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FEATURED REVIEW

Beyond Process Design: The Emergence of a Process Development Focus

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Abstract−This article suggests that process development, consisting of process research and innovation, pilot plant, technology transfer and manufacturing, will play a key role in the evolution of chemical engineering as a profession. By integrating science, engineering and management with a multiscale approach, process development helps break down artificial barriers, leading to performance optimization from an enterprise-wide perspective.

Key words: Process Synthesis, Process Design, Process Development, Technology Transfer, Munufacturing

INTRODUCTION

Chemical engineering as a discipline is evolving rapidly [Zukoski et al., 2002]. Consider the senior design course, in which the concepts and techniques in transport phenomena, unit operations, mathematical and numerical methods, process control, and so on are applied in the design of a chemical plant. Often, a large-scale commodity chemical plant is selected for investigation. This course is widely regarded as the linchpin of a chemical engineering curriculum. However, it is now under scrutiny for possible improvements because of the changing global environment of the chemical processing industry (CPI).

Four major areas of improvements can be identified. First, a typical design course assumes that most of the basic engineering parameters required for process design are known or are available in various databases. For example, there are three basic levels in Douglas' hierarchical procedure for conceptual design-input/output, recycle structure, and separation system [Douglas, 1988]. At the input level, production rate, reaction kinetics, etc. are assumed to be given. This simplification, while convenient from a pedagogical point of view, is not how most industrial process design projects happen. This problem is compounded by the powerful shift of emphasis from large-volume petroleum and petrochemicals, to low-volume, high-value-added specialty chemicals and consumer chemical products [Tirronen and Salmi, 2003]. For these new processes or new products, little physical and chemical information is known at the early stage of conceptual design. In fact, in **process research and innovation**, effective collaboration between chemists and chemical engineers on the concurrent development of chemistry and engineering has been identified as the key for shortening time-to-market and designing a better process. It is highly desirable that the integration of experimental effort and conceptual design be strengthened in our current undergraduate design texts [Biegler et al., 1997; Turton et al., 1998; Seider et al., 1999]. Another missing element is scaleup. **Pilot plants** are often indispensable in scaling up small scale experiments to the actual plant, and a process involving units such as multiphase reactors, crystallizers, and in general any solids processing units cannot be reliably designed without pilot plant testing [Bisio and Kabel, 1985]. Yet, little is covered in a design course, leaving a large gap between school and practice that has to be filled on the job [McConville, 2002]. A number of reference books on various practical issues are available [Mansfield, 1993; Woods, 1995]. Third, many companies are becoming increasingly global with R&D centers and manufacturing sites located in different parts of the globe. For example, GE has recently initiated research activities in India and China. There is increasing utilization of contract research and custom manufacturing. Thus, research collaboration can now involve people with different technical backgrounds and cultures in laboratories all over the world. Effective **technology transfer** is a crucial element in successful commercialization. Fourth, we need to redouble our effort on achieving **manufacturing** excellence through process development. As pointed out by Reklaitis [2000], the chemical industry, at 11% of the total, is the largest manufacturing sector of the US economy. There is a widespread perception that manufacturing is important only for commodity chemicals. This cannot be farther from the truth. For example, according to one estimate, a savings of US$500 million can be realized for each blockbuster drug on the market if the manufacturing process is properly designed.

For all these reasons, we submit that the traditional focus on process design in a typical design course should expand in scope to process development. This sentiment is reflected in industry as well, as is evidenced by the formation of a new Division in the American Institute of Chemical Engineers - the Process Development Di-

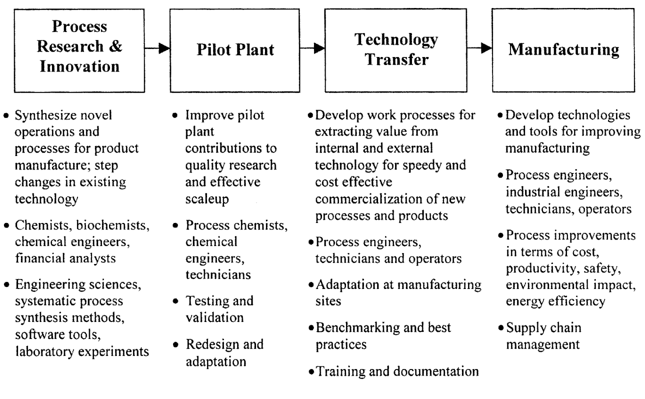

Fig. 1. The objective, stakeholders, and tasks in the four areas of process development.

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vision (www.pd-aiche.com). It consists of four areas: Process research and innovation, pilot plants, technology transfer, and manufacturing. Fig. 1 shows the four areas of process development, along with a brief description of the vision, the stakeholders, examples of activities and tools involved.

The objective of this article is to highlight some of the recent advances, trends, challenges and research opportunities in each area of process development. Since it is impossible to provide an exhaustive coverage of this broad field, special emphasis is placed on topics with which we have more experience. Furthermore, the evolution and education of chemical engineering as a discipline is also examined from the viewpoint of process development.

PROCESS RESEARCH AND INNOVATION

Demand for better quality products at a lower cost is the driver for process innovation. New processes need to be developed and existing processes need to be continuously improved to stay competitive in the market. Process vision and systematic procedures are crucial in meeting such a target [Basu, 1998; Basu et al., 1999]. We discuss below four selected topics that might help accelerate progress in process research and innovation: multiscale objective-oriented process development, systematic design methods, workflow, and product-centered processing.

1. Multiscale Objective-oriented Process Development (MOPD)

Douglas [1988] proposed a hierarchical conceptual design procedure, consisting of three basic levels: input-output, recycle structure, and separation system. The idea is to begin with an abstraction of the plant with input and output streams. Additional details are added to subsequent levels, while considering the overall plant economics at all times. Thus, the key objective of the input-output level is to check whether the process makes money if only material costs are considered. The recycle structure level considers the tradeoff between selectivity loss and reactor cost. The separation system level accounts for the impact of total equipment and operating costs on the economic potential of the plant. On reflection, Douglas' approach has two simple yet powerful concepts: one is to zoom in on a design problem from the plant scale to successively finer scales, and another is to evaluate the plant performance at every level of the zooming-in process.

The multiscale objective-oriented process development approach evolves from these concepts [Lerou and Ng, 1996; Ng, 2001]. We begin at the scale of the enterprise, which can be a multinational corporation with offices, plants and research centers located around the world. This is followed by the plant and equipment scales, which are covered in Douglas' hierarchical procedure (Fig. 2). Engineering sciences - fluid flow, reaction engineering, heat and mass transfer, and crystallization kinetics - are emphasized at the smaller scales. Computational chemistry considers the molecular level events. The objective of activities at each scale is different but cascades down the scales. At the enterprise level, the objective is to maximize the shareholder value added (SVA). This is not just the goal of the board of directors and the senior management team but should be shared by plant personnel and researchers. Similarly, the objective at the plant scale is to come up with innovative processes and to improve plant operations. This goal should be redefined into technical objectives by the engineers and chemists at the research centers. For

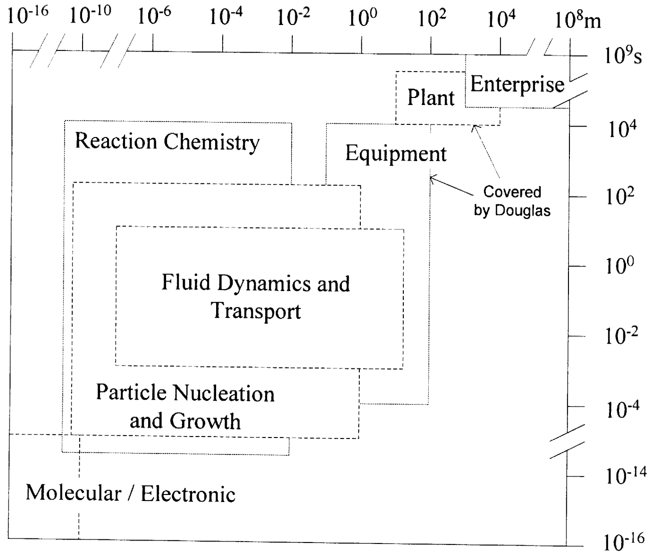

Fig. 2. The length and time scales covered in MOPD.

example, we can increase the product recovery by lowering the crystallizer temperature [Cesar and Ng, 1999] or raise the capacity by debottlenecking the downstream filtration-washing section in an adipic acid plant [Chang and Ng, 1998].

This framework is expected to promote vision-sharing and collaboration among all the employees of a company, particularly the business and technical personnel. Consider the following example. The researchers in the computational chemistry laboratory may seem far removed from an engineer working on supply chain management. Yet, as the overlapped regions in Fig. 2 suggest, the molecular level calculations can help predict reaction rates which in turn can affect reactor design and plant performance, and thus the supply of a particular product within the enterprise. In addition, the use of SVA as the overall objective ensures that all activities are in alignment with the corporate directions and helps identify those with a higher return.

2. Systematic Design Methods

Systematic design methods have played a significant role in process research and innovations. For one, Douglas' hierarchical procedure is a systematic method. Although the procedure was initially developed with gas-liquid petrochemical processes in mind, it has been extended to solids processes [Rajagopal et al., 1992]. Along the same line, conceptual design procedures have been developed for synthesizing distillation processes [Doherty and Malone, 2001], crystallization-based separations [Wibowo and Ng, 2000], reaction systems [Singh et al., 2002], and bulk solids processing systems [Wibowo and Ng, 1999]. Similarly, pinch analysis is a systematic design method that has significantly impacted energy integration in a chemical plant.

Let us consider in more detail crystallization process design. Developing such a process is like building a house; we start with the foundation and build upward (Fig. 3). Thermodynamics serves as the foundation. Rate processes such as kinetics and transport come next. Finally, all of these are capped under one roof using process systems engineering (PSE) techniques for optimization, batch plant scheduling, etc. [Biegler et al., 1997]. Addressing these issues in

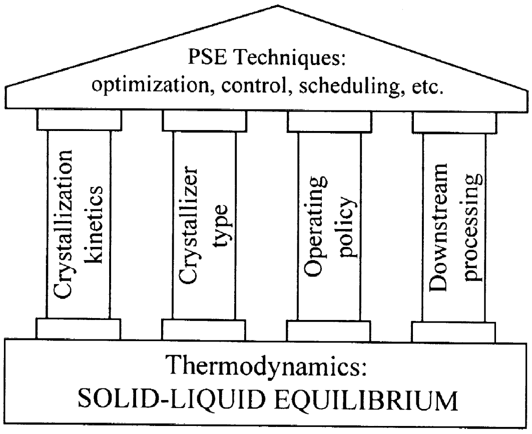

Fig. 3. Solid-liquid equilibrium serves as the foundation in the development of a crystallization process.

order greatly reduces the complexity one has to face in process research.

For crystallization, we focus on solid-liquid equilibrium (SLE) thermodynamics, and visualization of phase behavior in the form of phase diagrams is the key for process synthesis. Extractive crystallization, fractional crystallization and drowning-out crystallization have been considered [Rajagopal et al., 1991; Dye and Ng, 1995a, b; Berry and Ng, 1996; Berry et al., 1997; Schroer et al., 2001]. The phase diagram shows the compartment within which a compound can be recovered in pure form. By purposely moving around the phase diagram, the flowsheet configuration for producing the product or products can be created. This is analogous to the use of vapor-liquid equilibrium phase diagrams (residue curve maps) in synthesizing distillation systems. In addition, crystallization and wash solvents are recycled while impurities are purged through various exit points.

Then, nucleation and growth kinetics is considered to evaluate the necessary crystallizer size and to obtain the desirable particle size distribution (PSD). The process paths, deviated from the equilibrium process paths obtained by using material balances, can be determined using transport and population balance equations [Schroer and Ng, 2003]. The selection of crystallizer type and the operating policy is considered next. This is particularly important for batch crystallizers for which cooling profiles, seeding, etc. can significantly influence the crystal attributes. Downstream processing operations such as filtration, washing, and drying should be carefully designed [Wibowo et al., 2001]. For a typical crystallization plant, the downstream section often costs more than the crystallizers and can be a source of operational problems leading to downtime and products with excessive impurities. Then, scheduling and optimization are performed to ensure maximum return on investment.

Previous work on SLE phase diagrams has been extended in two directions:multicomponent and reactive systems. For a system with three components, a triangular diagram can be used. Similarly, a tetrahedron diagram can be used for a four-component mixture. For more than four components, a framework has been developed for visualizing such high-dimensional phase diagrams of molecular and ionic systems through projections and cuts [Samant et al., 2000; Samant and Ng, 2001; Wibowo and Ng, 2002a]. Reactions are rather common for solid-liquid systems. In addition to those formed in reactive precipitation, many solids form solvates and compounds. For example, sodium sulfate forms a decahydrate, phenol and bisphenol A forms an adduct, and fullerenes form solvates with tetralin. The procedure for calculating and representing such reactive phase diagrams has been developed [Wibowo et al., 2002].

It should be emphasized that systematic experimental procedures and protocols are equally important in process research. For example, an experimental setup as well as an accompanying systematic procedure has been developed for the determination of SLE phase diagrams including features such as eutectics, saturation points, compartments, eutectic troughs, etc. [Kwok et al., 2003].

3. Workflow

Indeed, when dealing with new chemical entities for which physical and chemical information is not available, it is crucial that experimental efforts be integrated with the development effort. Interaction between scientists and engineers becomes a key issue. Traditionally, screening of reaction pathway is performed by synthetic chemists, who then pass along a recipe to a group of chemical engineers responsible for process design. This is not the best approach, since production routes that give promising results in the laboratory may not be feasible when applied to large-scale production. Fully aware of this problem, chemists and engineers in most leading chemical companies interact closely from the very beginning of a process development project [Barton et al., 2000]. For example, the chemists are asked to perform the laboratory reaction experiments in a resin kettle, which mimics the real reactor, rather than in a flask [Sarafinas et al., 2000].

Recently, the workflow in the development of crystallization processes has been studied [Wibowo and Ng, 2002c]. A more generic workflow architecture for chemical process development has also been proposed [Wibowo et al., 2003; Ng, 2003]. It has six components known by the acronym RAT^{2}IO. *Resources* have to be secured and suitably distributed to enable the execution of properly selected *activities*, using appropriate *tools*, within an estimated period of *time*. In doing so, *information* is passed from one activity to another in a concise manner so as to achieve a clearly defined set of *objectives*. This workflow architecture is embedded in the MOPD framework and has the following properties:

• Hierarchical: it provides increased accuracy as the scale of focus is refined

• Modular: it suitably divides up the development effort by taking advantage of software tools, systematic design methods and experimental protocols

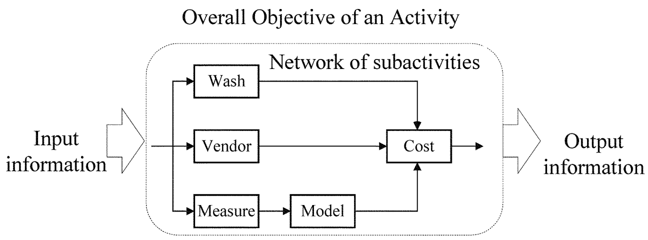

Fig. 4. An activity is decomposed into a number of sub-activities, each of which can be handled using a tool that may be a simulation program, a systematic design method or a standardized experimental procedure.

• Concurrent: it works on the different sub-activities in parallel, if feasible, so as to minimize the overall development time.

Fig. 4 shows such an activity which is made up of a number of sub-activities. For example, the overall objective is to select between a rotary vacuum drum filter or a centrifuge for a given duty. The input information is the slurry density and viscosity, the PSD, and so on. The desired output information is the drum diameter and rotational speed or the centrifuge size, among others. One can first measure the filter cake characteristics such as permeability and compressibility, and then model the performance of such a filter. Simultaneously, one can obtain equipment information from the vendor and perform washing tests. The costs and performance are then compared to reach a decision.

4. Product-centered Processing

Many of today's chemical products consist of multiple ingredients and have clearly defined size, shape, and structure. Examples include consumer and pharmaceutical products such as cosmetics, personal care products, drugs, adhesives, detergents, copier toners, and many others. In this connection, solids technology and product engineering have been identified as important research areas [Tanguy and Marchal, 1996; Wintermantel, 1999; Kind, 1999; Grossmann and Westerberg, 2000; Ng, 2002]. Moggridge and Cussler [2000] proposed a procedure for chemical product design, in which different products are conceptualized based on market needs and screened to identify the best candidates. The manufacturing process of these products should then be developed. Wibowo and Ng [2002b] introduced a framework for product-centered processing. It begins by defining the product quality factors, which are then translated into product specifications. These are related to material properties and structural attributes, then to process and operating conditions. At the end, the product and process are evaluated, taking into account the feedback from the consumer.

PILOT PLANT

Pilot plant tests are synonymous to scaleup which is defined as follows: "The successful startup and operation of a commercial size unit whose design and operating procedures are in part based upon experimentation and demonstration at a smaller scale of operation" [Bisio and Kabel, 1985]. On the basis of size, pilot plants can be classified as bench-top pilot plants, integrated pilot plants, or demonstration units [Palluzi, 1992]. They serve a number of purposes:

• Supply materials for marketing or clinical trials
• Check for impurity buildup over extended operations
• Test materials of construction for corrosion
• Investigate safety issues such as the explosion limit
• Check for effects not present in small-scale experiments such as mixing, spatial distribution of the gas, liquid and solid phases, etc.
• Obtain engineering data not available with small-scale experiments.

As an example for the last point, pilot plant tests are crucial for obtaining data for crystallizer scaleup. Crystallizer geometry, feed location, local crystal number density, etc. can lead to different nucleation and growth rates in the large-scale unit compared to the small-scale unit. Similarly, breakage and agglomeration of crystals can be significantly affected by the mixing conditions in the large-scale crystallizer.

We can identify four recent trends in pilot plant practice. The first is that many companies prefer investing in general purpose pilot plants as opposed to single purpose plants; for example, a packed bed reactor for a specific hydrogenation reaction. There are a number of reasons. It is more cost effective to build pilot plant equipment on skid. For a specific process, the engineer can mix and match the equipment without committing additional capital cost. Another reason is the use of outsourcing. For hazardous reactions and specialized equipment, it is far more cost effective to give the job to a vendor. Few companies would keep a Buss or Biazzi reactor on standby. Similarly, it is easier to perform pilot plant tests on centrifuge and rotary drum filters with equipment vendors. In small scale experiments, the economic limit to the vacuum level, the available amount of washing liquid, washing efficiency, possibility of channeling in the cake, cake permeability and compressibility, etc. are not considered. All of these have to be studied in a pilot plant filtration unit.

The second trend is towards intensification and miniaturization of pilot plant facilities to dramatically reduce equipment size and to accelerate the response to market changes. For an exothermic reaction, the size of a jacketed reactor that is limited by the rate of heat removal can be reduced if heat removal can be intensified using additional cooling coils. The reaction time for a semibatch reactor can be similarly reduced because the constraint on feed additional time is now relaxed.

The third trend is closer integration between pilot plant and modeling. For example, we witness the frequent use of CFD (computational fluid dynamics) simulations along with pilot plant tests. For process development, a hierarchy of models with different complexity and accuracy is highly recommended (Fig. 5). The short-cut models may not be very accurate. However, by capturing the dominant physical phenomena, they point out the correct trend under 'what if' scenarios, thus suggesting the right direction for problem solving. This approach was used by Wibowo and Ng [2001] in detecting potential operational problems such as plugging and segregation in solids processing by identifying causal and opposing effects related to particle interactions. Detailed models tend to be, but not necessarily, more accurate. As more phenomena and effects are accounted for in such models, the number of unknown model parameters is likely to increase. For example, despite a great deal of effort, CFD simulations of gas-liquid-solid systems with complex geome-

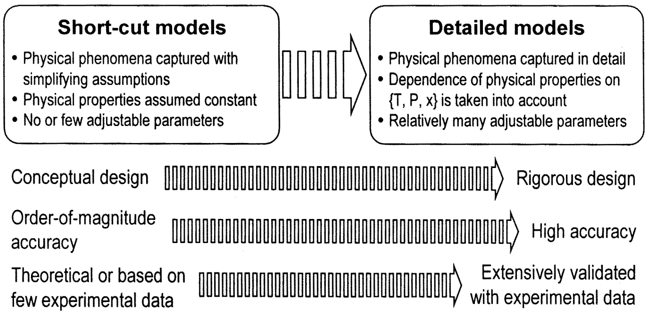

Fig. 5. A hierarchy of models for process development.

try still cannot be modeled reliably although the simulations provide useful insights to guide the pilot plant work. Similarly, it is hard to accurately simulate very fast micromixing-controlled gas-liquid oxidation reactions in large scale reactors. However, mathematical modeling helps quantify the relative importance of the relevant phenomena and can be tuned with pilot plant data to suggest improved reactor performance.

The fourth trend is the integration of process research and pilot plant studies. Let us consider the development of multiphase reactors. Traditionally, for a given reaction for commercialization, a reactor type is *selected* based on small-scale experiments, modeling, simulations, in-house know-how, etc. It has been proposed that reactors be *synthesized* instead [Kelkar and Ng, 1998, 2000, 2002]. The reactor is viewed as consisting of four building blocks: phase distribution attributes, topological and geometrical characteristics, reactor constituent parts, and transport and thermodynamic parameters. The selection of reactor constituent parts is guided by sensitivity analysis. Reactor type, attributes, and operating conditions are selected such that the best performance can be achieved. The dominant mechanisms are captured by identifying the corresponding dimensionless numbers in the governing equations for transport and reactions. In scale-up, efforts are made to keep these numbers constant such that reactor performance in the bench-scale reactor is obtained in the production-scale reactor.

A similar approach is taken for developing liquid-phase agitated reactors where the interplay of turbulent mixing and complex reaction schemes can lead to an excessive amount of impurities [Samant and Ng, 1999]. The desirable operating regime and the corresponding values for the Damköhler numbers and mixing index are identified. Reactor attributes and operating conditions, such as agitator type and speed, number and location of feed ports, and feed addition time are selected to ensure operation with the desired dimensionless numbers. An appropriate heat transfer policy is also selected by choosing the most appropriate type of heat transfer equipment. This is particularly important since the ratio of surface area to volume decreases as the reactor scale increases. More exact reaction performance can be obtained with CFD simulations. Appropriate scale-up rules have been developed based on a fundamental analysis to ensure similar performance upon scaleup. Not all these steps are needed for a given reaction system. For example, for a slow reaction with a sufficiently small Damköhler number of micromixing, we can safely scale up a 1-L laboratory reactor to a reactor of size in hundreds of cubic meters.

TECHNOLOGY TRANSFER

Technology transfer from the laboratory to the plant is an integral and essential part of any process development project. Recently, it has been broadened to include how to capitalize on internal and external technologies in commercializing new products and processes in an efficient and cost-effective manner [Williams and Gibson, 1990; Cherney and Rappaport, 2001]. Technologies may be outsourced to academia, government laboratories, or other organizations around the world so that a company can focus on its core competencies. Effective exchange of information among the stakeholders of a company, both internal and external, is the key to success in technology transfer. Fig. 6 shows the types of data passed

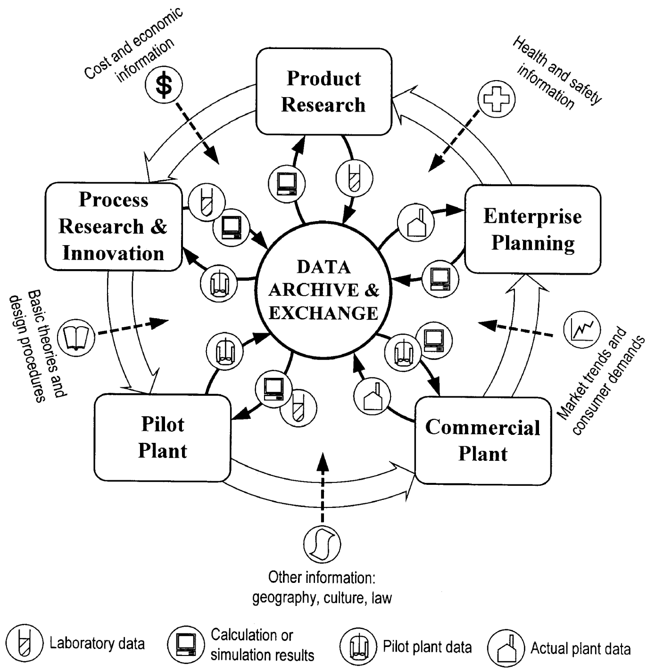

Fig. 6. Effective information exchange among the various levels of an organization is the key for technology transfer.

among researchers, pilot plant engineers and plant personnel, as well as the broader exchange of information with enterprise planning and product research. Since each segment in this range of activities can be carried out in a different part of the world, careful consideration must be given to issues such as the need for process customization to fit pre-existing manufacturing infrastructures, cultural differences that affect practices and procedures at various locations, and fostering good teamwork between stakeholders [Saban and Dale, 2001].

Along with the process, analytical methods must be transferred to manufacturing and testing sites during the early stages of product development. This is particularly important for pharmaceuticals, for which precision, analytical uniformity, and detailed documentation is mandated by regulatory requirements. It is therefore important to ensure uniform application of methods across different laboratories and within the same laboratory over time by incorporating procedures for establishing system suitability, data acceptance, and change control [Snodgrass et al., 2003].

When outsourcing is involved, one has to pay particular attention to two issues. One is the quality of the technology transfer for multiple-step processes that are still in the early stages of process development. Since process improvements and modifications continue to occur while the process is being transferred to the manufacturing site, free and open communication between the contractor and originator is the absolute ingredient for success [Davis, 2001]. Another key issue concerns intellectual properties such as patents, trademarks, and copyrights. When technology transfer occurs across national boundaries, one must be aware of the differences in intellectual property laws and common practices such as sales, licenses, joint marketing and joint development efforts in different countries.

Compared to process research and scaleup, technology transfer is based less on science and engineering, and more on management and information technology. For this reason, benchmarking is useful for determining the best practice in technology transfer.

MANUFACTURING

Manufacturing is not as glamorous an area as nanotechnology and biotechnology. Yet, considerable advances have been made in driving down manufacturing costs through innovative technologies. For example, the US downstream petroleum operating costs have gone down from US$10 per barrel to close to US$4 between 1982 and 2001 in constant 2000 dollars [Kim, 2002]. At the molecular level, improved catalysts offer enhanced productivity and selectivity. At the equipment level, we have simultaneous reaction and separation such as reactive distillation [Ung and Doherty, 1995] and reactive extraction [Samant and Ng, 1998]. At the plant level, improved process optimization, control and energy integration have all contributed to reducing capital and operating costs. It is now common that a number of international companies collaborate by sharing common utilities and providing feedstock to each other in an integrated petrochemical complex. One example is Jurong Island in Singapore and another is the Shell project in Huizhou, China, located just north of Hong Kong. At the enterprise level, significant savings can be realized by looking at the entire supply chain. A wide range of tools have been offered by companies such as Aspentech, i2, SAS and PricewaterhouseCoopers for enterprise resource planning, and demand, product and distribution planning. The advent of e-commerce is altering the supply chain landscape by bringing the customers and manufacturers in direct contact.

Developed countries, however, have witnessed a decline in manufacturing [Hoyle, 1997]. The import of chemicals now exceeds that of export for the US, resulting in a deficit in trade balance. As pointed out by Reklaitis [2000], this is because many new plants, primarily commodity chemicals, are being built in countries such as China where there is a huge internal market. In response, the developed countries will shift part of their effort to higher value-added products and processes, which depend on more developed human skill sets. These skill sets include batch processing, solids processing, biotechnology, discrete operations, and others.

Let us reiterate that there are opportunities for all kinds of processes. Historical data show that a typical chemical plant has operated at 80% of capacity during the past three decades [Arora et al., 1998], leaving plenty of room for improvements in manufacturing practices. Indeed, the downtime in solids plants is a well-known problem that still awaits a solution [Merrow, 1985].

CONCLUDING REMARKS

With the changing global CPI, there have been many discussions of the past and future of chemical engineering as a profession [Scriven, 1991, among others]. We believe, no matter how chemical engineering evolves, processing of chemicals of all kinds will remain to be the heart of chemical engineering, and process design, perhaps expanded to include process development, is still the linchpin of a chemical engineering curriculum. Different industrial sectors and subsectors do rise and ebb as the world economy and societal needs change, the demand for manufactured chemicals and chemical consumer goods remain the same.

An example is that of the petroleum and many upstream petrochemical processes which are becoming relatively mature. These high volume and low profit margin sectors still offer substantial profits and will remain the mainstay of chemical engineering although they offer fewer new job opportunities [Reklaitis, 2000]. While there will still be breakthroughs in the more mature sectors, it is crucial that **Process Research and Innovation** and **Pilot Plants** shift their focus to areas that offer higher profit margins such as pharmaceuticals and specialty chemicals. Two major opportunities are beaconing - biotechnology and nanotechnology. Regarding the former, a number of chemical engineering departments in the US have been renamed as Chemical and Biomolecular Engineering Department. This is natural because biology has always been part of chemical engineering. For example, molecular biology was a required course when the primary author was an undergraduate at the University of Minnesota. While many biopharmaceutical firms are not yet profitable, the realization of the full potential of biotechnology such as rDNA technology for manufactured chemicals is just a matter of time. Similar to biochemistry for biotechnology, the new physics at the nanoscale is the driver for nanotechnology. Carbon nanotubes are used in displays and have been shown to be very promising for use in memory chips [Economist, 2003]. Fullerenes can serve as drug delivery vehicles. However, if history is any guide, these nanomaterials will not take off unless the concomitant **Manufacturing** know-how can be developed to reduce the raw materials cost to an appropriate value level.

Observing that a business graduate can earn more money than a PhD chemical engineer, Landau [1997] made an interesting comment, “the rigorous training in the systems approach of chemical engineering often can qualify able chemical engineers to go into general management”. Let us understand why some business people command a higher income. While we can optimize the operations of a piece of equipment, a process, or even a plant site, we may not be optimizing the return on investment for the enterprise. Business decision-making is not a hard science or an engineering subject but has become the main theme for a Process Systems Engineering conference [Ng, 2003]. The MOPD approach integrates business decision-making, engineering, and basic sciences. In the area of **Technology Transfer**, the integration of engineering, information technology and management is again the key to success.

Fearing that there is excessive science and not enough engineering in the academic arena, Laudau also argued that “… chemical engineering’s third paradigm, if there is one, is to return the discipline closer to the practices in industry and to strengthen interdisciplinary ties …”. In a way, the emergence of the process development focus enforces close collaboration between industry and academia.

The purist may argue that we are mixing up management and chemical engineering. Actually, it is not unusual for reputable chemical engineering journals to turn down a submission on the grounds that the manuscript does not have sufficient hard science. We have to strike the right balance among science, engineering and management. For example, HKUST is offering a dual degree program on engineering and management (www.ust.hk). The decision on how to train our graduates and thus the future of chemical engineering is in our hands.

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