Perspective

# Chemical Engineering in Japan

**Shinji Hasebe, Masahiro Ohshima, and Kazuhiro Mae**
Dept. of Chemical Engineering, Kyoto University, Japan

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## Introduction

The Society of Chemical Engineers, Japan (SCEJ) celebrated its 75th anniversary in March 2012. In this memorial year, it is meaningful to review the history of Japanese chemical engineering and the chemical industry. In this Perspective, we will first provide a history of SCJE and briefly discuss its activities. Then we will present the characteristics and explain the motivating factors of chemical engineering education in the Japanese universities. A historical perspective of the Japanese chemical industry, its scope and evolution will follow. Finally, we will sketch and discuss the future directions of Japanese chemical engineering research and education.

## The Society of Chemical Engineers, Japan

First inaugurated as the Society of Chemical Machinery in 1936, the English name of the Society was changed to the Society of Chemical Engineers, Japan (SCEJ) in 1948. The regular membership was 1,329 in its second year. In an era that the Japanese economy depended heavily on chemical engineering and chemical engineers, through the systematic and persistent efforts of the Society's founders the regular membership rapidly quadrupled to 4,506 by 1945. To spread the concepts of chemical engineering to the industrial world, a series of technical books[1] on chemical engineering was published in 1936, consisting of 12 volumes and more than 3,000 pages in total. The publication of this series undoubtedly had a pivotal effect on the ensuing advances in the design and construction of chemical plants during this period. The first edition of the *Chemical Engineering Handbook*, called ''Kagaku Kogaku Binran,'' was published in 1950 by the SCEJ, and, subsequently, it was revised every 10 years, with the seventh edition published in 2011.

The yearly totals for each type of SCEJ membership during the last 25 years (1987–2011) are shown in Figure 1, and indicate a vibrant growth during the first 10 years followed by a gradual decline. This total is nearly the same as the total membership in 1990 with the regular membership having decreased noticeably. The dominant reason for this trend was the collapse of the bubble economy of Japan and the ensuing depression. It has also been argued that an additional reason for this decline was SCEJ's unpreparedness to offer meaningful services to some of its members. In response to this weakness SCEJ has expanded the set of services it offers to its members and has increased the value of these services, as manifested by the memorial projects of the 75th anniversary, with the following being among the most important.

- *Digital library*: more than 200,000 pages of conference proceedings, bulletins and textbooks published by the SCEJ have been digitized and become available to the members. The old editions of the chemical engineering handbook are also included in the library, with possible access from all over the world. The digital library will be helpful to all members, especially those working abroad.
- *Visual plant tours*: Photos and moving images of refineries, chemical plants and facilities have been opened to the public in order to deepen the understanding of chemical engineering and industry. They can be and are used in university classes as well as in high schools where the students gain a deeper understanding of chemical engineering and develop a healthier interest for the profession.
- *SCEJ Asia Research Award*: This award is granted to outstanding Asian researchers under the age of 45, who contribute to research and technological development in chemical engineering. The winners are invited to the annual meeting of SCEJ as guest speakers. Through discussions with guest speakers and Japanese researchers at the international sessions of the annual meeting, the SCEJ supports the globalization of Japanese research.
- *Vision 2023*: The SCEJ defined its Vision 2011 about 10 years ago and used it as a blue print to reform the structures and activities of the Society in the ensuing years. The results were assessed against the goals of Vision 2011 and the new vision for the next 10 years was announced.

Through these activities, the SCEJ stimulates and supports the activities of its members.

Correspondence concerning this article should be addressed to S. Hasebe at hasebe@cheme.kyoto-u.ac.jp.

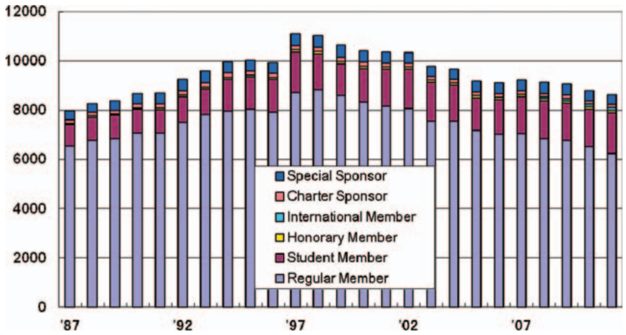


**Figure 1. The yearly totals for each type of SCEJ membership during the 1987–2011 period.**

## Chemical Engineering Education in Japanese Universities

### *History*

The first research laboratory in chemical engineering was established at Kyoto University in 1922. In 1940 the first departments of chemical engineering were founded at Kyoto University and Tokyo Institute of Technology. Along with the development of petrochemical industries, the number of chemical engineering departments increased rapidly and in the mid-1970s about 30 universities had a department named ‘‘Chemical Engineering’’. Unfortunately, the name ‘‘Chemical Engineering’’ did not invoke familiar concepts to high school students, and although the expansion of research in the discipline of chemical engineering proceeded with an accelerating pace, ‘‘Chemical Engineering’’ started to gradually disappear from the names of university departments. At present, only two universities have departments named ‘‘Chemical Engineering’’ in undergraduate education. The most popular names that replaced ‘‘Chemical Engineering’’ are; ‘‘Chemical and Environmental Engineering,’’ ‘‘Chemical Systems Engineering,’’ and ‘‘Biological and Chemical Engineering.’’

The other significant movement in the evolution of university-level education in chemical engineering came from the Japanese government, which introduced a policy with overriding priority given to graduate school, thus, leading the dominant universities in the 1990s to restructure their educational and research programs. The master's and PhD course programs were expanded, while some departments with primary focus to undergraduate education were merged into one department. Today, in Japan, ‘‘Chemical Engineering’’ is regarded as a part of applied chemistry, and in many universities, chemistry-related departmental entities were merged into one department. For example, Kyoto University had five chemistry-related departments, including chemical engineering, in the faculty of engineering. In 1993, they were all merged into the Dept. of Industrial Chemistry.

Figure 2 shows the number of graduates who have studied chemical engineering in Japanese universities[2] over a period of 60 years (1950–2010). The graduates are classified into three groups, taking into account the characteristics of the educational programs that produced them. The first group includes graduates from distinct departments of chemical engineering or departments with ‘‘Chemical Engineering’’, as mentioned previously. The second group includes graduates from a so called ‘‘chemical engineering course’’, which is part of a broader departmental unit. For example, ‘‘chemical engineering’’ graduates from Kyoto University belong to this group, since the ‘‘Chemical Engineering Course’’ is part of the Dept. of Industrial Chemistry, which enrolls 235 new students every year. The students in this department take general education in, e.g., chemistry, physics, mathematics, and before the second semester of the sophomore year, they select the course of chemical engineering or one of the other chemistry courses such as, polymer science or molecular engineering. About 40 students select the chemical engineering course every year. The last group of graduates comes from a variety of other departments, which include certain research laboratories related to the chemical engineering. It is clear from Figure 2 that the number of graduates increased rapidly in the 1960s with very little change afterwards. However, the percentage of graduates from each group has changed in the last 2 decades, i.e., the graduates from the second and third groups have increased. In the second and third groups, the number of classes related to chemical engineering has decreased. Thus, careful selection of the curriculum is needed in order to have graduates who have enough knowledge of chemical engineering.

The number of students who graduated the course certified by the Japan Accreditation Board for Engineering Education (JABEE) is also shown in the figure.

### *Features of the Japanese educational system*

The academic year in Japan starts in April. Most universities have adopted the semester system: the spring semester starts in April and ends in the middle of August, and the autumn semester starts in October and ends in the middle of February. Students graduate in March and either go to graduate school, the workplace, or research institutes in April.

Table 1 shows the number of faculty and students at Kyoto University. The department of chemical engineering at Kyoto University uses the research group system like most Japanese universities. Each research group consists of a full professor, an associate professor, an assistant professor, postdoctoral fellows, graduate students and undergraduate senior students. Graduate students need 2 years for the

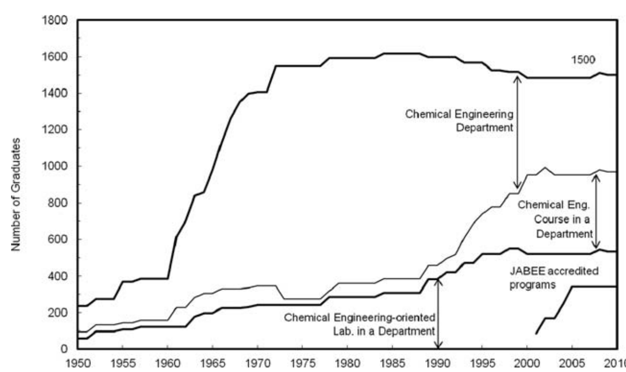


**Figure 2. Number of Japanese graduates who completed an undergraduate curriculum of chemical engineering.**

Table 1. Number of Faculty and Students in the Dept. of Chemical Engineering, Kyoto University

| | |
|---|---|
| Full professors | 9 |
| Associate professors and Lecturers | 6 |
| Assistant professors | 8 |
| Doctoral course students | 24 |
| Master's course students | 66 |
| Undergraduate senior students | 48 |

Master's degree, and another 3 years for the doctorate. As shown in Table 1, the number of students in doctoral courses is small compared with that of Master's students. This is one of the features of Japanese engineering education.

Why are there so few doctoral students? There are several reasons for this. One is the poor financial support (scholarships, fellowships, etc.) system of Japanese universities. Most scholarships are loans that students must repay after graduation. Recently, many universities have tried to establish a fund to support PhD candidates, but the resources are still limited and not enough to motivate students to do doctoral work. The other reason is related to labor practices in Japanese companies. It is common for Japanese to work at one company until retirement age. Thus, each company tries to educate newly enrolled persons through corporate educational/training programs. They can obtain remuneration from the company instead of paying a tuition fee to the university. Thus, many students think that on-the-job training in the company is more beneficial for professional advancement compared with the 3 years' doctoral research at a university. It is becoming clearer although that in addition to considering new schemes to financially support graduate students, the education and research experience in the graduate school should become more attractive. Universities must offer education and research programs which cannot be obtained in industry.

Table 2. Curriculum of Chemical Engineering Course in Kyoto University

| |
|---|
| **Sophomore 2nd semester** |
| Physical Chemistry I |
| Inorganic Chemistry I |
| Fundamental Fluid Mechanics |
| Mathematics for Chemical Engineering I |
| Computer Programming in Chemical Engineering |
| Chemical Reaction Engineering I |
| **Junior** |
| Transport Phenomena |
| Fluid-Phase Separation Engineering |
| Process Control |
| Physical Chemistry II, III |
| Mathematics for Chemical Engineering II |
| Numerical Computation for Chemical Engineering |
| Chemical Engineering Laboratory |
| Introduction to Environmental Preservation |
| Chemical Reaction Engineering II |
| Solid-Phase Separation Engineering |
| Fine Particle Technology |
| Process Systems Engineering |
| Simulations in Chemical Engineering |
| Biochemical Engineering |
| Chemistry and Environmental Safety |
| Industrial Organic Chemistry |
| **Senior** |
| Safety in Chemistry Laboratory |
| Process Design |
| Engineering Ethics |
| Global Leadership |
| Graduation thesis |

## Curriculum

In Kyoto University, students select their majors in the second semester of the sophomore year. Those selecting chemical engineering take the subjects listed in Table 2. These subjects are almost the same as those in the 1970's with the only difference the semester when the classes are offered. It may be said that the core of the chemical engineering curriculum is fully covered, but the content is old and too traditional. With the expansion of the chemical engineering discipline to cover new areas of scholarship and the maturing of the petrochemical industry, the subjects of the undergraduate course should be changed. It is difficult to answer the question of what the best curriculum should be. At Kyoto University, the faculty members agree that modeling and the analytical ability on core chemical engineering science (material and energy balances, transport, thermodynamics, kinetics and reaction engineering) are very important, as well as the synthetic (e.g., design) ability for unit operations and the systems approach. Graduates can adapt to a variety of industrial problems if they have the core educational abilities mentioned previously.

Figure 3 shows the age-specific distribution of the population of Japan, which underlines the demographic weakness in the age brackets 1 to 30 years old, and explains the continuous decrease in the university enrollment, both in terms of the recent past as well as the expected decrease over the next 20 years. To maintain sufficient numbers in university enrollment and insure levels of academic quality, the universities must increase the number of foreign students they admit. However, to achieve this goal, several barriers must be overcome, such as the following: In Japanese universities, most of the textbooks are written in Japanese and most of the lectures are given in Japanese, both of which have contributed to the smoothness of the educational and research processes and have ensured high levels of quality in science and technology. To increase the percentage of foreign students universities have introduced teaching in English, but

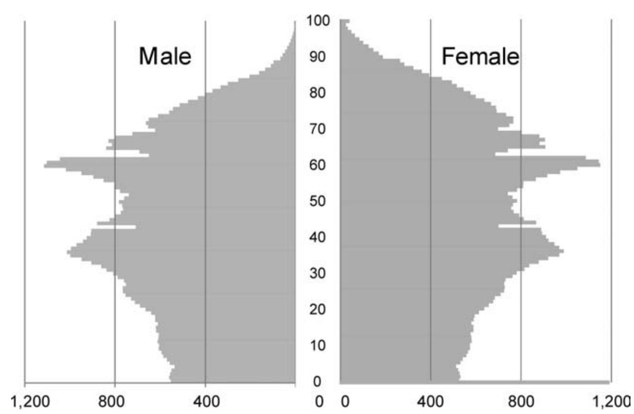


**Figure 3. Age-specific distribution of Japanese population in 2009.**

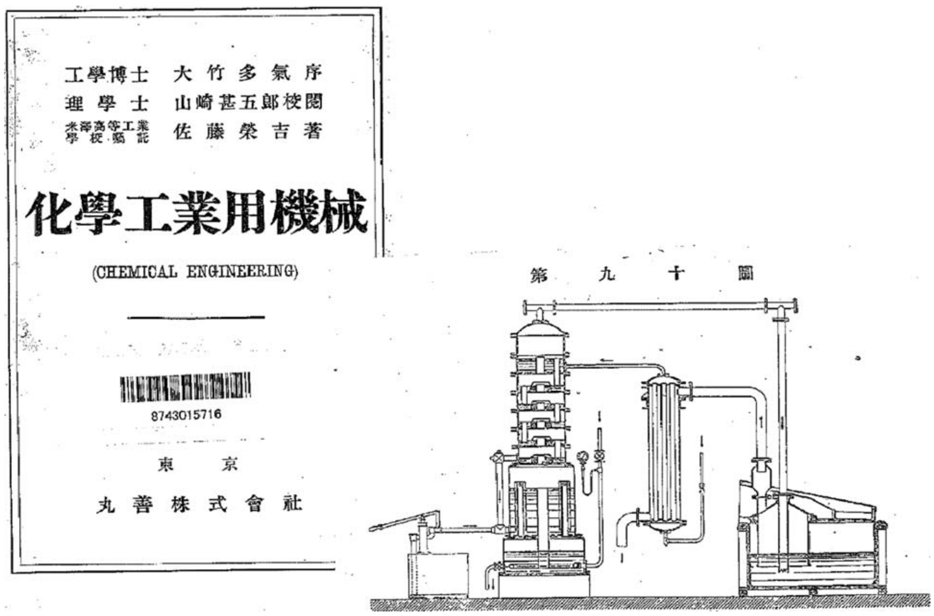


**Figure 4. Cover page of the book titled *Chemical Engineering*, published in 1916, and a distillation column drawing in the book.**

the percentage of classes in English remains small. In addition, as classes are modified to an all-English format, both the degree of understanding by the majority of the students and the quality of the educational process suffer. A systematic strategy to overcome these shortcomings needs to be developed, and various efforts are made in this direction. Furthermore, the limited availability of low-cost living accommodations, e.g., university dormitories, and the government's negative position in expanding the number of dormitories make it very difficult for the foreign students to find acceptable accommodations in the highly-priced real estate of Japanese cities.

## A Historical Perspective of the Japanese Chemical Industry

### *Birth of modern chemical technology in Japan*

The Meiji Restoration in 1868 destroyed the old feudal system and ushered Japan into the industrial economy, which allowed her to become a major world power within the span of 60 years. The modern Japanese chemical industry had its genesis in 1872 with the construction of a sulfuric acid plant by Japan Mint, Osaka.[3] The acid was needed for purifying gold and silver as well as rinsing the coins. British engineers, T. J. Waters, R. Finch and some others were invited to construct the mint and acid production line.[4] Soon afterward the Japanese chemical industry grew very rapidly, with the fiber and ammonia-based production of soda leading the way in terms of their degree of expansion. During World War I (1914–1918), the imports from abroad were stopped leading to a rapid growth of domestic chemicals production with the ensuing expansion in the numbers of chemical engineers needed and the extent of systematic use of the principles of the new discipline of "chemical engineering", that was being defined at about the same period of time. Figure 4 shows the cover page and the picture of distillation column of the book named *Chemical Engineering*.[5] This book was published in 1916, and is the oldest Japanese book having the title of *Chemical Engineering* in the Library of Kyoto University. After the War, the fiber-textile industries grew steadily and became among the dominant suppliers of fibers in the world, e.g., production of rayon in 1937 was the highest in the world.

### *The negative legacy of World War II and subsequent developments*

World War II (1939–1945), and the ensuing defeat disrupted the steady and sound growth of the Japanese chemical industry to preceding 60–70 years and left a negative legacy to the subsequent developments in the chemical industries.[4,6] For example, during the War, most of the Japanese chemical industries were forced to blindly concentrate all their efforts on the production of war-related materials such as gunpowder and synthetic oil, due to the lack of natural resources that supplied these materials, without the benefit of any technological information exchanges with other countries. There was no room in Japan at that time for the chemical industry to embrace new technological ideas and explore their commercial developments that were fueling the growth of new chemical industries in North America and Europe such as, synthetic rubber, polyethylene, and nylon and acetylene chemistry. The War hollowed out the research and development efforts in Japanese industries and reduced the creativity and ability of differentiating made-in-Japan technologies for products and processes from those developed in other countries. As a result, during the immediate postwar period the chemical industries invented few new products and new

**Table 3. Chemical Processes Originally Developed by Japanese Companies in the 1960s and 1970s[4]**

| Year | Company | Plant/Process |
|---|---|---|
| 1959 | Nippon Shokubai | Ethylene oxide |
| 1960 | Mitsubishi Kasei | Oxo octol |
| | JSR | Polybutadiene |
| 1962 | Toray | ε-Caprolactam by photo nitrosation |
| 1965 | Zeon | Butadiene extraction from C4 residuals |
| 1966 | Tosoh | Vinyl chloride monomer by oxychlorination |
| 1968 | Mitsubishi Gas Chemical | Meta-xylene separation and Isomerization |
| 1970 | Nippon Shokubai | Acrylic acid and acrylic esters by oxidation of propylene |
| | Asahi Kasei | Processes for electrohydrodimerization of acrylonitrile to adiponitrile |
| | Mitsubishi Kasei | Maleic anhydride from C4 residuals |

plant technologies. To recover rapidly from the depression caused by the War and its aftermath, Japanese chemical industries chose the strategy of importing the manufacturing technologies from North America and Europe and focusing their efforts on improving their efficiency and products' quality.

After World War II, even though most of the technologies were imported, there were certain technologies, which were originally developed in Japan by Japanese companies. Table 3 shows a partial list of significant chemical processes based on innovative technologies, developed by Japanese chemical companies in the 1960s and 1970s, and adopted by many companies worldwide. They are still in use today. While the number of chemical processes of Japanese origin is limited, there have been many Japanese-originated machines and material technologies that have contributed significantly to the improvement of production rate and product quality of chemical processes. For example, highly-reliable steam turbines and centrifugal compressors made by Japanese heavy industry companies played a pivotal role in the increase of production rate of chemical plants. The centrifugally-casting method and the seamless pipe drawing method led to the fabrication of anticarburizing reactor tubes, which in turn have had a large impact on the improved performance of ethylene and hydrogen production reformers.

On the positive side, the War destroyed the infrastructure of the prewar chemical industry. Now, anyone could build new companies by introducing foreign advanced technologies even if they did not possess their own production technologies. For example, many small scale oil companies came into existence as Japan had no national flag oil company. Furthermore, since 1958, the petrochemical and chemical complexes were built along the seashore of Japanese islands and were of modest scale, since the chemical and petroleum companies which owned them did not have sufficient capital to build world-class scale complexes. Finally, the protection barriers imposed for the protection of the domestic chemical industry allowed the companies to operate with satisfactory returns. These factors led to the development of *ad hoc* and nonintegrated Japanese chemical industries and delayed the modernization and revitalization efforts until the 1990s.

After the War, the type of raw materials used and the mix of Japanese chemical products underwent a revolutionary change: chemical industries changed their main focus from inorganic to organic products, and shifted from coal to oil as their primary resource for raw materials. Their growth was dependent on imported foreign technology, as discussed previously, which in turn came with important restrictions, e.g., the markets for the products of Japanese chemical companies were restricted to Asian markets. Thus, the growth of Japanese chemical industries relied heavily on the protected domestic market and as a result its international competitiveness suffered until the liberalization of Naphtha imports in 1982.[4,6]

## *From a primary materials industry to a processing industry*

The rapid and impressive in scale recovery of the Japanese industry from the devastation of World War II was slowed down in the late 1970s by the two oil crises and the seriousness of environmental pollution problems that had been created, such as the Yokkaichi asthma and Minamata disease.* To overcome these problems, cost reduction, energy savings and environmental protection became the focus of intensive engineering efforts. However, given the prevailing conditions in raw materials costs, the petroleum and petrochemical industries stagnated and in order to stimulate their further business growth the Japanese government introduced in 1982 the liberalization of Naphtha imports. At the same time, the government requested from the Japanese chemical companies the consolidation of production sites along with an adjustment of excess capacities, and the undertaking of joint investments. As a result of these initiatives, 32% of the ethylene production capacity in Japan was eliminated and four cooperative sales companies were established for polyolefin and polyvinyl chloride businesses.[8,9]

The petroleum and petrochemical industries were revitalized by this restructuring and the support of high-growth rates in the Japanese economy during the 1980s. The period from the mid-1980s to mid-1990s is known as the Petrochemical Renaissance, but from the mid-1990s the growth in

**Yokkaichi asthma*: A big pollution disease occurred between 1960 and 1972 in the city of Yokkaichi in Mie Prefecture, where the chemical complex was built and operated. Large quantities of sulfur oxide were released from the complex and severe smog was produced. It caused severe chronic obstructive pulmonary disease, chronic bronchitis, pulmonary emphysema, and bronchial asthma among the local inhabitants.[7]

*Minamata disease*: Another big pollution disease, which is sometimes referred to as Chisso-Minamata disease, occurred in Minamata city in Kumamoto prefecture, where the Chisso corporation had been producing acetaldehyde with mercury sulfate as a catalyst. A small amount of methylmercury was released from the plant into sea from 1932 to 1968 and bioaccumulated in shellfish and various types of fish. When eaten by the local populace, the mercury resulted in the severe neurological problems.[7]

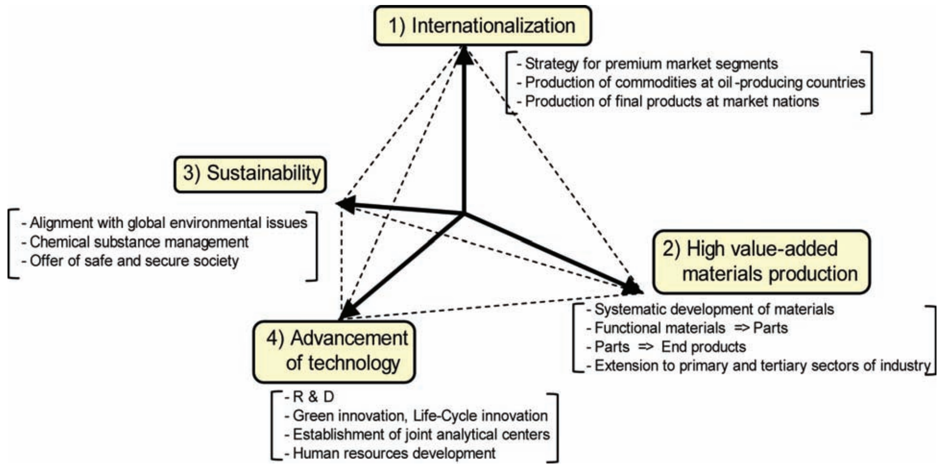


**Figure 5. The four directions for the future development of the Japanese chemical industry.**

materials industries started to slow down again. In parallel with these developments in basic chemicals, Japanese chemical companies had started to shift their strategic focus from basic chemicals toward intermediate chemicals or consumer products, such as pharmaceutical compounds, detergents, cosmetics, photographic sensitive materials and engineered plastic parts. This shift in the core operations of chemical industries led to gradual shift from a primary materials industry to a processing industry. During this period, the United States started accusing Japan for violating conditions attached to imported American technologies, and the U.S. government put direct or indirect pressure on Japan. In response to these pressures, the Japanese chemical industry started composing new strategic directions of growth, seeking new technologies and development of new business opportunities in three directions: biotechnology, electronics, and new materials. The common underpinning of these efforts was to be their dependence on knowledge-intensive technologies, cultivated in Japan after World War II.

## From a processing industry to a functional chemical industry

The end of cold war and the collapse of the Soviet Union reduced the significant conflict in global politics and motivated the globalization of industries. The Japanese chemical industries responded to the wave of globalization by establishing overseas bases and making extensive investments in foreign countries for new production facilities or the acquisition of local firms. The strong Japanese currency facilitated this strategy in a very decisive way. To remain competitive in the global market, selection and concentration of the core business activities were further advanced by the Japanese chemical companies. At the same time, many of them developed intense efforts in identifying differentiating and competitive technologies on which they would build their new business development efforts, and all of them kept improving their in-house technologies for an expanding market. During this period, Japanese chemical industry decreased its dependence on the imported technologies, became more research-intensive and started exporting competitive technologies to the rest of the world.

## Present situation

Through the selection-and-concentration movement, practiced by many Japanese chemical companies, today, the chemical industry of Japan can be seen as composed of two groups of companies. The first group consists of several large general chemical companies which produce a variety of products. The second group consists of a large number of relatively small companies, which produce specialty chemicals having large global share in the markets of specialized high performance products. The transformation in the structure of Japanese chemical industry from one where the emphasis was on the large-scale production of commodity chemicals to one that focuses on the production of high-performance products is still in progress. The era of dependency on imported technology is long over, and the Japanese chemical companies are heading toward a research-intensive chemical industry that allows them to establish and maintain their own identity and world-scale differentiating competitiveness on technologies, processes, and products they generate.

## Current trends and future directions of the Japanese chemical industry

Figure 5[10] shows the future direction of the Japanese chemical industry as reported by the working group organized by the Ministry of Economy, Trade and Industry, Japan. The working group consisted of the presidents of the dominant chemical companies and university professors. In the report, published in 2010,[11] the following four directions were pointed out:

1. International expansion of production.
   - Strategic production of commodities at domestic and oil-producing countries.
   - Strategic production of final products at domestic and market nations.
2. Shift to the production of high value-added materials: change of business model.

• Shift of the target products from intermediate feedstocks to high-quality end-products, based on high-quality intermediate feedstocks.
• Expansion of the market (range of products and amounts) to the agriculture field, and the enhancement of competitiveness through enhanced product quality and meticulous care to the broader environment.
• Promotion of corporate culture and practices on enhanced techniques for advanced product quality.
• Concentration in core businesses.
• Cooperation with similar and/or different types of chemical companies.

3. Promotion of sustainability.
• Innovative energy conservation by process and product design.
• Process and product design based on life cycle analysis (LCA).
• Intergovernmental dialogue on chemical substance management guidelines

4. Advancement of industrial technology capability.
• Contribution to ''Green innovation'' such as the shift of chemical feedstock to renewable materials.
• Joint management of high-precision analytical instruments.
• Support for excellent doctoral students.

The Great East Japan Earthquake of March 11th, 2011 forced industrial practitioners, government and academics to revisit the future vision of the Japanese chemical industry, published in 2010.[11] In addition to the reinforcement of international industrial competitiveness, the importance of risk management was recognized, and the following items were added to the proposal[12]:

• Strengthen the ability to supply high-quality materials.
• Develop production and supply chain systems that are robust in the presence of unusual situations, e.g., reduce the number of product properties with excessive specifications and/or have the supplier and customer agree ahead of time on the set of acceptable substitute materials in order to cope with shortages in the presence of unusual circumstances.
• Protect relocated factories overseas against shortages of electric power.
• Reform the social structure of the disaster area through chemical and technological innovations, e.g., intensive investment in the research facilities on renewable energy to the disaster area.

The newly added four items, presented previoulsy may be specific to the experience of present-day Japan. However, no one knows where and when a natural disaster of similar impact might occur. By overcoming effects of the great east Japan earthquake, the Japanese chemical industry can be regenerated, and the experience obtained in the process of overcoming the disaster becomes one of the competitive strengths of the future Japanese chemical industry.

Furthermore, in order to survive in a very competitive Asian market, Japanese chemical companies have been compelled to radically reform their production systems, and in doing so they have been taking the conditions mentioned previously into account. It has also become very clear that theoretical and applied research programs should be undertaken within chemical engineering in order to address the effects of natural disasters as those experienced by the great east Japan earthquake (see next section).

## Trend of Japanese Chemical Engineering Study

### *Fundamental direction of the research*

''The Limits to Growth''[13] was published 40 years ago and underlined the simple fact that continuous quantitative development was impossible. Thus, sustainability or sustainable development should be important key words in academic and industrial research. Sustainability is strongly related to the problems of resources, energy, food, and global environment, and although in the past, academics, governments and industrial practitioners have not invested sufficient time and resources in addressing them, the pressures exercised by these problems on a world-wide scale are changing perceptions and priorities.

How can Japanese industries and academia contribute to solving the sustainability problem? Two cultural elements, deeply imbedded in the Japanese tradition, offer partial answers and could constitute components of a multifaceted approach to sustainability. ''Mottainai,'' a well-known and popular Japanese word, means ''What a waste!'' From the viewpoint of Mottainai, materials should be used exhaustively, i.e., as far as they offer any function. In terms of thermodynamics, materials should be sequentially used with small exergy loss. The second Japanese cultural element is the long-standing perception by the people of Japan that ''small is valuable''. Everything is made small and has led to many miniaturized contributions from ''Hakoniwa'' (a miniature garden) to the transistor radio. By making a chemical plant small, the amount of construction material can be reduced and the operating efficiencies increased, e.g., energy consumption can be significantly reduced by intensifying processing to small areas and volumes.

These characteristics of Japanese culture may contribute to the development of materials and chemical processes which are suitable for a sustainable society. For this Perspective we have selected for further discussion four areas of research directions (see Figure 6) that promote and enhance sustainability.

### *Materials and energy conservation through innovative process design*

To drastically decrease energy consumption, the prevailing concepts of process design must be changed. In this paragraph the authors discuss various ideas on how new concepts of process design can have a significant impact on reducing energy consumption rate and exergy losses.

During the last 30 years, energy consumption rate per unit of product has been improved by increasing the plant scale, and has led to chemical plants of larger and larger production capacity. In a sustainable society, the desired amount of products should be supplied to the distributed customers at the desired time. In such a situation, mass production by supersized continuous plants may not be desirable, and production by distributed smaller plants would be more flexible and preferable. However, production in smaller plants has

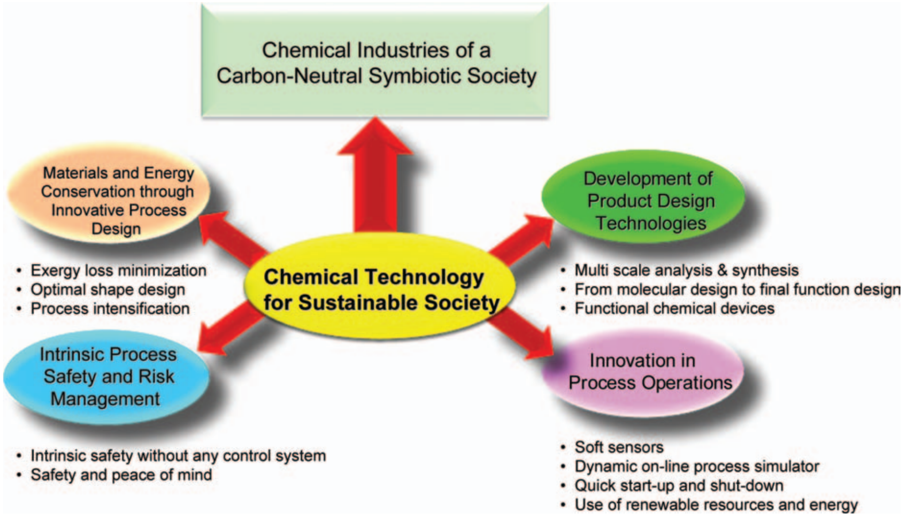


**Figure 6. Fundamental directions of chemical engineering research that promote and enhance sustainability.**

been perceived as inefficient. To reduce the energy consumption rate even though the plant scale is decreased, new process design concepts and operating procedures should be invented. Moreover, the supply chain from the suppliers to the customers must be reconsidered, when readily available biomass is used as raw materials or energy source.

Exergy losses can be reduced by operating the plants under small driving forces. Usually, the reduction of a driving force on the operation increases the size of the processing unit and/or makes the production time longer. However, when the size of a processing device decreases, the driving force per unit length becomes larger. Thus, microprocessing devices offer an attractive option to overcome the aforementioned drawbacks. For example, using microchannels in processing devices, one can significantly accelerate the heat-transfer rate. Suppose the heat transfer rate is 10 times larger than that of the conventional heat exchanger. Then, the temperature difference of a micro processing device can be 10 times smaller than that of the conventional heat exchanger, when the heat-transfer areas are the same. Thus, heat exchange can be carried out with small exergy loss. The size of heat exchangers can be drastically reduced when the temperature differences are the same. To efficiently use small driving forces, the flow and temperature conditions in the devices must be estimated and controlled precisely, requiring detailed and precise modeling of flow patterns for the design of the microprocessing devices.

Plant performance can, in principle, be significantly improved through the solution of judiciously formulated optimal design problems. However, undesirable phenomena such as imperfect mixing, residence time distribution and temperature distribution deteriorate the overall plant performance. Conventionally, a design margin is added to the calculated design. It works well to avoid the production of off-specification products, but it is counterproductive in terms of efficient energy utilization; it always increases the amount of energy required and the amount of energy lost. Even under such circumstances, the plant should be designed optimally, and the expected products should be produced by the constructed plant as designed. To achieve this goal, the mathematical process model, used for process design, must be expressed by partial differential equations, and process design approaches based on partial differential equations should be developed. Typical example is the successful use of computational fluid dynamics for the simulation and design of processing units involving complex flow patterns.

Executing a variety of operations simultaneously is also an effective method of process intensification. Reactive distillation is a typical example. The concept of standard unit operations has been a powerful framework in the design of chemical plants. However, the design procedures for chemicals plants in a sustainable chemical industry must abandon the notion of standard unit operations and invent new processing units, which integrate several standard operations. Figure 7 (top) shows an example of an intensified micro

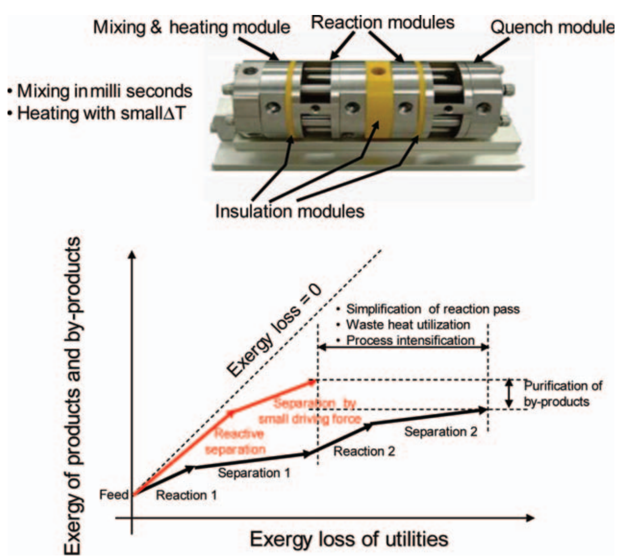


**Figure 7. Intensified microdevice (top), and an image of energy loss reduction (bottom).**

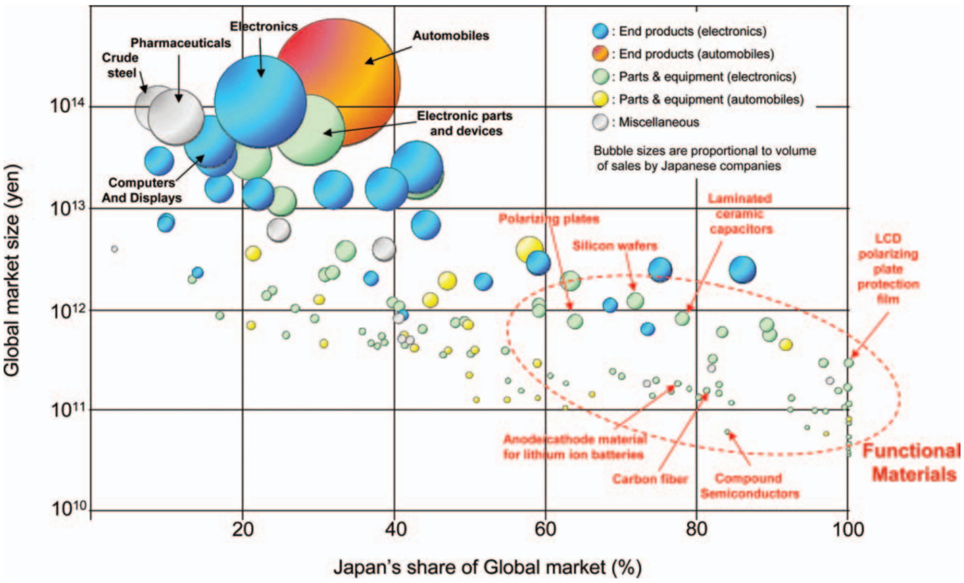


**Figure 8. Japanese share in the global market[11] for various groups of products.**

The original figure was modified by the authors.

device.[14] In this device, a variety of operations are possible by changing the components. Suppose successive reactions occur and the intermediate is the desired product. By mixing reactants perfectly within a short time, such as 0.01 second, the desired reaction occurs uniformly. By precisely controlling the residence time, the product can be quenched before it changes to an undesired byproduct. When micro devices are used, the mixing, reaction and cooling times can be controlled at the scale of milliseconds. If a membrane can be embedded in the component, the reaction and the separation can be carried out simultaneously, thus, drastically decreasing the exergy losses for the plant (see Figure 7, bottom).

## *Development of product design technologies*

Chemical companies supply chemicals and materials to a very broad range of manufacturing companies (e.g., electronics, automobile, aviation, personal care, health care, construction, and others) for the production of a very large number of consumer products. As the needs and preferences of the consumers change with time and cultural norms, the needs of these manufacturing companies for chemicals and materials change as well. Thus, in addition to improvements on materials and energy utilization/conservation for a sustainable future industry, continuous progress in product technologies is also indispensable. Figure 8 shows the global market share of Japanese companies in various major groups of products and components, and indicates that Japanese chemical companies have a dominant market position in the markets of chemicals and materials related to electronic devices (see product groups enclosed by the dashed lined ellipse), an area where market growth is driven by technology innovation. One of the reasons for successful positioning of Japanese chemical companies in these product groups has been their long-standing adherence to the continuous improvement philosophy, known as ''Kaizen'', and its effective deployment to the continuous improvement of fast evolving materials and components. The quality and functionality of the products are continuously improved step by step, and are quickly adjusted to the needs of the customers.

To maintain strong market share in each core material, continuous advancement in systematic product development technologies is essential, in addition to the product and process improvement through Kaizen. As underlined by many researchers, seamless integration of physicochemical models and design activities at multiple scales, as shown in Figure 9, is critical for the rational development of systematic procedures for the design and manufacturing of new functional materials.[15–17] This requirement entails the development of two systematic approaches, which may interact at various degrees. The first concerns the development of a simulation-based design procedure, which successively carries out the molecular design, physical property design, and final function design of the desired product. The key problem here is how the properties at one scale are transferred to the design activities at another scale. The second systematic approach must address the development of precise production processes, which can produce the desired materials without losing the desired function, designed by the simulation-based method. The manufacturing process itself must be optimized

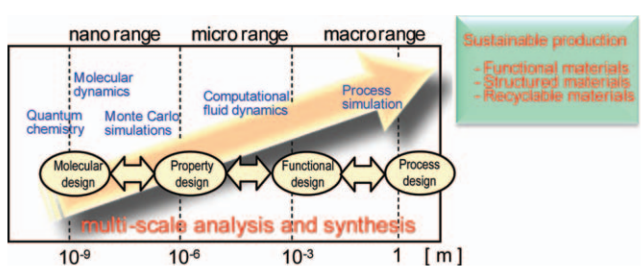


**Figure 9. Fusion of multiscale models and problems.**

so as to produce the desired materials in the most effective manner. The implication is that functional chemical manufacturing devices, which are essential to produce the desired materials, should be developed. Microchemical devices and plants are candidates to be such devices.

### *Intrinsic process safety and risk management*

The importance of intrinsic process safety has been reaffirmed by the experience from the Great East Japan Earthquake and Tsunami. Chemical plants have been designed and engineered on the foundation of the fail-safe and foolproof concept. Systematic approaches such as fault tree analysis (FTA), and hazard and operability studies (HAZOP), have been routinely carried out. However, the uneasiness of the residents close to the chemical plants has not decreased. In the future if distributed, regional production and consumption are promoted to reduce transportation costs and losses, chemical plants may have to be located closer to residential areas. In such situations, the need to ensure the protection of residential communities and provide them with peace of mind will become a very important factor and will have to be considered along with classical considerations on process safety. A systematic approach which can treat both safety and peace of mind must be developed. In addition to the development of risk management systems, it is desirable that the chemical plant have intrinsic safety without any control system. For example, if the size of a reactor tube is properly designed, a flame does not propagate even when an explosion has occurred. The reduction of the holdup in vessels is effective not only to reduce the damage, but also to shorten the response time.

### *Innovation in process operations*

The operation of plants within the scope of a sustainable chemical industry imposes new challenges that need to be addressed. For example, in order to ensure carbon-neutral effluents, chemical companies must use renewable resources and recycled materials. The quality of these materials is not stable compared with the raw materials obtained from petroleum. Yet even in such situation the high quality of final products must be ensured by the operation of a plant. The key point here is to determine the appropriate plant operating conditions, including the potential variability in feed quality. The development of new types of sensors, which can measure the feed composition or quality, is essential. In addition to the hardware sensors, soft sensors, which can estimate plant operating conditions, and dynamic process simulators, which can reproduce with sufficient accuracy real-time plant operations, are very helpful to the operators, who try to keep the plant operating conditions within the range of normal operations, even when various disturbances have entered into the plants. When biomass and/or recycled materials are used as raw materials, the treatment of solids cannot be avoided. Sensors which can detect the solids' composition and quality are also required.

In addition to fluctuations in quality, the supply of renewable resources may be uncertain. Furthermore, if renewable energy, such as solar power and/or wind power, is directly used, the energy supply will also fluctuate. The operation of future plants must be robust to such disturbances. The key issues are how to achieve quick startup and shutdown and efficient operation of chemical plants over a wide range of compositions and levels of production. If the plant can startup and shutdown easily, it is possible to discontinue the operation of a continuous plant at night or during a weekend. A variety of products can be produced by changing the raw materials and operating condition even in continuous plants. In such plants, sophisticated operations are required to minimize the loss during unsteady-state conditions. Dynamic optimization with discrete variables helps the derivation of such operational schemes. The operability depends strongly on the plant design. For example, smaller holdup makes the dynamic response quicker. Thus, the integration of optimal plant design with optimal operation is an essential problem to solve within the scope of a sustainable chemical industry.

## Conclusion—Future Direction of Chemical Engineering Education

Research in chemical engineering has expanded to areas such as bio-, nano- and environmental technologies. This trend is the same all over the world. In this Perspective, the focus has been on sustainability, and the related engineering problems to be solved have been discussed. These problems address product and process design issues, which are characterized by, small driving forces, low material and energy densities, and/or the processing of solid materials. Although conventional production technologies have been used to tackle the problems in this field, it is abundantly clear that chemical engineering should create new process design engineering approaches and practices, as well as new approaches in operating future chemical plants. The use of dynamic models with sufficient fidelity will become the basis for addressing these problems, i.e., develops methodologies that allow the engineers to carry out process design considering the dynamic operation of plants. Such methods are not yet available and must be developed.

A number of thematic areas of new engineering problems that must be solved by chemical engineers have been discussed in this Perspective. However, it is difficult, if not impossible, to embed all these themes into the educational curriculum of chemical engineering. Taking the aforementioned discussion into account, one may ask: how should chemical engineering education is changed? In trying to answer this question, one needs to recognize several important (and relatively new) factors, such as the following: The diversity of career paths after graduation is continuously expanding. Even in traditional chemical companies, the relative significance of classical petrochemical processes is decreasing, while the production of functional materials such as the parts and intermediates of electronic devices, parts of automobiles is increasing. Indeed, graduates may not even see a distillation column after graduation. Commercially available process simulators, computational fluid dynamics packages, and many other computer-aided tools allow fairly accurate modeling of physicochemical phenomena occurring in a variety of reactors, separators, and other unit operations, some of which are quite complicated in geometry and intrinsic physical or chemical processes. In the milieu of such powerful technological tools, should unit operations and transport phenomena be taught? The authors' reply is "Yes." Through the study of distillation and transport phenomena, the students can learn the concepts of unit operations and modeling techniques. Such concepts and techniques are valid for the synthesis and analysis of new processes. However, teaching methods must be adapted to make room for the classes in advanced fields, as explained in the next paragraph.

As discussed in the section "*Development of Product Design Technologies*," multiscale analysis and synthesis constitute essential tools for new product design. Even though unified approaches for the design of products with desired qualities from molecular level information have not yet been established, the models at each scale and the relationships among the models are well established and should become part of the regular curriculum. Dynamics plays an important role in developing functional materials as well as in operating and controlling the plants. The derivation and treatment of dynamic models at several scales should be taught more intensively. In addition to developing further the modeling capabilities of students, their ability to solve the new and more complicated should be enhanced because it is the basic strength of chemical engineers. To cultivate this ability, project-oriented exercises should be included in the curriculum. The product and process design projects carried out by a group of students contributes to enhancing this problem-solving ability, as does participation in an industrial project.

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