and junior years, followed later by more integrated projects. Our new curriculum requires students to learn and apply chemical engineering principles by completing a series of open-ended design projects starting during their sophomore year. The new curriculum is spiral in that students' understanding of basic concepts is reinforced by revisiting them in different contexts with ever-increasing sophistication. A more detailed explanation of the concepts and curriculum design behind this effort was described in the first paper in this sequence.[1]

In this paper we will present the details of the spiral curriculum, together with illustrative examples of some of the projects used in the novel curriculum.

BACKGROUND

Worcester Polytechnic Institute (WPI) has a non-traditional academic-year structure, consisting of four seven-week terms. A fifth term is taught during the summer, but our spiral curriculum is restricted to the regular academic year. Students take three courses during each term, usually meeting every day and averaging 5-6 contact hours per week, with differing proportions of lecture and conference time. While this structure, more modular than traditional programs, allows greater flexibility in allowing students to pursue opportunities for study abroad and/or to carry out off-campus senior- and junior-year projects, it results in an intensive and fast-paced learning environment within a given course.

The conventional sophomore year at WPI for chemical engineers addresses concepts that require an understanding of equilibrium but not rate. It consists of the sequence of chemical engineering courses: stoichiometry and material

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and energy balances, classical thermodynamics, solution thermodynamics, and staged (equilibrium) separation processes. Concurrently, the students take an advanced chemistry sequence of physical chemistry, organic chemistry (two courses), and an organic chemistry laboratory. Their third course each term varies according to background, but usually includes differential equations and liberal arts/social sciences electives. The freshman year consists of a calculus sequence, an introductory chemistry sequence, physics, and some humanities electives. The conventional sophomore chemical engineering sequence was taught by four different faculty (including one of the coauthors) in the years during which the spiral curriculum was offered in parallel. The content of the courses is reflected by the course textbooks,[2-5] which are widely used and which were also used in the spiral curriculum (note that the book by Wankat was used in the first-year offering and the book by Seader and Henley was used in the second-year offering). For the spiral curriculum, the students purchased all their books at the start of the sequence instead of course-by-course, as in the traditional sequence.

> ***The introduction of new topics occurred when faculty judged that students needed the topic. The students were not at a level where either their experience or their confidence was high enough for them to ask for new material at the appropriate time. Thus, the instructional activities throughout a project were quite structured, with the faculty attempting to anticipate the students' needs.***

SPIRAL CURRICULUM

To construct topic sequencing and levels, we itemized specific skills and content for the four traditional courses in the sophomore year. Over 135 items were identified for the four courses in addition to general skills such as report writing, oral communication, etc. We then prioritized the topics and skills and rearranged them into a four-course spiral sequence. The first spiral course introduced key concepts from all four traditional courses at an introductory level (Level 1). Subsequent spiral courses revisited the same fundamental concepts with increasing levels of complexity (Levels 2-4). More details on this phase of the curriculum development are presented in Part 1 of this series.[1]

The instructional components of the spiral curriculum consisted of formal lectures, homework, problem-solving sessions, group projects, and exams. Students were evaluated on both individual work (homework, exams) and group-based assignments (projects). The projects were used to motivate and focus the study of the topics described in Part 1, but since they could not include all topics it was necessary to supplement them with formal lectures within which some topics were discussed exclusively. Typically, individual work counted for 60-70% of the term's grade, with group-project work making up the remainder.

The curriculum was delivered by the three coauthors, with a teaching assistant and a peer learning assistant (PLA) who assisted in facilitating group dynamics. Each project, with the associated lectures, classes, labs, homework, and exams was taught by an individual faculty member. Thus, since the students participated in three projects each term, they were taught by all three faculty each term, although not always in the same order.

In year one, 16 students were randomly selected from a class of approximately 56, whereas in year two the experimental section was 20 students from a class of 46. Students were not allowed to self-select for the experimental group. Any student who did not wish to participate would have been allowed to return to the traditional section prior to the beginning of the academic year. Transfer out of the experimental section was allowed at any time, but students could not elect to transfer into the sequence. We did not replace dropouts after the beginning of the academic year.

TEACHING METHODS

A mixture of instructional methods was used in the new curriculum in order to address the diverse learning styles of the students. We used in-class active-learning problem-solving sessions and mini-sessions, combined with lectures, throughout the year. During the course of each project, class time and homework assignments were aimed at helping the students acquire the required fundamentals on a "just-in-time" basis through an assortment of channels, including multimedia computer instructional modules, lectures, workshops, reading assignments, and student discovery from experimentation and/or the literature. Homework problems were assigned that assisted the students with calculations and concepts that they were about to need for the project. After each project period of two to three weeks, an exam was given that covered concepts from the lecture material, project material, in-class work, and homework.

The "just-in-time" approach to the projects had to be moderated with an appreciation of the maturity level of the students, especially in the early part of the curriculum. The introduction of new topics occurred when faculty judged that students needed the topic. The students were not at a level where either their experience or their confidence was high enough for them to ask for new material at the appropriate time. Thus, the instructional activities throughout a project were quite structured, with the faculty attempting to anticipate the students' needs.

The curriculum featured several laboratory experiences, associated with the projects and described in the following section. In addition, use was made of computer-aided instruction (CAI) and multimedia tools. Two interactive multimedia disks were developed for this curriculum by one of the authors (WMC) on the properties of pure fluids and on chemical reaction equilibria.[6] In addition, learning tools from the University of Michigan[7] were used. The reaction-equilibria CAI disk was used in combination with a project, and the others were used as supplements to lecture. A portable collection of notebook computers facilitated in-class problem-solving and computer skill-building sessions.

Students were assigned to four-member cooperative learning groups and were reassigned to new groups every seven weeks. The assignments were made randomly, but adjustments were made to distribute the strongest students evenly across the groups. Some group meetings were held during class time, but most were held outside of class. All group members received the same group project grade.

As an illustration, a generic timetable used for a project is shown in Table 1. Several variations on Table 1 were used, depending on the project, but the essential elements are included there. The class met every day (as is typical for WPI courses), and one class per week lasted for a two-hour period, allowing more extended in-class participation. In the example shown, Tuesday was the double period, so there could be lecture and in-class problem solving on the same day.

To show how the instructional sequence was structured around the project, we will here consider a specific example and refer to Table 1 for comparison. In the middle of Level 2, we asked the students to design a new steam power plant. Students determined heat and work requirements in a boiler, a condenser, a turbine, and a pump. They determined the thermal efficiency of the cycle, compared it to a Carnot cycle, and determined ideal and lost work for various components. Early in Level 1, the students were exposed to material balances on reactive processes and to energy balances without reaction. In this Level 2 project, they made material and energy balances on a reactive system, combustion in the power plant boiler. In Level 1, they also studied PVT properties of pure fluids and performed energy balances on steady-flow devices in a refrigeration cycle. Here in Level 2, they combined 1st and 2nd law analysis for power cycles (and refrigeration cycles in a subsequent project). The steam power-plant project also required them to consider environmental issues. A proposed catalytic reduction process for removing 1000 ppm NO from the boiler flue gas by reaction with NH_3 was analyzed. This twist on the typical power-plant problem required the students to think about heat exchange to cool the flue gas and at the same time vaporize and heat the ammonia that was stored as a liquid under pressure.

The student teams were confronted with this project before they had learned all the fundamentals required to complete it. Because it was still early in the sophomore year, this project had an itemized list of intermediate deliverables and an associated timetable, as shown in Table 1. On day one, the project was assigned and groups brainstormed about how to approach it and determined what they did and did not know about how to solve it. A brief memo report (Part 1) analyzing the methane combustion reaction in the boiler was due a few days later. A second memo report (Part 2) and a brief oral report on the thermal efficiency of the power plant were due a week later. A third memo report discussing the entire project, including an open-ended call for suggested improvements to the process, was due at the end of the two-and-a-half-week period.

At the beginning of this project, reading assignments, a

TABLE 1

Generic Timetable for a 3-Week Project Segment of the Curriculum

Week	*Monday*	*Tuesday*	*Wednesday*	*Thursday*	*Friday*
1	**Introduce Project;** Brainstorm	Lecture; In-class problems	Homework due; In-class MathCAD session	**Part 1 Due** Lecture; discussion	In-class problems
2	Homework due; Lecture	Lecture; In-class problems	Lecture	**Part 2 Due** Oral reports; Discussion	In-class problems
3	Homework due; Review	**Exam**	**Project Due** Start new project		

lecture, homework, and in-class problems were given on combustion reactions. A portion of a class period was used for hands-on computer calculation of heats of reaction with temperature-dependent heat capacities using Mathcad. As the project progressed, lectures and assignments were given on the main ideas of heat effects of reactions, entropy and the second law, power cycles, thermodynamics of flow processes, refrigeration, and fundamental property relations. Some of these topics had been briefly introduced earlier in the curriculum, and some were revisited in later projects—for example, refrigeration. Frequently, lectures gave the essentials of a subject only, with further material being introduced through the in-class problems and/or discussion, which forced the students back to their texts or to the instructor for more explanation or information.

TABLE 2
Spiral Curriculum Projects by Level

Level 1

Dehydrogenation of ethanol to acetaldehyde • *This project introduces students to a simple acyclic process with chemical reaction and separation.*[8] *Material balances are made, using the reaction stoichiometry with one main reaction and two side reactions, to calculate reaction conversion and yield. Concepts of separation are introduced (flash, absorption, distillation) and simple splits are calculated without any equipment design being attempted.*

Methylene chloride recovery • *This project addresses the recovery of a solvent from the air above a parts-washing tank by using a refrigeration unit to cool the air stream and condense the solvent. Students use ideas about partial saturation to calculate the composition of the air, then use energy balances to analyze the refrigeration process to determine circulation rates of refrigerant and cooling water, and the compressor power requirement.*

Chemical process tank explosion • *An indoor surge tank contains a multicomponent mixture at an elevated pressure. Students are presented with a scenario in which the pressure control fails and the tank vents directly into the room. They are asked whether an explosion will occur in the presence of an ignition source. They are required to calculate multicomponent VLE over a given temperature range to obtain the vapor composition and check explosion limits.*

Level 2

Design of plant-scale distillation column • *This is a laboratory project in which students conduct a preliminary design for an ethanol/water staged distillation column. They obtain experimental values for stage efficiency from an existing laboratory column. Their analysis includes number of stages and feed location, condenser and reboiler loads, tray diameter from flooding curves, and a preliminary cost estimate.*

Steam power plant • *The design of a new steam power plant is proposed. Students use thermochemistry to calculate the flue-gas composition and heat of combustion of the fuel. They use thermodynamic principles of flow processes to analyze the turbine to obtain ideal work and then use efficiencies to obtain actual work. They address the environmental issues and perform energy balances for a heat exchanger to cool the flue gas prior to a proposed catalytic reduction process.*

Ammonia process synthesis • *Students perform material balances on a process with recycle.*[9] *An energy balance for a turbine is carried out to obtain work available that involves real gas calculations and use of residual properties. An isothermal staged gas absorber is designed, using Henry's law. A staged distillation column, including the refrigeration loop on the condenser, is designed, forcing students to revisit these concepts.*

Level 3

Mixer feed strategy for isothermal operation • *This project involves the feed, in six separate hourly additions, of a solid to water. The mixing tank is heated/cooled at a constant rate. The objective is to operate as nearly isothermal as possible. Students use heats of solution data in combination with material and energy balances to calculate heats of mixing and determine the amount of solid that can be added each hour.*

Design of a pressure-swing distillation sequence • *The student teams are given VLE data for the methyl acetate/methanol azeotrope system at 1 atm. They are asked to choose a higher pressure, corresponding to a different azeotrope composition, and to design a pressure-swing distillation sequence to separate the components, using methods presented in the texts.*[4,5] *They fit VLE data at 1 atm under low-P assumptions to obtain activity coefficient correlations, then use these correlations together with high-P fugacity coefficients and the Poynting correction to predict the VLE at the higher pressure.*

Liquid-liquid extraction • *The ternary system acetic acid/water/ethyl acetate is studied. A laboratory experiment is performed using a two-stage crossflow extraction, and students compare their measured results to predictions obtained using a constant distribution coefficient model. After verifying the LLE model, a multistage crossflow extractor is designed for industrial conditions.*

Level 4

Catalyst regeneration • *A catalyst regeneration process is described in which a catalyst that has deactivated due to the deposition of carbon on it is regenerated by passing a stream of hydrogen over the catalyst at high temperature. Students are asked how long it will take to remove 90% of the deposited carbon under given operating conditions. This requires them to calculate the equilibrium product composition for a single reaction, and integrate their results into material balances for the regeneration process. They are also asked to consider using steam for catalyst regeneration, leading to an analysis of multiple reaction equilibria.*

Batch distillation • *Students design and test an experimental project related to the basics of multistage batch distillation. The student group plays the role of the teaching team for the course. They have available a glass distillation column in the unit operations laboratory with provision for adjusting the reflux ratio. Unsteady material and energy balances are used to analyze column behavior.*

Simulation of vinyl chloride process • *A steady-state simulation of a vinyl chloride process*[5] *is performed using the ASPEN PLUS flowsheeting package for combined material and energy balances. Students are given a relatively detailed flowsheet for the process and an approximate material and energy balance table, under some simplifications such as perfect splits. They have to decide what level of detail to put into the flowsheeting model and perform a more rigorous simulation.*

The exam at the end of this project period covered heat effects for industrial reactions and 1st and 2nd law analysis for flow processes, including power and refrigeration cycles. It was convenient to have the project final report due on the day after the exam. This gave students the opportunity to polish the reports on an evening when nothing new was assigned due to the transition between topics and instructors.

COOPERATIVE GROUP PROJECTS

Brief descriptions of all the projects used in the course are presented in Table 2, ordered by level and in chronological order within each level. Three of the projects involved laboratory work, while one short one used ASPEN PLUS in a simulation. Several of the projects contained components of engineering design. On average, the students completed the projects, including a team-written report, in two weeks, although the laboratory-based projects sometimes required a little longer.

Four of the projects, one from each

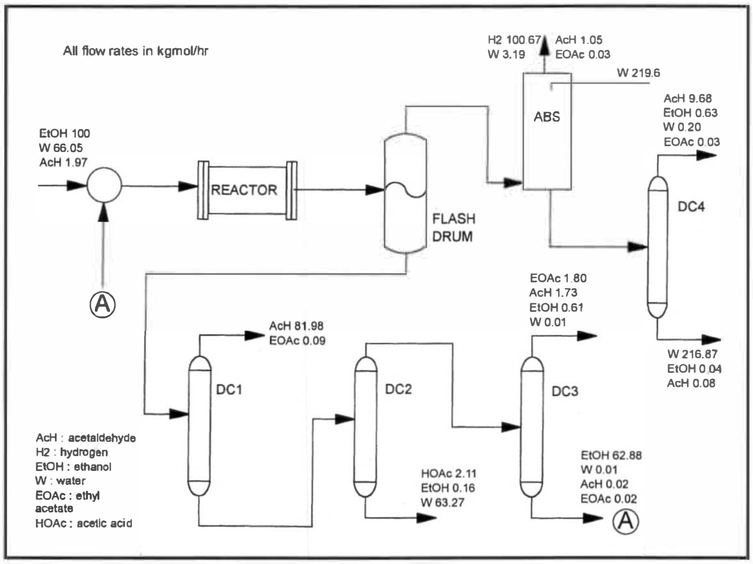

Figure 1. *(Level 1, Project 1) Process flowsheet for ethanol dehydrogenation to acetaldehyde.*

level, have been selected for more detailed discussion below to illustrate both how they were integrated into the curriculum and the evolution of the students' abilities throughout the year.

▶ Ethanol dehydrogenation

(Level 1, Project 1)

This was the first project that the students saw in the new curriculum. Since they had no chemical engineering background at that stage, the project was very simply stated and all engineering jargon had to be explained. They were given the process flowsheet depicted in Figure 1, and the functions of all blocks representing pieces of equipment were carefully explained. Written descriptions of the process chemistry and the process itself were provided. The flow rates of most of the streams were provided, and the primary project goal was to work backwards to determine the conversions of the ethanol to the desired product (acetaldehyde) and to the by-products (acetic acid, ethyl acetate). Some secondary goals were also set, requiring the students to work with mole/mass conversions, make some further balances to scale up production, and calculate the splits obtained in the separations equipment for the various species. Although the process itself did feature a recycle stream, by giving the flow rates for it the material balances reduced to those for an acyclic process.

As the project teams considered this task over two weeks, they received more formal instruction on units, analysis and measurement, non-reactive material balances, material balances on multi-unit systems, stoichiometry, reactive material balances, and combustion. The material was quite structured to respond directly to what they needed to complete the assignment—they were not expected to "dig it out" for themselves at this stage. The project introduced them to a variety of chemical engineering terms, allowed them to see the work they were doing in the context of a complete, although much simplified, process, and helped to motivate the study of the introductory material.

▶ Ammonia synthesis

(Level 2, Project 3)

The students were at a quite different stage at the start of this project, almost exactly halfway through the year. They had covered material and energy balances, 1st and 2nd law thermodynamics, and could design and analyze flashes and staged distillation columns as well as power and refrigeration cycles. They had seen recycle on a small scale, for individual equipment and power cycles, but had not yet attacked a complete flowsheet with recycle. They were still using ideal-gas concepts or steam tables for properties, and Raoult's law for phase equilibria.

The function of this project was to introduce the students to a moderately complex recycle process, as shown in Figure 2. The process included recycle of unconverted reactants, purge, and make-up streams, and recycle of absorber cooling water. The process was gas-phase, running at 225 bar, except for the absorber (40 bar) and distillation column (1 bar). This high-pressure process motivated the introduction of real gas behavior, although as the gases were mostly hydrogen and nitrogen, the actual deviations were not large. In addition to performing a complete material balance, the students were asked to design several aspects of the equipment. They were asked to evaluate the possibility of replacing the expansion valve, VAL-1, by a turbine to recover useful work, and to determine the cooling duty required for the cooler, CLR-2, in that case. They had performed such calculations before in the ideal-gas case, but were now instructed to use the Lee-Kesler generalized correlations to calculate residual properties. The presence of the absorber motivated introduction of some lecture material on the design of this equipment, which provided an opportunity to revisit the operating-line concepts seen before in distillation design and to contrast the use of Henry's law for gas-liquid equilibria with that of Raoult's law for vapor-liquid equilibria. Their last task was a design of the distillation column and the refrigeration cycle used to condense the ammonia in the overhead, which again forced them to re-use prior

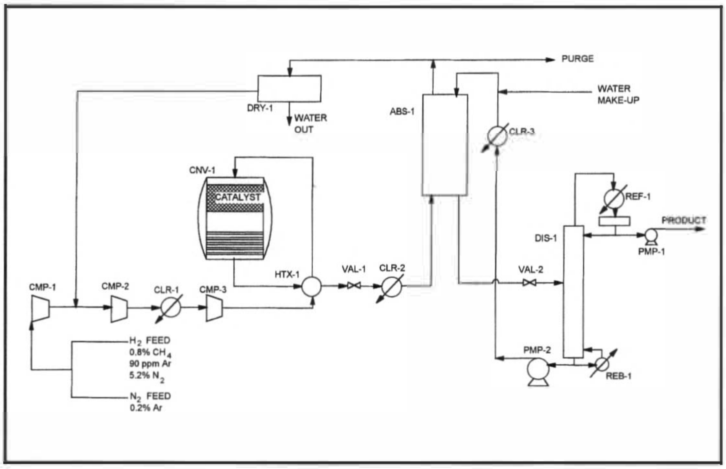

Figure 2. *(Level 2, Project 3) Ammonia synthesis process flow diagram.*

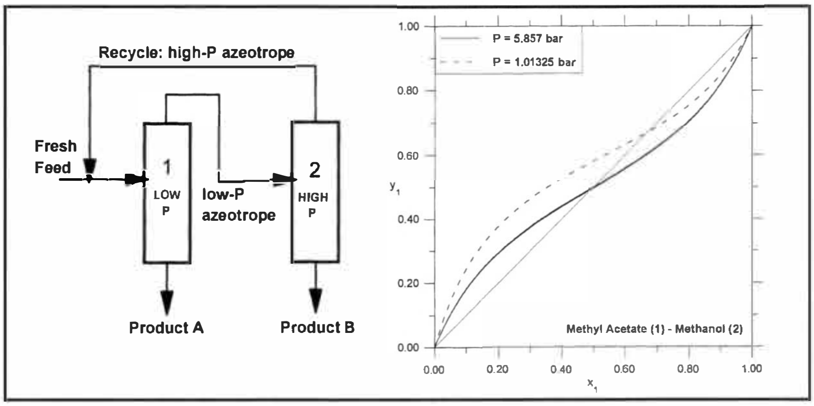

Figure 3. (Level 3, Project 2) Methyl acetate/methanol separation by pressure swing distillation (schematic redrawn from Reference 5).

material, this time in the context of a complete process. Thus, this project introduced a significant element of the spiral nature of the curriculum, requiring several of the skills previously acquired, but either in extended form or in a different setting.

► Pressure-swing distillation

(Level 3, Project 2)

The material with which students have the most difficulty during their first set of courses is usually solution thermodynamics. The concepts are more abstract than material balances, for example, and the frequently heard lament in the traditional section is "What's the use of a fugacity anyway?" or similar not-so-polite expressions. We found it difficult to break up the material usually taught in this course or to introduce much of it earlier when the conceptual abilities of the students would be even less developed. Our approach, therefore, was to leave the material relatively intact, but to motivate it with the project shown in Figure 3 and to emphasize the practical use of the ideas before introducing the theoretical background.

From their previous work on distillation, including a laboratory project using the ethanol-water system, the students understood the difficulties of separating azeotropes. Some methods of dealing with this were briefly reviewed, and the focus was put on pressure-swing distillation. In this method, two columns operating at different pressures were used. The azeotropic composition was pressure-dependent, and advantage could be taken of this to effect a complete separation. These methods were well-described in the class texts.[4,5] Following a review of minimum-boiling and maximum-boiling azeotropes, the students were given VLE data for the system of interest, at 1 atm. Concurrently in their classroom exercises, they were asked to use Raoult's law to fit xy-data for the ethanol-water azeotropic system, to convince them that more sophisticated methods were needed. The Wilson equation was introduced, and they had to use it to fit the supplied data, under low-P assumptions. They picked a higher pressure to operate the second column and used the constants for the Wilson equation to predict the activity coefficients at the new conditions. In addition, they were told that they could not assume low-P for their new conditions and that they had to use the fugacity coefficient corrections and Poynting factor. When they had the new xy-data (see Figure 3 for an example), they tested their understanding of McCabe-Thiele methods by re-using them (more spiral structure!) to design the columns for the azeotropic system separation, which required them to work in terms of the less volatile component.

Concurrently with their work on this project, the class was introduced to the usual definitions and derivations of solution thermodynamics in formal lecture and class exercises. They accepted these concepts more readily with the project and a realistic application as motivation.

► Batch distillation

(Level 4, Project 2)

Level 4 represented the end of the sophomore year. By this time, the students had gained considerable maturity and had acquired a wide range of skills. Topics covered in this level included transient material balances (batch distillation) and combined material and energy balances (psychrometric charts, humidification and enthalpy-concentration diagrams). We felt they were ready for a very open-ended, somewhat different type of project.

We asked them to design a project that might be used in subsequent course offerings. The project had to include topics that were currently under study, could include anything appropriate from earlier in the year, and had to use the batch distillation column available in the unit operations lab. The project not only provided a chance to "think outside the box," but also provided an application of transient balances and revisited distillation for the fourth time in the academic year. After designing their project, the student teams had to test it in the laboratory and modify their design accordingly.

The lab column is a two-story high, 11 bubble cap, glass column with a steam reboiler and capability for operating at variable or constant external reflux ratios from 1 to 40. Early in Level 2, students performed energy balances, equilibrium, and efficiency calculations using this column operated at total reflux. They were familiar with column operation, data taking, sample analysis, and safety procedures. A sketch of the column is shown in Figure 4.

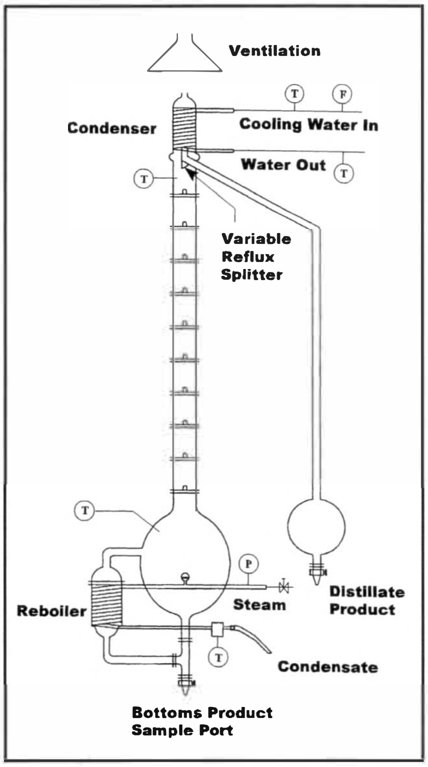

Figure 4. (Level 4, Project 2) Pilot batch distillation column.

Proper project design required each student group to develop educational objectives, write a scenario providing context for their experiment, and specify deliverables from the fictitious students who might use the project in subsequent years. This "design your own project" assignment had the potential for groups to incorporate lots of material from earlier projects, including nonideal thermodynamics, McCabe-Thiele analysis, column efficiency calculations, and energy balance (heat loss) calculations.

Our experience from two implementations of the "design your own project" was somewhat mixed regarding the results. Reports from the first set of student teams had very creative and original scenarios and showed that most teams spent many hours testing their projects. But their educational goals were somewhat naive, limited only to current course topics, and the reports were poorly written. We modified our own assignment description and provided a little more guidance for the second implementation. The results of this change were much improved, and we were generally quite pleased. Substantial incorporation of appropriate material from earlier in the year was not evident, however, even in the best groups. Reasons for this result are currently under evaluation and will be reported in Part 3 of this series.

PRELIMINARY ASSESSMENT

One of the primary aims of the new curriculum was to develop the students' ability to work on open-ended projects, to work in teams, and to communicate the results of their work. In order to evaluate the success of the curriculum in achieving these goals, relative to the traditional curriculum, a design competition was held near the end of the academic year. Student teams were assigned a difficult open-ended chemical engineering design project requiring integration of material covered during the year. They were asked to develop a process flowsheet and present their analysis of a process for the production of 10^6 lbmol/hr of 99% pure formaldehyde. They were given the reaction

$$CH_3OH \Leftrightarrow CH_2O + H_2$$

and told that a catalyst was available that was active enough to attain reaction equilibrium for stated conditions of temperature and pressure. They were also told that a membrane process was available that completely separated H_2 from any stream at any T, P. Physical properties information was supplied. Students were asked for a quantitative analysis of their proposed process and the associated material balances.

A sketch of the type of flowsheet we anticipated the teams would come up with is shown in Figure 5. Students were expected to recognize the need to separate the product formaldehyde from unreacted methanol and to recycle the methanol. They had to decide whether to do this by flash or staged distillation and then design the unit. They needed to make reaction equilibrium calculations to obtain the composition of the product stream from the reactor and perform a material balance with recycle once they had the equilibrium conversion.

> ***. . . we anticipate that other faculty can step into the spiral curriculum with relative ease. The preparation time would certainly be no worse than for any new teaching assignment in a conventional course.***

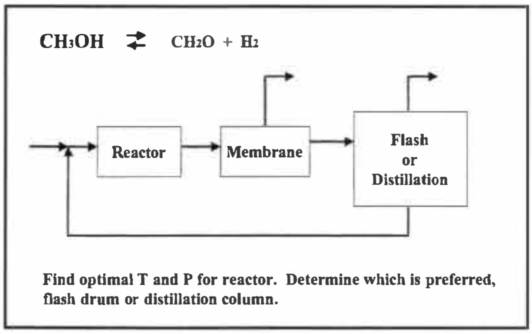

Figure 5. *Problem for design competition.*

Twelve students from the new, spiral-taught section (intervention section) and twelve students (volunteers) from the traditional section (control section) participated in the competition. The students from each section were randomly subdivided into three teams of four students each. Students were paid $50 each for participating, and (to increase motivation) a $50 prize was awarded to each member of the teams with the best designs. We awarded a prize to the best effort from the three intervention-section teams and also to the best effort from among the control-section teams, so that students competed only within their own section. Winners were determined by independent judges. The competition took place during a single two-and-a-half hour period, comprised of two hours of work and two ten-minute presentations. Three rooms were used, with one team from each section in each room. Both the students' working sessions and their oral presentations were videotaped for later analysis.

Three professional chemical engineers from academia and industry served as judges for the competition. These judges had no connection with either the intervention or the control sections of the course and did not know the identity of any of the students or from which section the various groups came. Judges were instructed to view the videotape of the students' oral presentations and to rank the work of the six groups based on the quality of the technical content, disregarding presentation style in their rankings.

The judges unanimously ranked the students from the intervention section in the top three positions, with students from the control section ranked in the bottom three positions. This evaluation showed that the students in the intervention section had an increased ability to apply chemical engineering principles to the solution of integrated design problems. Our own viewing of the videotapes showed that the intervention-section teams made more progress on the analysis, successfully integrated material from different areas of chemical engineering, and gave more consideration to alternative solutions.

SUMMARY

We learned several lessons from the development of the project-based spiral curriculum structures. The integration of project-based activities involved considerable work for the faculty, not least because of the degree of inexperience of the students at this stage of their development. The degree of open-endedness and type of project that could be given to seniors in their design project would be overwhelming for sophomores. Instead, it is necessary to orchestrate the projects in a way that will lead the students in the desired direction and to coordinate them very tightly with more formal material and resources. The concept of spiraling all four courses, although appealing, needed tempering. It became apparent in structuring the content that the majority of the material and energy balance content still has to appear early in the year, while the more difficult solution thermodynamics cannot be effectively introduced early in the course and should wait until after the classical material has been presented. We ended up with a structure that was more parallel in concept—it seems to be very effective to teach applied material alongside the more abstract or theoretical material. This seems to happen naturally for the material-balances course, but it requires positive efforts to integrate solution thermodynamics with applications in separations.

The preliminary assessment results showed that the new curriculum met the educational objectives that we had in mind when it was developed. The technical proficiency of the group of students under the spiral curriculum was at least equal to, if not better than, that of the traditional group. Their attitudes toward chemical engineering and teamwork were better. Their teamwork and communication skills were better than those of the traditional group, and they showed enhanced ability on "real" projects. More extensive assessment results based on the complete two-year experimental program, plus follow-up on the groups after their sophomore experience, will be reported in Part 3 of this series.

The new spiral curriculum could be readily adapted to the traditional semester system, either whole or in part. The most obvious translation would be to cover our first two levels during the fall semester and our next two during the spring semester, thus combining two seven-week terms into one fourteen-week semester in each case. This would require introduction of staged separations earlier than is often the case and separately from the rate-based separations of the mass-transfer operations course popular in many schools. Our sequence of material and energy balances followed by classical thermodynamics followed by solution thermodynamics is fairly standard. If this amount of restructuring were not feasible, then it would be possible to import some of the projects into existing courses and use them as motivating exercises, although the benefits of ongoing teamwork might be reduced. Also, if separations applications could not be used in conjunction with thermodynamics, then one of the advantages of the approach would be lost.

Now that the structure and projects have been put in place, we anticipate that other faculty can step into the spiral curriculum with relative ease. The preparation time would certainly be no worse than for any new teaching assignment in a conventional course. New faculty could also bring different projects to the curriculum, corresponding to their own experiences and expertise. A major difference from the faculty point of view is that such an assignment is for an entire academic year rather than for a single semester or term. Involvement with the course is ongoing throughout the year due to the need to coordinate with other teachers, but is relatively low-level when others are actually involved in the classroom. One advantage is that when a faculty member needs to be out of town on other scholarly activities, it is relatively painless to find a substitute!

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