Int. J. Engng Ed. Vol. 9, No. 1, pp. 99–103, 1993
Printed in Great Britain.

0742–0269/91 $3.00+0.00

Chemical Engineering Education in Japan, Germany and America

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Engineering practices in Japan, Germany and America are different and no individual one is arguably the best overall. German programs lead in laboratories, support-personnel, funding, and industrial rapport. The Japanese lead in chemical/molecular orientation and in organization. The United States leads in mathematical and computer applications, and in faculty development. At least equally as important as these purely intellectual aspects, cultural and historical attitudes permeate the educational programs of each nation. Cross-national sharing and enrichment is essential for the optimum education of engineers to lead the global, corporate enterprises of today.

INTRODUCTION

CHEMISTRY has been called the 'enabling science' because of the central role it plays in supporting the pursuit of a better quality of life. Chemical engineering is the professional field that applies chemical and physical understanding to the manufacture of materials, fuels, pharmaceuticals, and even foods that together enhance quality of life. This manufacturing must be both economically and environmentally sound, and this leads to a complex cluster of concerns for sustainable development. Chemical engineering is the action-arm that translates chemical and physical understanding into products and services that create wealth.

Pure chemistry, applied chemistry, and chemical engineering are a whole cloth with no dividing lines. The development and nature of chemical engineering education and its relationship to chemistry on the one hand, and to the rest of engineering on the other hand, has taken rather different pathways in Germany, Japan and the United States. This results in varying strengths that influence the international competitiveness of each nation. The organization of chemical engineering education is generally similar within each country, but not completely so.

UNITED STATES

American chemical engineering was codified in 1915 by Arthur D. Little with the concept of the unit operations when he wrote, 'Chemical Engineering as a science—is not a composite of chemistry and mechanical and civil engineering, but a science of itself, the basis of which is those unit operations which in their proper sequence and coordination constitute a chemical process as conducted on the industrial scale.' The profession thus identified itself, it moved away from chemistry, and universities taught the unit operations of distillation, filtration, extraction, etc. It remained so until the landmark text, *Transport Phenomena* in 1960 initiated a new epiphany devoted to sophisticated mathematical analysis and computer modelling and simulation, that remains today the hallmark of American academic chemical engineering. A love of chemistry and a devotion to that science is sometimes absent, as is even chemical literacy itself. The dominance of mathematical analysis is evident from any issue of the archival journals selected by chemical engineering faculties for publication of their research. This separation from chemistry was also exemplified by a long-time Executive Director of the American Institute of Chemical Engineering (AIChE) who opposed any joint conferences or other ventures with the American Chemical Society.

Initiatives in biotechnology and in materials synthesis are stimulating a renaissance of chemistry, for they demand chemical expertise. Federal government financial resources in these areas have been growing for years, finally leading to major initiatives of the Federal Coordinating Council for Science Engineering and Technology (FCCSET). These FCCSET initiatives would add US$163m and US$271m to materials and to biotechnology respectively in a cross-federal agency coordinated research program for the 1993 fiscal year. Such numbers are powerful stimulants for faculty and for academic departments to enhance their relevant expertise, including that of applied chemistry. Chemical engineering departments are usually part of the college of engineering, but at three institutions, Caltech, Berkeley, and Illinois, chemical engineering is part of the school of chemistry.

GERMANY

Some of the leading programs in chemical engineering in Germany are at Karlsruhe, where there is much emphasis upon linking physical chemistry and chemical engineering, Aachen and Munich. However, chemical engineering, as it is known in the United States, and Japan, is not usually presented as a separate discipline. Karlsruhe and a few others are exceptions. Rather, the German universities offer Chemie (chemistry) and Maschinenbau (mechanical engineering). Technische Chemie (technical chemistry) is sometimes offered by the science faculty, not by the Engineering Faculty, which, at Aachen, for example, includes basic processes and plant design, chemical reaction engineering, heat and mass transfer, and separation technologies. A person trained as a Technischer Chemiker (technical chemist) is essentially a person trained in chemistry but having also a basic understanding of engineering. An Institute of Technical Chemistry and its faculty, are part of the Faculty of Sciences, not a part of the Faculty of Engineering. At Aachen, research in Technische Chemie is built around the catalytic upgrading of low-priced materials as in, for example, Fischer–Tropsch conversion of CO and H_2 into gasoline and alcohols. Also, work occurs on the hydroformylation of olefins and aldehydes, alcohols, or acids. But whatever the specific subject area, the work centers upon chemistry and upon products or processes needed by the German chemical industry.

Verfahrenstechnik (process technology), like Fertigungstechnik, Kunstofftechnik, and others, are major fields of study offered as specialties within mechanical engineering departments. Students of Verfahrenstechnik will typically attend the same lectures as do all majors in mechanical engineering for the first two years, i.e., to the Vordiplom, before separating for the last three years to learn transport phenomena, separation processes, process design, and multi-component thermodynamics. The Diplom graduate (a five-year program) is approximately equivalent to the masters graduate from US or Japanese engineering schools. Research programs in Verfahrenstechnik at Aachen, for example, are similar to those in a chemical engineering department in America or Japan and include such topics as, membrane technology, biomedical technology, crystallization, rheology, liquid/liquid extraction, and multi-component thermodynamics.

Aachen and Darmstadt retain their designation as Technische Hochschulen. Karlsruhe and others have changed their designation to Universität. Schools are frequently large. Aachen, for example, has 18,000 engineering students and awards 1,500 Diplom degrees and 150 Ph.D.s in engineering each year.

There are other major components of the German system that impact on chemical engineering education. The Fachhochschulen, established in 1970–1, produce graduates with greater emphasis upon the more applied aspects of the chemical engineering subject matter. Research at these institutions is concerned with immediate application and with the transfer of new technology into practice. Professors at the Fachhochschulen are involved in applied research, and they can also pursue research at a Universität or Technische Hochhschule as well. Diplom graduates of both types of institutions are frequently more than 25 years of age, and that is a problem. Schooling takes too long.

Although there are other research institutes in Germany, two groups that impact on engineering education deserve special note. The Max Planck Gesellschaft zur Förderung der Wissenschaften (the Max Planck Society for the Promotion of the Sciences) or the MPG has about 50 largely state-financed institutes devoted to the natural sciences, medicine, and the humanities. Some have staffs of several hundred, others just a few staff members, but they are devoted fully to research. MPGs such as Fritz-Haber-Institute in Berlin and the Institut für Kohleforschung in Mülheim are notable for chemical technology. The Fraunhofer Gesellschaft zur Förderung der angewandten Forschung (the Fraunhofer Society for the Promotion of Applied Research) with about 30 institutes, pursues research in the natural sciences and in engineering on behalf of industrial development. The institutes are state supported, with funds equal in amount to their industrial contract research. The goal is to stimulate research on behalf of industry and to speed the transfer of scientific findings from the universities into industry; the result is an increased rate of industrial innovation. As an example, the Fraunhofer Institute für Lasertechnik at Aachen occupies a large, new, and architecturally beautiful building, with all of the latest and best lasers from all manufacturers. It has related material-handling facilities for industrial scale testing and experimentation with laser-based welding, cutting, forming, etc. This institute employs about 200 people, some of whom are affiliated with the university as well as with the institute itself. The laboratories and facilities are excellent. Proprietary work is readily done.

The Federal Deutsche Forschungsgemeinschaft (the German Research Society), the DFG, provides grants for fundamental research in response to proposals from professors, in a way reminiscent of the American National Science Foundation (NSF). Some 25% of research funding at Aachen is from the DFG. The Bundesministerium für Forschung und Technologie (Federal Ministry for Research and Technology), the BMFT, supports research that addresses immediate national goals. BMFT is more industrially-oriented in the work it supports than is the DFG. The Alexander von Humboldt Foundation that awards fellowships and prizes to researchers from abroad has a major impact on German education, including engineering education. One program brings distinguished foreign scholars in all fields to work for extended periods at a university or institute in Germany. The foundation maintains lifelong contact and rapport with its Fellows. So, today there is a growing number of outstanding scholars from all over the world who have deep intellectual ties with their German counterparts. This is a strikingly positive contribution to German intellectual life.

Some patterns are evident. German companies want multicultural and multilingual engineers. Aachen seeks exchange programs with universities in other countries for about 10% of their 1,500 engineering graduates per year although now only about 1% are so involved. For every 100 German students in the United States, there is about 1 American student in Germany. Only about one-third of the universities offer programs in technical chemistry, so better bridging between chemistry and engineering is still an unmet goal. DECHEMA, the Deutsche Gesellschäft für Chemisches Apparatewesen, Chemische Technik und Biotechnologie, in Frankfurt is the leading German organization in chemical engineering and it is an excellent example of success in bridge building. German universities produce about three times as many Ph.D. scientists and engineers each year as industry can absorb for doctorate level research. It may be difficult to develop co-operative ventures on a campus because each professor is so autonomous. The tradition of a few very autonomous professors does not foster the fullest development of all the faculty, for some excellent people never get the chance to become professors. Unlike American practice, candidates for German professorships must have industrial experience, and some become a professor and institute director having had *only* industrial experience.

JAPAN

The universities of Tokyo, Kyoto, Tohoku, and Osaka are among the best engineering schools in Japan. These are national universities directly supported by Monbusho, the Ministry of Education, Science and Culture. An academic department in Japan is composed of several koza, or chairs, which usually consist of a professor, an associate professor, an assistant professor or lecturer, perhaps two research associates, and five to six graduate students. There are usually two or three times as many masters as doctoral candidates. Engineering students constitute about 20% of all undergraduates, about 50% of all masters candidates, and about 15% of all doctorate candidates in Japanese universities.

The University of Tokyo was founded in 1877, and engineering was established immediately, and that faculty now has 22 departments covering all fields of engineering. There is a Department of Chemical Engineering with seven koza, but in addition, in Engineering there are departments of Industrial Chemistry with eight koza, Synthetic Chemistry with five koza, and Reaction Chemistry with five koza. In the senior year, each student selects a koza for his graduation thesis, is assigned a desk, and he or she becomes one of the laboratory members concerned with both experimental and computer work. The Industrial Chemistry Department specializes in applied quantum chemistry, intelligent materials, industrial analytical chemistry, applied laser spectroscopy, and bioorganic and bioinorganic chemistry. The Synthetic Chemistry Department specializes in catalysis and surface chemistry, chemical sensors, synthetic organic chemistry, chemistry of nitrogen fixation, biologically important polymers, electrochemical conversion of light, and photoelectrochemistry. The Reaction Chemistry Department specializes in combustion science, fire research, aerothermochemistry, chemistry of energetic materials, free radical chemistry and biochemistry. The Chemical Engineering Department has specialties typically found in American colleges of engineering including catalysis, transport phenomena, ultrafine particles, fluidization, and membrane separations.

Engineering at Kyoto University began with the founding of the university in 1897, and engineering is today a major component of the campus. The Chemical Engineering Department of seven koza is very similar to an American counterpart. Like Tokyo, there are however some programs that are distinctly unlike German or American practice. The Industrial Chemistry Department of eight koza has typical specialties of natural product chemistry and industrial analytical chemistry. The Hydrocarbon Chemistry Department of seven koza studies the physics and chemistry of catalysis. The Polymer Chemistry Department of eight koza studies polymer synthesis, properties, radiation effects, etc. The Synthetic Chemistry Department of six koza has typical specialties of bioorganic catalysis, synthetic organic chemistry, and free radical chemistry. The Molecular Engineering Department of seven koza studies quantum molecular science and technology, molecular design, etc. These are parts of the Faculty of Engineering. There is also research and education in chemistry as a basic science in the Faculty of Science.

Kyoto also has koza in engineering devoted to very practical subjects including transportation engineering, global environment engineering, foundry technology, and welding engineering. In summary, engineering at Kyoto offers very practical programs, programs equivalent to American practice, and sophisticated programs found only in chemistry or physics departments in Germany and the United States with a basic science, as opposed to an application, orientation. Very notably, Professor Kenichi Fukui, of the Engineering Faculty at Kyoto, won the Nobel prize in chemistry in 1981. Colleges of engineering are broader than those found in either German or American colleges.

The Engineering Faculty at Tohoku University, located in Sendai, abolished its departments of chemical engineering and of applied chemistry in 1988 to reorganize in a form to give greater emphasis to the relevance and impact of chemistry, and biochemistry, on the economic well-being of the country. The two new departments, each of eight koza, are Molecular Chemistry and Engineering, and Biochemistry and Engineering, and together they present much more than is found in a typical Chemical Engineering Department in the United States or in Verfahrenstechnik in Germany. These departments offer undergraduate courses across the whole field of chemistry, chemical engineering, and bioengineering. These occur in the final two years while the first two years are devoted to a more liberal-arts intensive curriculum. There is a senior research project with a goal of training students to be independent engineers. Graduate students may take advanced courses from the Engineering Faculty in organic, inorganic, physical, biological, biomimetic, biophysical, analytical, quantum, structural, ceramic, and macromolecular chemistry. In addition, classes are offered in process control, separation, catalysis, heat and mass transfer, fluid mechanics, and computer-aided engineering. Across this panorama, engineering students take lectures in accordance with their preferences. The masters program, of rather fixed two-year duration, requires a research thesis; the doctorate is exclusively research-oriented and usually requires three years beyond the masters.

The Engineering Science Department has a Chemistry Division with three koza devoted to theoretical chemistry, electrochemistry, scanning tunnelling microscopy, and organometallic chemistry. These are all within the Faculty of Engineering. There are more koza in the Science Faculty that are devoted to basic chemistry. In addition, at Tohoku there is an Institute for Chemical Reaction Science of about 180 faculty, students, and staff organized in eight koza. Each accepts students from basic science as well as undergraduate and graduate students from engineering. Typical projects in the institute include: molecular design of selective extractants, synthesis, properties, and reactivity of π-electron compounds for molecular electronic devices, enantioselective catalysis, and molecular design of biomimetic functions, such as photosynthesis.

Osaka University, was founded in 1931, the Faculty of Engineering began in 1933, and it now has 20 departments with a total of 128 koza. Interestingly, within the Faculty of Engineering, there are seven so-called 'common koza' including three devoted to statistical mechanics and quantum mechanics, physical chemistry, and statistical mechanics of gases and liquids. Chemical engineering at Osaka is part of the Faculty of Engineering Science charged with going beyond state-of-the-art practice in engineering to develop new types of creative (right-brain) engineers to complement the more usual analytical (left-brain) engineers. One koza within chemical engineering, called Molecular Engineering, is devoted to studies of the electronic structure and reactivity of organic intermediates and to kinetics. Osaka tries to emphasize the development of interdisciplinary fields. Osaka also has about 15 institutes and centers devoted to research in subjects such as oncology, molecular immunology, materials synthesis and processing, protein biosynthesis, welding, laser ignited thermonuclear fusion, and superconductivity.

Some patterns are evident. The Japanese structure in engineering education strongly reflects the reality of chemistry as the enabling science of much of modern technology. Certainly, all these things are also studied in German and American universities, but in Japan these subjects are major themes of koza in engineering. Professors enjoy high status in Japanese society. Assistant or associate professors are not independent scholars, they have no voice on the Faculty Senate, no chance for independent funding, and little chance for promotion due to lifetime employment practices. The koza works as a team with the professor in charge.

Half to two-thirds of baccalaureate graduates continue to graduate school, unlike American experience where perhaps 20% will continue. Research projects undertaken by a koza support perceived national needs, but there seems to be little, although growing, interaction between faculty and industry. University laboratories are poor by German and American standards. In contrast, industrial laboratories are world-class; MITI laboratories are in between.

Japanese engineers must be technically broad, while American companies seem to be narrowing their focus to concentrate on core businesses, Japanese companies, like, for example, Kobe Steel, are expansive, moving into areas where related engineering skills are needed. There is concern for the image and appearance of research as well as with its technical merit. Each koza gets is basic funding on a formula basis that covers all salaries and indirect costs. It may also submit brief proposals to cover direct costs in pursuing more expensive projects. Japanese universities seem oriented toward education for industry, and they seek to double the number of foreign students by the year 2000. The not-invented-here syndrome seems non-existent, with a willingness in Japan to adopt a new technology from anywhere and then to apply it effectively to produce new products. Government laboratories support industrial needs and national projects while many government laboratories in America tend to do basic research. Companies hire few university doctoral graduates; over 40% of doctorates are awarded for company-based research with little or no formal advanced course work.

SOME SUBJECTIVE CONCLUSIONS

Some comparisons which represent the author's subjective judgement follow. German laboratories and support-personnel are by far the best, America second, and Japan a distant third. The merging of sophisticated mathematics and computer usage into chemical engineering education is best in America, followed by Germany, and then Japan. The merging of chemical and molecular thinking into chemical engineering education is significantly superior in Japan, followed by Germany, and America distinctly third. Industrial involvement of faculty is greater in America and in Germany than it is in Japan. Funding of individual university research programs is best in Germany, with America second, and Japan a distant third. The intellectual integration evident in engineering education, and certainly including chemical engineering education, is superior in Japan with Germany and America second. But it is an integration not yet come to fruition.

A relative comparison of factors influencing the quality of chemical engineering education appears in Table 1 where the relative rankings are not changing other than for the growth in chemical and molecular understanding in America.

Table 1. The nature of chemical engineering education

Important factors	German	Japanese	American
Laboratories	10	3	7
Support-personnel	10	3	6
Math/Computer	7	5	10
Chemistry/Molecular	6	10	7
Funding	10	5	8
Organization	7	10	7
Industrial rapport	10	4	8
Faculty development	7	4	10

Rankings are on a scale of 1 (poorest) to 10 (best).

A central concern in chemical engineering education is for creativity or innovation. Which system of education seems to foster these essential characteristics? The locus of innovation in chemical engineering is in applied chemistry, molecular thinking, and intellectual integration. The organization of engineering education would lead one to expect the Japanese to be leaders, but they really are not. By contrast, the American chemical process industry produces a positive balance of trade exceeding that of any other industrial sector in America. Perhaps the absence of Japanese leadership results from the chemical industry having not been given a national emphasis as have, for example, automobiles and consumer electronics, where Japanese innovation and design frequently lead the world. Perhaps the lack of a national agenda for the chemical industry is related to the sensitivity of the selling price of chemicals to raw material costs. Japan has no raw materials.

Analysis of a specific outstanding innovation may help illuminate national differences. A central function of chemical engineering is separations, and the atomic vapor laser isotope separation process (AVLIS) is a sophisticated innovation in this area. It utilizes the slight difference in ionization potentials of atomic isotopes and the sharp monochromatic energy available from a properly tuned laser. Here only one isotope is ionized by the laser irradiation of the mixture and an imposed electric field causes the newly formed ions to drift to a collecting electrode. The laser process has been installed in a pilot plant. Data suggest it to have both installation and operating costs of about 10% of conventional gaseous diffusion technologies in separating ^{235}U and ^{238}U. Laser separation is the process of choice. A graduate of which national chemical engineering program would be most likely to produce such a beautiful and successful innovation? The process was in fact developed in America but by physicists and not by American chemical engineering graduates. But it could have been developed by Japanese graduates in engineering. At least the relevant koza are present in the Japanese colleges of engineering. A similar postulate could be made of probable leadership in adapting chemical and molecular insights in other innovations by Japanese chemical engineers. The same innovation might well come from America or from Germany, but there the responsible persons would most likely have been scientists rather than engineers.

Educational practices in the three nations are clearly different. One cannot label any one of them as the best, but it is clear that each can profit from a diligent consideration of other national experiences. Engineering practice in industry is increasingly global, while chemical engineering educational practice, at least in America, remains largely parochial. Educational programs can be improved from cross-national comparisons and enriched by cross-cultural experiences from student and faculty exchanges. Both are essential for the education of the global engineers of the future that are so sorely needed by German, Japanese and American firms.

Henry McGee was trained as both a chemical engineer and a physical chemist, and his research, teaching and writing continues to reflect this dual orientation. He is Professor of Chemical Engineering at Virginia Polytechnic Institute and State University where he has served ten years as Department Head. He is on loan to the National Science Foundation from 1990–3 where he serves as Director of the Chemical and Transport Systems Division with responsibilities for budgets and priorities in a program of research grants serving both chemical and mechanical engineering departments. His latest book, *Molecular Engineering* (McGraw-Hill) appeared in 1991.