AN INTEGRATED DESIGN SEQUENCE

Sophomore and Junior Years

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The recent information explosion in science and engineering requires careful selection of what topics to present to the undergraduate. In the limit, as the amount of material covered in class approaches infinity, student comprehension approaches zero; the inverse is also true. Both limiting conditions are intolerable. It is important to back away from saturation coverage and to focus on the material that future engineers will need.

The future engineer will need to understand (analyze, optimize, synthesize, evaluate) the interaction of a series of steps that work together to achieve some desired result. The engineer (today and in the future) must be able to

- *Work in teams to solve a problem*
- *Identify the need to know information*
- *Locate material to satisfy these needs*
- *Learn the content material*
- *Solve the problem with appropriate methodology*
- *Communicate effectively*

The design sequence presented in this paper requires students to practice and develop all of these skills. They learn to recognize the interrelationship between courses; they learn that the courses are not isolated, only to be forgotten as soon as a grade is received.

Our faculty members agree that a common goal of producing graduates with the above skills is the most important aspect of our undergraduate program. Under the leadership of two or three faculty, all other faculty teaching the affected courses participate in the design projects. We discuss the undergraduate curriculum and adjust course emphasis if necessary; if an instructor feels that students do not have adequate mastery of a prerequisite subject, similar adjustments are made. We believe that any design project which requires students to learn for themselves, which demonstrates that engineering is more than a series of well-defined problems at the end of some chapter, which demonstrates that engineering knows no traditional course-work boundaries, and which forces students to synthesize material as it is learned, will benefit the student and, ultimately, produce a better engineer.

We recently introduced an integrated design project that spans the sophomore and junior years. A single chemical process design is analyzed, synthesized, and evaluated over the course of these two years. The first-semester sophomore project focuses on material balances and applies simple economic criteria based on the costs of raw materials, products, and by-products. Each subsequent semester requires additional knowledge, and by the end of the junior year the design yields an economic optimization of an improved process which the students synthesized and which required selection of operating conditions and sizing of chemical reactors, heat exchangers, pumps, compressors, separators, and recycle rates. The economics include both capital costs and operating costs such as pay-back period (time value of money is not introduced until the senior year).

These are group design projects that are integrated into

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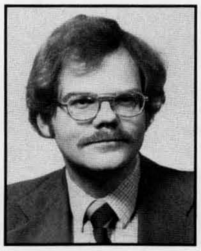

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existing courses—three in the sophomore year and five in the junior year. Different grades are assigned for all team members on the project, based on an evaluation of the content of the design project relevant to that course. More details are presented elsewhere.[1]

The rationale for this approach is uncomplicated. We want to prepare our students for a group senior-year design project, for a sequence of individual comprehensive problems required in the senior year, and ultimately, for a forty-year career in chemical engineering. These senior-year design activities are described elsewhere.[2,3]

As a result of the design projects, students develop a number of personalized strategies for life-long learning—they learn self-evaluation and experience team work, they recognize the role of economics in decision making, they appreciate the need to understand basic principles, and they understand the various sources of engineering information. Since (group) oral and written reports are required most semesters, they also learn the importance of developing communication skills.

In addition to the direct impact on students, faculty are provided with the necessary input to assess student performance in their application of engineering principles. The feedback provided by the senior-year design projects affect the content of the sophomore/junior design projects. This is one mechanism we use to ensure that graduates meet minimum standards of knowledge and skills. The feedback directly measures learning and aids in curriculum development and improvement.

ABET is in the process of changing the design and engineering science requirements to eliminate the "bean counting" in favor of an "integrated design experience" throughout the curriculum, ending in a capstone course. The program described in this paper is one type of integrated experience which appears to satisfy these new criteria.

This paper will briefly summarize the design sequence, review some of the experiences the students had during the sequence, describe changes in student development, report on the "student culture" that has evolved, and attempt to explain why these changes took place. The paper will focus on the first-semester junior design for the 1992-93 year to illustrate how the process operates.

REVIEW OF DESIGN SEQUENCE

A single chemical process is the basis for the design sequence during the sophomore and junior years. Each subsequent semester's design requires additional knowledge and more detail, including mastery of the previous design. All chemical process designs used for this sequence are symbolized by a generic process block diagram (see Figure 1). These include four essential elements: a pre-reactor system, a chemical reactor system, a recycle stream, and a post-reactor system (*i.e.,* one or more separation units).

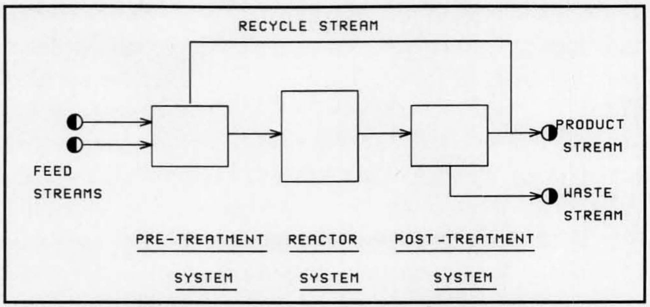

Figure 1. *Generic chemical process*

We introduce first-semester sophomore students to a simple process flow sheet that includes a reactor, a separator, and a recycle stream. We give them cost data for feed and product streams; we provide several feed stocks and recycle rates and require the students to select operating conditions.

In the second semester we give the students a more complicated flow sheet that includes heat and work units. Utility costs are provided and are included in the evaluation. Students learn that heating, cooling, and power cost money. The advantage of high conversion at elevated pressures is offset by the high cost of running the gas compressors. This affects the selection of operating conditions. As the students' understanding of the process is enhanced, the quality of their decisions improves.

In the first semester of the junior year, we cover thermodynamics, heat transfer, and fluid flow. For the first time, students learn how to calculate the area of heat exchangers, to evaluate the work/heat requirements for systems of staged compressors with intercoolers, to determine the number of adiabatic (equilibrium) reactors in series, to handle the nonideal behavior of gas mixtures, and to determine the size of process piping. All of these studies are needed for the new design. For the first time, capital costs are considered in the analysis. The optimum operating temperature and pressure changes because of this change in the objective function.

The final design in the second semester of the junior year differs in one major aspect. We do not give the students a flow diagram as a starting point. We provide kinetic information that yields different reactor performances and require the students to examine the separations units of the post-reactor system. Combining their experience from the previous designs with the new information on separations and kinetics, they synthesize a new, improved, process.

Details of the First-Semester Junior-Year Design Project

A few details, taken from the first-semester junior year, are presented here, and they illustrate the types of activities that result from the design sequence. Recent first-semester juniors involved in their third design continued their investigation of a process for the production of ammonia from synthesis gas. Figure 2 shows the process flow sheet provided to the students with the problem statement. It is a "caricature" chemical-process diagram and includes certain attributes that have been distorted. They are not tricks, nor are they necessarily realistic. They are often naive design choices meant to focus students' attention on a specific concept. Two examples are absence of any heat integration and compressing a vapor when pumping a liquid is possible. From this flow sheet, we expect students to discover a *need to know* more about separations and reaction kinetics to develop a credible design. This established groundwork for the following semester's content. The "caricatures" included in Figure 2 and the problem statement are:

1. *High concentration of CO_2 in the feed*
2. *Questionable solubility data for CO_2 in liquid NH_3*
3. *Fixed reactor cost independent of temperature, pressure, concentration, and flow rate*
4. *Single-stage compressor for feed*

Students started this design with valuable experience gained from previous projects with a somewhat simpler ammonia process flow sheet. They had discovered the high cost of gas compression and the effect of conversion on process profitability (that the higher conversions were obtained at lower temperatures and higher pressures). The problem statement had provided cost information on feed material, equipment, and a wide range of utilities along with introductory relationships for estimating the capital costs for major equipment units.

The students soon realized they were not able to evaluate chemical conversion for this new feed material and did not understand how to reduce the cost of compression. Also, the relationship for heat-exchanger costs required knowledge of the area, and they could not calculate the area. They could not deal with non-ideal gases. They had unmasked several "needs-to-know." These needs were satisfied by the concurrent class work.

Figure 3 is a composite design that represents the students' response to the project. The major characteristics are

- *The reactor operated at low pressure (in spite of lower conversion)*
- *A three-stage compressor replaced the single-stage compressor*
- *A 3-7 stage adiabatic reactor with intercooling was used to obtain high conversion*
- *A single-stage condenser replaced the two-stage system*
- *High recycle rates were required.*

While group solutions differed in detail, all the groups presented a modified flow sheet that was an improvement over the one they were given. They had all correctly identified the need for class content, had learned that content, and had applied it to the design. They had gained the confidence to challenge and to make changes to the original flow sheet.

Students are traditionally trained to mimic what they have seen and heard, but this seldom translates into an ability to make meaningful changes. Individually, they fear looking foolish—but as a group they are braver, more willing to express their ideas and opinions. Previously, they had probably had little practice in challenging things that were presented to them—the "caricature" problem helped them recognize that they *can* contribute better ideas.

Students wanted to use a chemical process simulator to perform the many required calculations, but prior to their junior year, our students are not allowed to use a simulator for class problems or projects. Having observed seniors working with the software, the juniors wanted to exploit this tool. Faculty encouraged them to use it whenever appropriate; however, no class time was spent in instructing students on its use. The juniors solved this problem by finding knowledgeable colleagues (in this case, seniors) and asking them how to use it. In response, the seniors set up individual tutoring sessions and were available to help as needed. (This required a user-friendly, interactive, readily available simulator.) Given this self-discovered need-to-know, the juniors picked up the fundamentals quickly, gaining proficiency with practice. They took the initiative and learned what was necessary on their own. This is how our sophomores and juniors learn about plotting, spread-sheeting, and graphics software; no formal class time is devoted to these activities.

ILLUSTRATIVE STUDENT EXPERIENCES

In navigating a passage from the starting point represented by Figure 2, and the destination represented by Figures 3, students encountered many obstacles that had to be overcome. How the students hurdled these barriers is revealing. Some of their solutions follow:

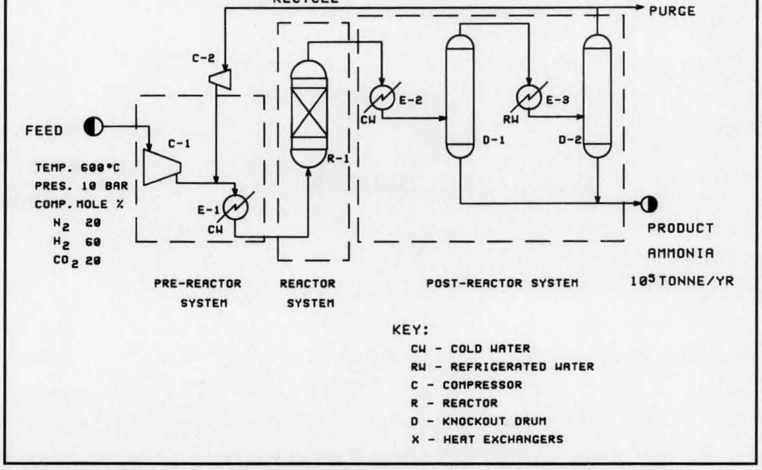

Figure 2. *Ammonia (caricature) process flowsheet*

Event 1. Most design groups established a computer simulation as a first step. They studied the effects of changing recycle ratio, pressure, and temperature on the conversion. It was only after many hours (days) of toil that they considered economics and found that the system was an economic disaster. Unlike those groups, one group chose to consider economics first. They contrived what they labeled a "magic black box" containing a chemical process to produce ammonia. This box cost nothing to build and operate, it converted 100% of the limiting reactant to product, and all the energy released in the reaction was converted to steam that was sold at the highest value provided in the problem statement. This was the best conceivable case that satisfied a material balance; the simple analysis took little time and required no simulation. This group came directly to the conclusion that the system was an economic disaster.

The other groups did not focus on the goal and developed information on the performance of a system that could not possibly achieve the goal. They eventually came to the same conclusion, but they wasted significant time in the meantime. The professor had advised them to focus continuously on the goal (economics) and not to set it aside for later consideration, but the advice had little impact. When the one group presented their "little black box" concept to the class, the other groups realized (without being told or criticized) how they had wasted time by not focusing on the goal.

Event 2. The design problem, as originally stated, had no payback. The students were shocked! (This was probably their first experience with a totally unexpected result.) At this point the design objective was modified, with the new objective of minimizing losses. Students were also encouraged to suggest the maximum price that could be paid for feed material in order to get a positive payback and to consider any recommendation that would make the process profitable. The groups considered several alternatives to reduce the feed costs:

- *Paying only for the reactants and not for the inert CO_2 portion of the feed*
- *Removing the CO_2 from the feed and selling it as a by-product*
- *A combination of the above*

The "magic black box" analysis showed that there was a possibility of a five-year payback period if high yields and low capital costs could be achieved. Among the alternatives considered for making the process profitable were:

- *Separating the CO_2, H_2, and N_2 from the purge stream and selling them all in pure state*
- *Reacting the NH_3 and CO_2 in the product gas to produce urea*

The students found references showing that the composition of the product gas, the temperature, and the pressure are all appropriate for feeding directly to the reactor unit of a urea plant. Applying the "little black box" showed that there was an opportunity to obtain a reasonable payback period. It was now time to consider details on how to reduce the capital costs and increase the yield.

Event 3. Many groups recommended the removal of CO_2 from the feed, and the most common reason given for doing this was to reduce the amount of CO_2 in the product ammonia. Several groups concluded that the reduction in equipment and operating costs would be significant. One group found their way into the library and came up with flow sheets for ammonia plants showing a water scrubber that removed the CO_2 (they also found design information on the scrubber, but did not understand how to use it). Another group found out that CO_2 could not be tolerated in the reactor because it poisoned the catalyst—this uncovered the fact that *no* design would work unless the CO_2 was completely removed before the reactor or unless a new catalyst was found. The critical importance of catalyst behavior was identified.

It became evident to the students that their design was at risk until they understood more about reactor design and separations. The direction the students took at this point depended on their assumptions, but whatever direction they took, the merit of their design depended upon the *validity* of the assumptions they made. Until the assumptions were justified, their solution offered a higher-than-necessary risk of failure. To reduce the risk, students saw the need for future course content covering reactor design, separations, and the properties of the catalyst.

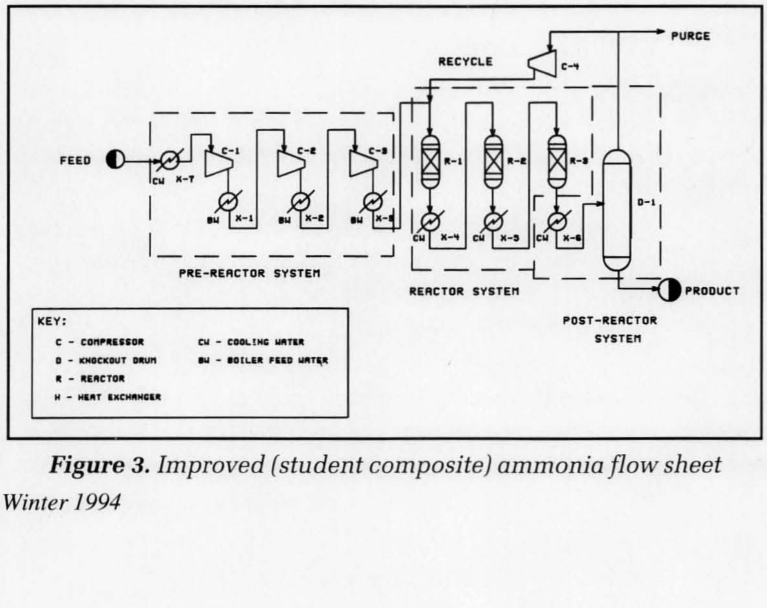

Figure 3. *Improved (student composite) ammonia flow sheet*

Event 4. The ammonia is removed in a partial condenser. This presented a major problem for the students. It required a condensable material to be removed from a non-condensing gas—a situation for which calculation of the heat transfer rate involves simultaneous heat and mass transfer considerations. Initially, the students thought they could not deal with this complex system because it was not included any-where in the curriculum. Once they recognized the problem and brought it to the attention of the faculty, however, it was added to the concurrent course material. The coverage of radiation and numerical solutions to unsteady state heat transfer had to be reduced, but this was not judged to be a serious problem.

This last event demonstrates that when a major problem arises, it can be taken care of by the faculty and the necessary principles can be added to the curriculum. For lesser problems which are brought to the faculty's attention, the students are referred to other sources of information (such as the seniors). Many smaller problems, however, are never even brought to the faculty's attention and are simply solved by the students on their own—obviously, a very satisfying development.

DISCUSSION

The design sequence represents a framework for the curriculum. Students need to know where their education is taking them and how the materials they study fit in—seldom do they simply accept the professorial assertion that, "Trust me, it is critical for you to know this material." After discovering the importance of course material on their own, students usually pursue an understanding of all course materials more aggressively. In other words, students who know where they are going are more likely to get there!

The goal of this comprehensive sequence is made clear to the students. They will be expected to learn how to analyze, design, and handle comprehensive chemical processes on their own; they are told that problems in their senior year and beyond, throughout their careers, will require this ability. They observe the effort the seniors put into these problems and understand that they, too, will at some point be presenting and defending their solutions before a panel of professors or supervisors .

Each semester begins with all the ideas from all the groups on the table. Then each individual group has to analyze this new information, rejecting the poor ideas and selecting those ideas that are worthy of follow-up. The teams listen to all of the other presentations, acquiring a good understanding of a variety of feasible solutions to their problem.

In our department, the program's effectiveness is enhanced by the department "culture." Graduates and seniors, excited about what they are doing, pass their enthusiasm on to the other students. Also, we find that motivation is not a problem if students can observe their progress toward a final goal. In a sense, our department may be viewed as a one-room schoolhouse; faculty offices, the classrooms, and the undergraduate computer room/work area/lounge are all on the same floor. In this close-knit setting, students can see that they are doing things that they could not do the previous semester, and that seniors are more capable than juniors and juniors are more capable than sophomores. The culture provides beneficial peer pressure as well as a student network where upper-level students support lower-level students.

Although the culture described above has existed in our department for many years, it is not a prerequisite to successful use of such coordinated design projects. If the projects are viewed by faculty and students as a coordinated framework for the curriculum, features of the culture will spontaneously emerge. A few faculty may become champions, but all will actively participate. Sophomores will seek assistance from juniors, who in turn learn from seniors.

It is not necessary to develop design projects from scratch. We seek new project ideas from colleagues in other departments as well as from those in industry and government. We recently got an idea from a departmental seminar speaker, and we have also obtained ideas from former students. Over the years we have developed several successful projects for the sophomore-junior sequence, and we would be happy to share them with others.

Questions often arise regarding the opportunity for students to free load and be carried along by the group. This has not been a problem—probably because of peer pressure and knowing that the time will come when each of them must appear alone to answer questions from a faculty or employer panel.

Introduction of the design sequence has not reduced the amount of course content provided. While our students still have ample opportunity to solve differential equations and integrate the Navier-Stokes equations, some changes in subject material were made. The major impact on course content was made previously when we decided to incorporate modest design activity in each course. The subsequent integration of the design into a single problem for each semester and to retain a single theme for the problems over four semesters was expected to reduce the time taken away from formal course work. The amount of time the students elected to devote to the design has increased and exceeded our expectations. There is some concern about the excessive time many students spend on these problems.

CONCLUSIONS

The integrated design process involves features that are largely overlooked (or dismissed), but which can significantly impact a students' overall development. Some of these features are

Focus • Students must focus on a goal. Once they understand what they are expected to accomplish, they can appreciate the process used to achieve the goal, the relevance of the course work, and the progress they have made toward that goal each semester.

Group Projects • Students benefit from group participation in the design sequence in several ways. Groups are more willing than individuals to express new ideas and to make judgments. They find comfort in numbers and are less fearful of looking foolish. While individual students are unlikely to have sufficient experience to manage a design problem, the situation is different for several students working together. The sum is truly greater than the parts.

Culture (One-Room Schoolhouse) • Students benefit a great deal from observing the performance of other students at the same level as well as in the levels above and below theirs. It is obvious to them that the higher-level students can do what they cannot do, and that they can now do what they could not do earlier. Upper-class students can be a great help to other students in their courses, telling them what to expect in future courses and why they need to know the subjects they are studying.

Need-to-Know • Students are more motivated to understand and to retain knowledge and principles when their studies are the result of a sequence of events that begins with a need-to-know. The steps following the need-to-know are to gather information, learn the necessary principles, and apply principles to an original problem.

Depth and Breadth • It is essential that students be exposed to a wide range of knowledge. It is also essential for students to pursue some knowledge in depth and to understand how it is applied to the development of chemical processes.

All the items listed above have a common element: they require the student to take an active, rather than a passive, role in learning. Their design skills (not the subject of this paper) are significantly advanced by this process. Students' success in this program provides them with additional attributes resulting from focused participation in activities invariant with time—attributes that will serve them well throughout their professional careers.

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REVIEW: Unit Operations Handbook

Continued from page 43.

lished in *Encyclopedia of Chemical Processing and Design*, edited by McKetta and Cunningham, first printed in 1976 and reprinted at one- to two-year intervals through 1990. Many of the sections do not appear to have been updated since their first appearance. The most recent reference found by this reviewer in any section was from 1986; most of the sections cite nothing more recent than the 1970s. The section on batch distillation cites only a single reference that was published in 1958, while the section on packed towers shortcuts cites only material from two chapters in the 4th edition of *Perry's Handbook*, which appeared in 1963.

As a result, many of the sections are seriously out of date. For instance, the section on absorption presents an overly long, highly empirical example for calculating steam stripping that makes no use of computer techniques. The section on packed column internals (as well as the introductory section on distillation) contains nothing about packings that have been introduced in the past decade. The section on the costs associated with gas adsorption cites the price of activated carbon that prevailed in 1977, which may or may not correspond with current costs when the M & S cost index is employed.

As is to be expected in a multi-authored handbook, the sections are uneven in quality. Many (but by no means all) of the sections are highly tilted toward petroleum processing. The section on estimating naphtha cuts in distillation, for instance, uses so much oil-company jargon that it is almost unintelligible to someone who wasn't working in that area in the 1960s. A diagram of the VLE data for methanol/water shows a non-existent tangent pinch, and absorption is described as a purely physical phenomenon (despite the use of the alkanol amines to remove acid gases). To illustrate the separation of azeotrope-forming compounds by distillation, using benzene to break the ethanol/water azeotrope, a four-column sequence is presented even though the use of three columns is more common and two columns can do the job.

Some of the examples used to illustrate principles are curious: The case of an absorber with a pinch at the bottom tray is illustrated with a column in which an insufficient stream of pure water is used so that only a specified fraction of the SO_2 is removed from a flue gas. No mention is made of the improbability of a) using water, with its low capacity for SO_2, as the absorbent, or b) not using a stream of absorbent that is sufficiently large to shift the pinch point to the top tray when designing a scrubber to remove SO_2.

In a similar exercise, natural gas is used to strip H_2S from crude oil in a process deemed advantageous because it would be once-through for both the gas and liquid streams. No mention is made of the fact that the H_2S will subsequently have to be recovered before the natural gas can be used for any other purpose, and that this requirement may make its use as the stripping medium somewhat less attractive.

Of course, much of the basic material on the key unit operations (adsorption, distillation, liquid-liquid extraction, crystallization, etc.) is timeless and can bear retelling by a master in the field. Nevertheless, one may question the value of a handbook of this type in which many of the sections are one to two decades out of date in the first year of its publication. ❒