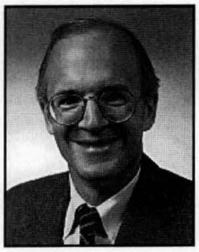
Award Lecture . . .

DO CHANGES IN THE CHEMICAL INDUSTRY IMPLY CHANGES IN CURRICULUM?

E.L. CUSSLER
University of Minnesota • Minneapolis, MN 55455



Edward L. Cussler, Institute Professor at the University of Minnesota, received his BE degree from Yale University in 1961, his MS from the University of Wisconsin in 1963, and his PhD from the University of Wisconsin in 1965. He rose from Assistant Professor to Professor of Chemical Engineering at Carnegie-Mellon University during the years from 1967 to 1980, at which time he joined the faculty at the University of Minnesota as Professor of Chemical Engineering. In 1996 he became Institute of Technology Professor at the University of Minnesota, and is currently at Cambridge University in the United Kingdom as Professor of Chemical Engineering.

Ed has won numerous awards during his professional career, some of which are the AIChE Alan P. Colburn Award in 1975, seven Minnesota Institute of Technology Teaching Awards through the years, the George Taylor Distinguished Teaching Award from the University of Minnesota in 1987, the Donald Katz Lecture Award from the University of Michigan in 1996, and the Danckwerts Lecture from the Institution of Chemical Engineers in London in 1997.

Ed serves as Associate Editor of the *AIChE Journal* and is on the Editorial Board of the *Journal of Membrane Science.* He also has served as a Director, Vice President, and President of AIChE, and was Chair of the American Association of Engineering Societies.

He has also been author or co-author of over 160 publications. He is co-author with Belter and Hu of *Bioseparations* (John Wiley and Sons, New York, 1988) and with Baker, Eykamp, Koros, Riley, and Strathmann, of *Membrane Separation Systems, (Noyes Data Corporation, New Jersey 1991).* He is author of the books *Diffusion* (Cambridge University Press, London, 1984; second edition, 1997) and *Multicomponent Diffusion* (Elsevier Publishing Company, Amsterdam, 1976).

This paper is a synopsis of my Union Carbide Lectureship, an award given at the 1998 meeting of the American Society of Engineering Education. I am flattered to have my research and teaching on diffusion acknowledged. I know that this lecture can often be a review of the past research, centering on a scattering of old slides, like a photograph album of half-remembered vacations.

But the lecture and this paper are too good a forum to waste on my past. Instead of the past, I want to consider the future. In doing so, I remember a conversation I had thirty years ago with the historian, L. Pearce Williams. I was visiting him to gush about his biography of Michael Faraday,[1] which I had enjoyed enormously. I suspect that he found my naive enthusiasm both flattering and embarrassing. To make conversation, Williams asked if I knew the real difference between science and the arts. I did not. He responded that in the sciences, we wrote papers and books when we felt we knew everything about our topic. In the arts, he asserted, authors wrote when they knew little initially and used the writing as a way to focus new questions and to explore possible answers.

Whether this arts-science contrast is true or not, I want to use this paper as a way to learn about possible changes in chemical engineering curricula. I am not yet sure if these ideas are correct, but I want to see if they make sense. In the next few years, I'll try them out. For now, though, they're best described under three headings: the changes in the chemical industry, the status in academia, and possible curricular changes.

CHANGES IN THE CHEMICAL INDUSTRY

Last spring, I taught our introductory chemical engineering course—the one that covers stoichiometry. Early in the course, I showed pictures of chemical plants to the students. I told them that the tall towers were for distillation and the short, fat ones were often for gas absorption. I pointed out the reactors, with their preheaters and recycles. I spoke of the excitement of running a chemical plant and the satisfaction of using chemical technology to improve our well being.

I did so with hidden reservations that I did not have ten years ago. I know that the chemical industry has changed and that many of the students will not work in the commodity chemical plants I was describing. To see why, we need to review the history of our industry, using as an example the development of synthetic textile fibers.

From 1950 to 1970, the chemical industry produced ever-increasing amounts of synthetic textile fibers, as shown in Table 1. Over the decades, while the production of natural fibers was about constant, the production of synthetics grew 20% per year. This growth was comparable to that of the software industry today; indeed, Du Pont in the 1950s was like Microsoft in the 1990s. It was a golden age for chemicals.

But from 1970 to 1990, synthetic textile fibers grew only four percent a year—at about the same rate as the growth of world population. That's not surprising; after all, any logarithmic growth can't continue indefinitely. From 1970 to 1990 the industry stayed profitable by using larger and larger facilities. Bigger profits came from consolidating production into bigger plants, designed for greater efficiency in making one particular product. The interest in computer-optimized design is a vestige of this consolidation. Such optimization meant small producers were forced out. For example, the number of companies making vinyl chloride shrank from twelve in 1964 to only six in 1972.[2]

TABLE 1
Growth of Synthetic Fibers From 1950 to 1970
(Source: Spitz, U.S. Department of Commerce)

	1948	1969	1989
Cotton, Wool	4353	4285	4794
Synthetics	92	3480	8612

In the last ten years, the industry has used other strategies to stay profitable. These strategies often centered on restructuring, which was three times more likely to affect engineers than the general population. Whether called "restructuring," "downsizing," "rightsizing," or "rationalization," the strategy meant many mid-career engineers were suddenly looking for a job. The Engineering Workforce Commission now feels that engineers will average seven different jobs per career, a dramatic change from two per career when I graduated in 1961.[3] Middle management, that traditional goal of our B-students, is no longer a safe haven. Starting salaries remain high, the envy of other technical professions, but they have not increased faster than inflation in thirty years. In this environment, I applaud the decision of the American Institute of Chemical Engineers (AIChE) to be a "lifetime home" for members of our profession, providing more help in job transitions and financial planning. The AIChE can no longer be only a nineteenth century-style learned society.

Most recently, the chemical industry has become enchanted with the life sciences, often called "biotechnology." Biotechnology in the industrial sense is most successfully represented by applied agronomy, *i.e.,* by genetically modified seeds. It is usually different from the biotechnology represented in academic chemical engineering that often centers on separations and reactions involving specialty pharmaceuticals. The model for corporate enchantment is Monsanto, which has spun off its commodity chemical operations to compete largely in this new biotechnology. Other companies are imitators. In recent five-year projections, Du Pont has relabeled its chemicals as "materials," is spinning off Conoco, and plans to double its life-science efforts to one-third of the company's sales. Hoechst, by some measures the world's largest chemical company, plans to leave chemicals for the life sciences. It's a different world beyond our ivory towers.

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THE STATUS IN ACADEMIA

While these industrial changes occur, academic chemical engineering continues along well-established paths. I think that this is good. Universities are both stable and resilient; Clark Kerr, the long-time provost of the University of California, is said to have asserted that universities make up more than 90% of the social institutions that have lasted over 500 years. Moreover, courses in any field evolve slowly. Woodrow Wilson, at the time President of Princeton, said that "changing curricula is like moving graveyards."

Chemical engineering curricula in the USA are no exception. To a large extent, they reflect the scheme first suggested in 1917 by a commission chaired by Arthur D. Little, founder of the firm that bears his name. Building on British precedents, the commission suggested an organization around "unit operations." This was based on the assertion that distillation was based on the same principles for any chemical system, be it rum or crude oil. This organization was codified by the book *Principles of Chemical Engineering.*[4] L. E. Scriven tells the possibly apocryphal story that the book was written only because the authors isolated themselves at a camp in the Adirondacks, where they could not be interrupted.

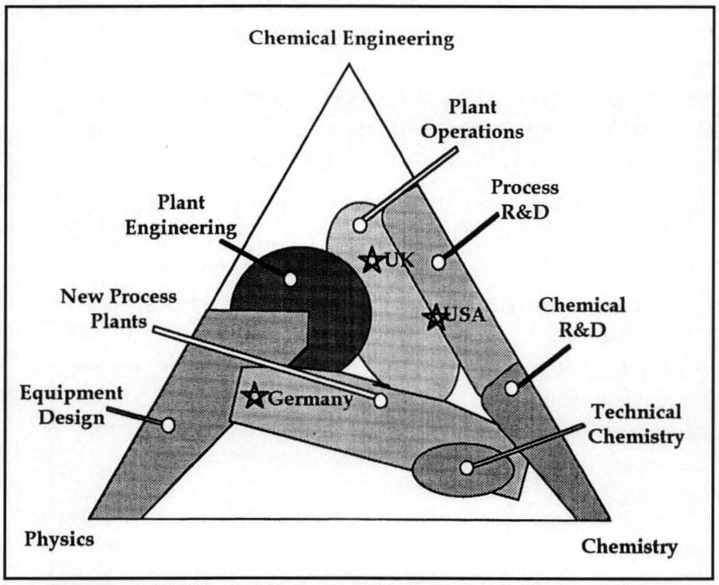

***Figure 1.** Skills in Chemical Engineering. These skills are ideas from chemistry, physics, and engineering. Different jobs use different proportions of these ideas.*

Principles of Chemical Engineering outlines much of what would be a reasonable, accreditable major today. It begins with a chapter on stoichiometry and then covers fluid flow and heat transfer in three chapters. Four chapters on combustion seem the intellectual ancestors of today's reaction engineering. Four chapters on separations center on distillation, humidification, and drying. Only the two chapters on mechanical separations (crushing and grinding) have material missing from modern chemical engineering curricula. I don't mean to overemphasize these parallels, because the contents of these chapters are often qualitative and dated. Still, I find the parallels vivid.

The curriculum implied by *Principles of Chemical Engineering* was challenged most successfully by *Transport Phenomena,* the book by Bird, Stewart, and Lightfoot.[5] This book, circulated in 1957 and formally published in 1960, injected more needed science and mathematics into our field. For a while, our profession was divided into those who believed in the older *Principles* testament and those who converted to the newer *Transport* gospel. In one recent stimulating article, Astarita and Ottino[6] argued that these two books have supplied the only two organizing ideas that our profession has had.

In hindsight, I believe that there are two main reasons why *Transport Phenomena* was so successful. First, by stressing parallels between different transport processes, the book supplies a pedagogical template that helps all to learn and think about these processes. This template is a mixed blessing. For example, the fact that there is no parallel to chemical reactions in heat transfer means that chemical reactions are superficially treated. This may contribute to our continuing tendency to teach mass transfer without chemical reactions, even though much industrial mass transfer, *e.g.,* acid gas treating, takes place with reaction.

The second reason that *Transport Phenomena* was so successful is a reflection of the boom taking place in the chemical industry when the book was published. As outlined above, this boom centered on petrochemicals, which of course included the monomers used to make synthetic fibers. When you make petrochemicals, you often deal with a plethora of compounds characterized by a near continuum of boiling points. In such a case, continuum mathematics is appropriate; one can basically ignore the discrete jumps of the periodic table. Indeed, one can ignore most of chemistry, with

$$A + B \rightarrow C$$

i.e., argon plus boron goes to carbon. Moreover, as the petrochemical industry became more competitive, minor improvements in existing processes were important to profitability. These minor improvements could often be found using the mathematical approach in *Transport Phenomena.*

While Astarita and Ottino argue powerfully that these two books provide the only two paradigms in our profession, I feel that Levenspiel's *Chemical Reaction Engineering,*[7] first published in 1963, is also important, but for a different reason. The first two books provided a definition of a profession, which implied a curriculum. Levenspiel, on the other hand, reorganized what was already acknowledged into a

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way that made it easier to learn. This can be hard for the founder of a discipline to do. For example, I view T.K. Sherwood as a founder of mass transfer. I find his 1937 book *Absorption and Extraction,*[8] more understandable than its 1952 successor *Absorption and Extraction,*[9] co-written with Pigford. This second edition is in turn easier for me to understand than the 1975 revision, *Mass Transfer,*[10] co-written with Pigford and Wilkie. Levenspiel built on earlier reaction engineering books such as Hougen and Watson's *Chemical Kinetics,*[11] but he achieved a new presentation that was much easier to understand.

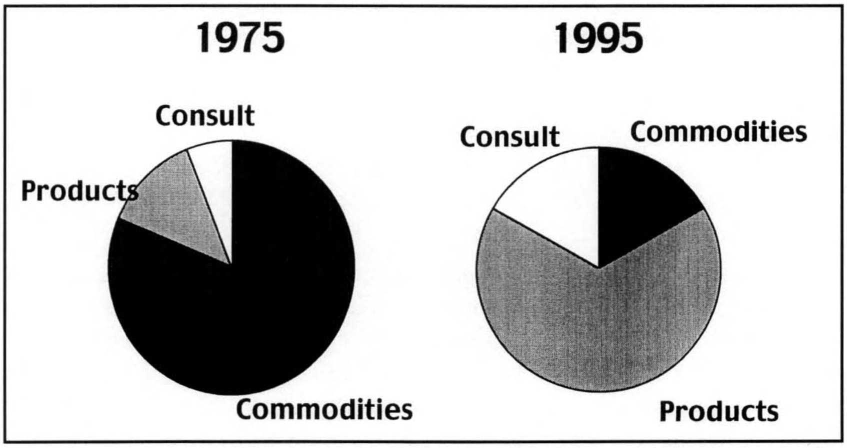

Figure 2. *Employment in 1975 versus 1995. Current graduates are much less likely to work for commodity chemical producers and more likely to be involved with products.*

These various subjects in the chemical engineering curriculum can be represented on the triangular diagram redrawn from Gerhard Froelich, the 1999 AIChE president, and shown in Figure 1. The three corners of this plot represent training in the physical sciences, in the chemical sciences, and in the chemical engineering subjects. Different jobs use these three elements in different proportions, as shown in the figure. There is no surprise in this; plant engineering will demand a greater knowledge of mechanics and a smaller background in chemistry than research and development. Figure 1 also suggests national averages. British chemical engineers seem to have somewhat more chemical engineering and less chemistry than their US counterparts. Please don't take this diagram too literally; use it instead as a catalyst for thought, perhaps for deciding how your department's curriculum should evolve.

DO INDUSTRY CHANGES IMPLY ACADEMIC RESPONSES?

So far, I have summarized the revolution in the chemical industry and the evolution of academic chemical engineering. I now want to compare the two to see what, if any, changes are needed in what we teach.

Basically, I don't think many changes are indicated. The skills we currently teach seem to prepare our students well. Starting salaries remain high, the envy of most other engineering disciplines. The number of jobs is again high, after almost a decade of bad years caused by restructuring.[12] In fact, the job market right now is better than I thought it would be three years ago. Industrial complaints about our teaching seem scattered, with about the same number urging more, say, kinetics as those who urge less kinetics. Most industrial complainers who urge us to teach more of a particular topic are hard pressed to suggest which current topics they would omit to make room for their favorite.

Thus, I believe our current curriculum is basically in good shape. One frequent omission does concern me, however. I want to explore this omission next.

My concern centers on the jobs our graduates now hold compared with those they held perhaps twenty years ago. My data for this are fragmentary, so I would be interested in any other data that are available. My data are probably biased toward large corporations, about whom our placement office has better records. My data also have a regional bias towards 3M and food companies such as General Mills that are based here in Minnesota. Still, the data suggest major changes in the last twenty years.

The focus of my analysis is the employment in 1975 versus that in 1995. I chose 1995 because the students often need several years to settle down, to decide which sort of job they really want to do. As shown in Figure 2, there are enormous differences between 1975 and 1995. In 1975, three-quarters of our graduates were working in the commodity chemicals business. The small number who were not were split between work on products, either product design or product development, and work in other areas, which for convenience I have labeled "consulting." That would include those working directly for consulting firms as well as those carrying out specific tasks such as environmental impact statements.

In 1995, the distribution of jobs is different. The majority of students (in Minnesota's case, about two-thirds) now work primarily on products. This includes not only students who work on materials, but also those who work on pharmaceuticals, on specialty coatings, on adhesives, and on specialty chemicals. The number who work in commodity chemicals has dropped so that it now is less than a quarter of our graduates. The number who work in consulting has risen dramatically, as commodity chemical businesses outsource many of the in-house functions they used to do. For example, in one case, a commodity chemical company took its process engineering group from 1500 to fewer than 50 people. This is not a business cycle; this is a change in the way they expect to do business. This is why the number of people involved in consulting has gone up.

Thus, the nature of the jobs that our students are doing has changed dramatically. The next question concerns where the changes are reflected in our curriculum. To explore this, I have shown a basic generic curriculum in Table 2. It contains the usual stoichiometry, the thermodynamics, and the transport classes. The three classes in kinetics, process control, etc., are the place where departments will have unique offerings. For example, this is the location of courses in polymers or biochemical engineering or environmental engineering. Such uniqueness is a strength of our departments, a way in which we add special skills to a common core.

There are a few places in these classes that contain material on products, that subject on which our students are most likely to work. The most logical place to add this type of material is in the capstone design class. This class usually focuses on process design, the tradition of our discipline. The hierarchy suggested by Jim Douglas[13] for this process design seems to me especially strong and appropriate. It is summarized on the left side of Table 3. After deciding whether a process is batch or continuous, one then moves on to flow sheets, which are almost always continuous. The initial flow sheets center on the stoichiometry. The next level in the hierarchy, which adds the recycles, often involves a discussion of the chemical reactions. Once these are established, one moves on to the separation trains and finally to the heat integration. All of this makes for a good course.

If we want to emphasize product design, we need to go beyond this hierarchy. We cannot simply substitute a product for drug delivery for the existing process and carry out the same kind of hierarchy. Instead, the hierarchy suggested by books on product design (*e.g.,* Ulrich and Eppinger[14]) is exemplified by that on the right side of Table 3. After first identifying a corporate need, one generates ideas to fill this need. One then decides between these alternatives and finally decides how to manufacture the chosen product. The manufacturing step essentially includes all of Jim Douglas' hierarchy.

Thus the important steps in product design anticipate those in process design. Product design implies a focus on the initial decisions around the form of the product and implicitly de-emphasizes its manufacture. Such an emphasis shifts the curriculum away from the common engineering calculations that have been our bread and butter. Such an emphasis includes subjects that are normally left to those directly concerned with the business. I am concerned that if I make this shift in a design class, I will wind up teaching my students watered-down business school principles rather than "real" engineering. I undertake this change because

TABLE 2
Generic Chemical Engineering Curriculum

Most universities teach a similar sequence.

- Stoichiometry (1 course)
- Thermodynamics (3 courses)
- Transport Phenomena and Unit Operations (3 courses)
- Reactors, Process Control, etc. (3 courses)
- Process Design (2 courses)

TABLE 3
Process Design versus Product Design

All of process design is contained in the last step of product design.

Process Design	***Product Design***
1. Batch vs. Continuous Process	1. Identify Customer Needs
2. Inputs and Outputs	2. Generate Ideas to Meet Needs
3. Reactors and Recycles	3. Select among Ideas
4. Separations and Heat Integration	4. Process Design for Manufacturing

TABLE 4
"Sick House" Ventilation

1. Customer need; ventilate for under $800
2. Ideas: Open window
   Controlled vent
   Heat exchanger
   Heat and humidity exchanger
3. Select heat and humidity exchanger
4. Manufacture follows kidney dialysis

so many more of my students are encountering this shift in their professional lives. I want them to see how product design works.

When I've discussed these ideas with other faculty, I often get the indignant reaction that the faculty are already doing this. Some have mailed me syllabi and reports that include aspects of product design. Without exception, what I have received represents good education, but almost without exception, the material seems to skip all steps except the last in the product design hierarchy in Table 3. These earlier steps seem to me too important to leave to the MBAs.

As an example of these ideas, consider the so-called "sick house syndrome" that has developed as houses were built to be energy efficient. Such houses exchange their air as infrequently as twice a day. In contrast, a house built fifty years ago exchanges its air almost every forty minutes. Thus, while the modern house does not cost much to heat, it can concentrate radon from the basement, formaldehyde released from carpeting and drapery, and carbon dioxide from the people who live in the house. The modern house needs more fresh air. Thus the product needed is a device that allows a house to remain energy-efficient, but which provides fresh air at the ASHRE standard of 19 cubic feet/minute/person in the house.

The way in which the product development might proceed is shown in Table 4. The need is for a device costing less than about $800 that can provide this degree of ventilation. Ideas include opening a window, providing automatic control for opening a window, providing a heat exchanger, and providing an exchanger for both energy and mass. Opening a window sacrifices the energy benefits of insulating the house in the first place. Opening the window with an automatic controller that might anticipate weather cycles makes sense. For example, one could open the window only on sunny winter days and keep the house closed on cold winter nights. Using a heat exchanger can provide the necessary ventilation at an order of magnitude less heat loss. As anyone who has bought a house with such a heat exchanger knows, however, the heat exchanger also exhausts the water vapor in the house. The heat of evaporation of the water is about a third of the heating value in the humidified air. If the heat exchanger runs, the house dries out and becomes very uncomfortable.

The final alternative is the most complicated, but the most satisfying. In this case, one uses a heat exchanger in which the walls are membranes selectively permeable to water vapor. As a result, one captures 90% of the energy and 90% of the water vapor, but exhausts the carbon dioxide, formaldehyde, and radon in the house. The question is cost. The students need a more complete design, perhaps using the manufacturing technology developed for kidney dialysis, to make the membranes. This is an area of active commercial development by several heat-exchanger companies.

CONCLUSIONS

We are now ready to answer the question posed in the title of this paper: "Do changes in the chemical industry imply changes in the chemical engineering curriculum?" The changes in the chemical industry are clear—a movement away from commodities, a romance with biotechnology, and a long-term interest in specialties. Major changes in the curriculum are probably not needed; our students still have the basic skills necessary not only for the changed chemical industry but also for the other jobs they now hold.

These changes in the industry do mean that our students will work much more on chemical products than on chemical processes. As a result, we will want them to think more about product design in addition to process design. The work on product design will follow a different hierarchy than that which effectively organizes process design.

But I'm not sure of this. You may remember that I began this article by saying that I was going to follow the lead of Pearce Williams to write a paper on what I thought might be done rather than what I had already found effective. With Geoff Moggridge, I am going to teach product design as a Zeneca fellow at Cambridge University in the academic year 1998-1999. If we are successful, I will try to move some of these ideas back into our design courses here at Minnesota. I am not yet sure they will work. I look forward to discussing with you what parts do work and what parts do not.

REFERENCES

1. Williams, L. Pearce, *Michael Faraday,* Simon and Schuster, New York, NY (1964)
2. Spitz, Peter, *Petrochemicals: The Rise of an Industry,* Wiley, New York, NY (1988)
3. Ellis, R.A., "At the Crossroads," *Eng. Workforce Bull.* No. 130 (1994)
4. Walker, W.H., W.K. Lewis, and W.H. McAdams, *Principles of Chemical Engineering,* McGraw-Hill, New York, NY (1923)
5. Bird, R.B., W.E. Stewart, and E.N. Lightfoot, *Transport Phenomena,* Wiley, New York, NY (1960)
6. Astarita, G., and J.M. Ottino, "Thirty-Five Years of BSL," *Ind. Eng. Chem. Res.,* **34**, 3177 (1995)
7. Levenspiel, O., *Chemical Reaction Engineering,* Wiley, New York, NY (1963)
8. Sherwood, T.K., *Absorption and Extraction,* McGraw-Hill, New York, NY (1937)
9. Sherwood, T.K., and R.L. Pigford, *Absorption and Extraction,* McGraw-Hill, New York, NY (1952)
10. Sherwood, T.K., R.L. Pigford, and C.R. Wilke, *Mass Transfer,* McGraw-Hill, New York, NY (1975)
11. Hougen, O. A., and K.M. Watson, *Chemical Process Principles III: Kinetics and Catalysis,* Wiley, New York, NY (1947)
12. Weatherall, R.K., "Strongest Market in Years for New Graduates," *Engineers,* **4**, 2 (1998)
13. Douglas, J.M., *Conceptual Design of Chemical Processes,* McGraw-Hill, New York, NY (1988)
14. Ulrich, K.T., and S.D. Eppinger, *Product Design and Development,* McGraw-Hill, New York, NY (1995) ❒