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Editors

CHEMICAL ENGINEERING: VISIONS OF THE WORLD



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Chemical Engineering: Visions of the World

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Preface

The 6th World Congress of Chemical Engineering took place at Melbourne in Australia between 23rd and 27th September 2001. At the initiative of the organisers it was distinguished by the presentation of several “visions” of the future. The visions acted as both guides and discussion pieces for the very many other presentations that were taking place at the Congress, putting that “dazzling array of advances and potential benefits” (Lord May, see Chapter 1) into perspective.

That these visions complement each other is partly by design: each author was given a particular remit, with the intention of covering the whole range of chemical engineering activity and its place in the world, whilst avoiding too much overlap. Some common themes are immediately apparent, and indeed were widely discussed at the Congress. The role of Sustainable Development and the contribution of engineers and companies to it is a feature of all the visions. Changes in industry and in modes of working, the shift of manufacturing to lower-wage economies, and the need to deal with very rapid advances in science and technology, the implications for University courses, exercise the visionaries, just as they did delegates to the Congress. These, and many other issues you will find discussed here.

We are most grateful, as editors, to the authors who contributed to this book, and who have shared with us their wide variety of visions. They are presented here as views from a particular time (September 2001), but as visions of some future period, they are, from their very different perspectives, essentially timeless.

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Chapter 1

Opening Address

Chemical Engineering and Tomorrow's World

Lord May

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This essay set outs some speculations about the changing role of Chemical Engineering in the 21st century. To this end, I first look back — well beyond my own undergraduate experiences of Chemical Engineering at Sydney University in the 1950's — to the earlier shape and traditions of the subject. I then sketch a personal vision of how ever-accelerating advances in our understanding of the molecular machinery of life, and the consequent biotechnological applications, are likely to affect us, bringing both new benefits and new problems. Chemical Engineering, defined more broadly than most current practitioners can imagine and shading into biomedicine, will be at the heart of delivering the benefits, and caught up in most of the problems. Specifically, I will touch on: implications for curricula, and the linked question of attracting adequate numbers of able students; patterns of partnership between academia and industry; questions of intellectual property, and what should and should not be patentable. I will conclude with thoughts about the interplay between science/engineering and society.

1. Changing patterns in the definition of a discipline

Later in this volume, John Perkins gives an excellent account of the history of “the first 100 years” of Chemical Engineering, and Utz-Hellmuth Felcht discusses the more recent past. I would chauvinistically claim for Chemical Engineering the credit, in the mid-19th century, for the first foreshadowing — in the synthetic production of dyes and other chemicals, mainly in Germany — of today's vast and varied enterprise of organised research. One conspicuous difference between those early times and today is often overlooked in such narrative histories. It is the earlier relative

lack of narrow specialisation and, more significantly, of the individual practitioners' sense of being specialists. This difference reaches well beyond Chemical Engineering itself. In the 18th and 19th centuries, the creators of the Industrial Revolution, whether individuals like Wedgwood, Pasteur, Faraday or Armstrong, or small groups like Erasmus Darwin's Lichfield "lunatics", or indeed the Royal Society's members collectively, had interests which reached from basic science through engineering applications to commercial exploitation. Today's discussions, in the UK and elsewhere, of the need to make schoolchildren more clearly aware of the gulf between "science" and "engineering" would, I think, have struck these earlier people as incomprehensible. One striking illustration in support of this view comes from the iconic statues placed at the high flood of Victorian confidence on the Holborn viaduct (a bridge over a sunken road beneath which the tamed Fleet River flows invisibly) in London. Four statues symbolise the bases of prosperity: Commerce, Science, Agriculture, Fine Arts. Each holds a representative object. And what is this canonical symbol of "science" to Victorian eyes? Watt's governor (which today many would not only relegate to "engineering", but to its lower social strata as a regulatory device of steam train engines and other machines).

It is, of course, easy to argue that our hugely expanded body of knowledge has made ever-narrower specialisation inevitable. There is much truth in this. But if this is all there is to it, then the future is ever more fragmented partitioning into sub-disciplines; further proliferation of departments, programmes, and professional societies. The implications for curricula are bad enough. But the implications for the dialogue between science/engineering/technology and the many publics to which it increasingly must relate are worse.

Other views see proliferating specialisation as being driven as much by social forces as by the expanding bulk of bodies of knowledge. Gore Vidal writes cruelly of "squirrel scholars" in academia, fragmentingly focussed on the detailed topology of their own little caches of information, and largely uninterested in any larger landscapes of the life of the mind. Clive James has suggested that some of the more bizarre excesses of specialisation in the humanities represent tacitly agreed academic devices for securing "tenure without talent". It is easy to dismiss such smears as the insecurities of freelance polymaths manqué, and/or to note that they refer to the humanities anyway. But I think the notion of specialisation as, in part, a social construct deserves more thought than it usually gets.

2. Chemical engineering in the 21st century

Regardless of the disciplinary framework within which we view them, most of the things which affect our daily lives remain, as yet, in the idiom of the Industrial Revolution. Most of the materials in everyday use are still made with stuff dug from the ground, wrought in processes powered by fossil fuel energy. And the ranges of

materials which do not fit this wild generalisation (“plastics”, in the memorable opening scene from *The Graduate*) mostly have their origins in the petrochemical industry. Our food, which in the developed world on average costs 10 calories of fossil fuel energy subsidy to put 1 calorie on the table, likewise remains in the Industrial Revolution idiom; plant breeding and genetics may have given us the Green Revolution, doubling global food output on only 10% additional land, but it depended on the Chemical Engineering of fertiliser, pesticide, fungicide and herbicide production, along with other mechanical inputs, for implementation.

The half-century since Watson and Crick unlocked the secret of DNA's double helix have seen astonishing, and still accelerating, advances. With first drafts of the human genome recently published, and work proceeding apace on other plant and animal genomes, we are moving closer to understanding, at the most basic molecular level, how living things assemble themselves. The Industrial Revolution derived from our understanding of how the external, physical world works; from the physical sciences. The life sciences — themselves dependent on enabling instrumentation from the physical sciences (and it would be a costly mistake to forget this) — hold the promise of a new revolution, the Biotechnological Revolution. Ultimately, we will be able to modify the molecular machinery of living things, to create products that work with the grain of nature, rather than being wrenched to our purposed by unsustainable inputs of fossil fuel energy (in effect, stored solar energy from plants of past ages), as the Industrial Revolution did.

A catalogue of specificities immediately does two things. First, happily and most obviously, it suggests a possible future in which health and other benefits may be delivered more sustainably. Second, however, many of these self-same potential benefits raise worries about ethical issues, or about safety for ourselves or our environment, which are not easily answered.

For many, the application of biotechnology that will first come to mind is so-called “GM Foods”. We have, of course, been genetically modifying crops (and animals) since the dawn of agriculture, some ten thousand years ago. But recent developments enable us, on the one hand, to be much more precise in introducing only the new genetic material that is desired (as distinct from “conventional” plant breeding, which even in recent and highly sophisticated forms typically reshuffles something like 10% of a plant's genome, in unknown ways), and, on the other hand, to introduce genes from widely unrelated organisms (which happens also, albeit rarely, in nature and which can be very difficult with conventional plant breeding methods). The possibilities are thus to “design” crops which will be drought or salt tolerant, or resistant to particular pests or pathogens, or even (further off as yet) perhaps fix their own nitrogen and otherwise minimise the need for industrially produced fertilisers, with their often adverse environmental side-effects. Conversely, others fear this will lead to yet more intensive agriculture, realising the ages-old dream of farming where nothing shares our crops — no weeds (plants in the wrong place), no pests (insects with the wrong appetites) — resulting in an ever more Silent Spring. Two things are clear.

First, the delivery of any such potential Biotechnological Revolution in agriculture lies squarely in the domain of Chemical Engineering. Second, in tomorrow's world we cannot leave all the issues to science and technology; the social/ethical/political questions will need full and open airing.

The broadly similar application of genomics to medicine, producing new drugs (antivirals, antibacterials, and other chemotherapeutic agents) and new vaccines, also will involve core skills of Chemical Engineering in the production processes.

Less widely discussed are other likely transformations, whereby today's "brute force" technologies give way to greener biotechnological production methods. Current clean-up of oil spills, for example, which lie mainly in the civil/mechanical engineering idiom, are likely in future to depend on appropriately constructed bacteria or other organic agents. A wide range of other clean-up or restoration processes are, I believe, set to evolve into a major sub-discipline of genomics-based Chemical Engineering.

Perhaps a bit more visionary, many of the everyday materials of the future may be grown — self-assembled from a purpose-designed genetic blueprint — rather than hammered out in Blake's satanic mills. And doubtless, as with GM foods, some latter-day Blakes will see this as even more satanic, the polluting clouds made more frightening by their invisibility. This too, both benefits and worries, will be the province of Chemical Engineering.

In short, I believe the widening sweep of the Biotechnological Revolution has implications for Chemical Engineering practice beyond the dreams of its wildest chauvinists. By way of anticlimax, I now turn to some of the more prosaic implications for the present and near future of the subject.

3. Some implications for the teaching and practice of chemical engineering

3.1. *Curricula*

As emphasised at the beginning of this essay, I dislike those contemporary fashions which seek to create new disciplines, new professional bodies, newly-narrow chartered this-and-that. But the scope of Chemical Engineering, if the above analysis is accepted, is already very wide and set to become still wider, making clear the difficulties for constructors of curricula.

I have no easy answers. Already, 40 years ago at Sydney University, 2nd year Chemical Engineering was widely conceded to be the most difficult year in any subject (with its combination of chemistry, mathematics and engineering subjects). Today, I believe that a Chemical Engineering curriculum must include a basic grounding in what once could have been called simply "biochemistry", but which today must be interpreted to extend from molecular biology and genomics all the way through physical, organic and inorganic chemistry. An introductory acquaintance with basic

organismal biology (ecology and environmental science; biomedicine; plant science) would also be desirable. And understanding the rudiments of evolution might ward off yesterday's many mistakes by underlining that, in the living world, all targets respond to attack by moving (there are no exceptions; all you can do is buy time for the useful life of your pesticide, say, by focussed and frugal use). Then, on top of all that, you need all the basic skills of Chemical Engineering *qua* engineering. Preferably in 4 years at most.

The solution, insofar as one exists, is I believe to aim for broad and rigorous coverage of basic ideas and principles, complemented by a few, carefully selected, applications in depth. Not knowing "everything about nothing", nor "nothing about everything", but a compromise. Easy to say.

The problems in execution are many and varied. They begin with the teacher/researchers. Too many of today's academics wish to teach their own speciality in excruciating detail, and the hell with anything else. Too many professional associations, or particular industrial specialisations, believe that the 11th commandment which Moses dropped on the way down from Mt Sinai was that *their* particular subject area *must* be part of the core curriculum. Too many employers want graduates who can instantly take a place in a particular research project, or managing a specific industrial process (or even running a particular machine), with all the appropriate information at their fingertips; never mind that in three years everything will have changed. The remedy is wider recognition that an engineering degree in general, and especially (given the coming challenges) a Chemical Engineering degree, must be a broad but rigorous preparation for a lifetime in a profession which itself is changing, with respect to important aspects, on a timescale of a decade or shorter. Of course detailed acquaintance with specific examples must be part of education, to endow general principles with a sense of concreteness; but such in-depth examples will leave others (perhaps your favourite area) not covered. Too bad. The alternative is balkanization, and consequent diminishing ability to grasp new and different opportunities.

3.2. *Attracting students*

The problem of declining applications for engineering degrees is worldwide. The problem is one of decline in engineering numbers relative to total enrolment, and in some places it is even an absolute decline (especially if attention is confined to indigenous students). In the UK, for example, in 1975 roughly 3% of all 24-year olds had degrees in science or engineering, and this was about 43% of all university degrees then; by 1996 the total in science and engineering had climbed to 8%, but the overall five-fold increase in university student numbers meant this had fallen to 25% of all university degrees among the 1996 cohort of 24-year olds. And disaggregating science from engineering gives further cause for concern: between 1994/95 and 1998/99, first degrees from UK universities increased 11% overall, but in science only 5.9%, whilst engineering degrees decreased 0.3%.

Given the demand for good professional engineers, we all need to do better. But how bad the situation is depends to some extent on how you present the statistics. Furthermore, the details vary among countries, and among branches of engineering.

All this being said, I think that part of the problem is that the impression given to younger people, both by the media in all its forms and perhaps more importantly in school, is that the sciences — especially the life sciences — are exciting booming areas, whilst engineering is a bit nerdy. The fact, we can all agree, is that Chemical Engineering is right on the cutting edge of the excitement in the life sciences.

So a big part of the solution is, in many different ways, to do a better job of informing young people, through schools and through stories in the media, of the essential indivisibility of pure and applied science; of the seamless vein of fascination and job satisfaction that runs from the life sciences (or “science” in general) through Chemical Engineering (or “engineering” in general). This task is not helped, and the consequent cause of recruitment of able students to engineering is hindered, by those who wish to emphasise some great difference between “science” and “engineering” — a difference that, as emphasised above, Pasteur or Faraday would not have recognised.

3.3. *Partnerships between academia and industry*

With the pace of current advances in basic research in the life sciences, and the frequent closeness between fundamental discovery and its application, close partnerships between academics and industrialists are increasingly common.

In this context, the first thing to recognise is that the simplistic paradigm of new technology emerging as a result of blue skies research, although very often true, is by no means invariable. The causal arrow can go either way. The Second Law of Thermodynamics, acquaintance with which was seen by C.P. Snow as the litmus test for the truly educated individual, did not emerge from any curiosity driven, fundamental investigation. Rather, it emerged as a direct consequence of practical studies towards designing a more efficient heat engine. These days, while admittedly fashion, to a degree, requires that basic studies often have a veneer of creatively-acquired “applicability”, an equally common — and happier — occurrence is genuine interplay between practical problems and new science, as academia and industry collaborate, each playing to its own strength. But “each playing to its own strength” is the keynote.

Problems can arise in many ways. One route is when subsets of bureaucrats or politicians decide they should focus basic research money on useful projects only. This is a bit like deciding to invest only in stocks whose value will increase. It may be a sensible general guide to investment policy, but only so long as you realise that, in reality, if you do not have enough failures you are not taking enough risks!

Other problems can arise when university staff find themselves caught up in commitments to teaching, research, supervision of postgraduate students, and also active participation in commercial development of an idea. No harm is this, provided the university has very clear rules, widely disseminated and rigorously enforced, about

conflicts of interest, well-being of students at all levels, and amounts of time that university faculty can devote to external activities. Handled well, such tooing-and-froing can enliven a research group, a department, a university. Many US universities, with a wealth of experience, illustrate this well. But if, lacking experience, such adventures are undertaken in an existential and unplanned fashion, unhappiness is likely to result.

3.4. *Patents and other intellectual property*

With rising numbers of university-industry partnerships, cooperative research centres, and the like, there come questions of ownership of intellectual property (IP). It is a subject rife with misunderstanding.

For one thing, income from IP is never more than a small percentage of annual turn-over, even in the most successful universities (for example, less than 2% at MIT in the late 1990's, and 3.8% at Heriot-Watt, one of the UK's very top performers in this category). For another thing, and somewhat contrary to the first, an important recent study by Narin et al. [1] shows that publicly funded research — predominantly in universities — accounted for 73% of all papers (46% US, 27% “foreign”) cited in US industrial patents in 1993–1994; the corresponding sectoral breakdown is 79% for patents for drugs and medicines, 76% for chemicals, through to a low of 49% for electrical components. Notice that, broadly speaking, Chemical Engineering lies at the end of the spectrum where publicly funded basic research is the predominant inspiration for patent-based products.

There is no paradox here. The results of most basic research are, by their nature, unforeseeable and often unownable. Eventually, such new knowledge inspires inventions and applications, leading to new products. But the chain is usually long and complex, which is why the discoveries in basic papers are so cited in patents, yet usually with the direct financial benefits accruing to subsequent development.

The reason I emphasise these seemingly peripheral issues is that, as mentioned above, in a lot of contemporary molecular biology the connection between basic discovery and subsequent invention or new product can be unusually close. Nowhere is this more true than in sequencing the human genome: the detailed map of all the genes which provide the codebook whereby a human is self-assembled from a single fertilised egg. This enterprise is one of the most significant intellectual achievements of all time. Yet, despite the immense complexity and expense of the sequencing enterprise itself, its outcome remains a discovery, not an invention much less a product. For this reason, essentially everyone in the science community believes the sequence data, as such, should not be patentable.

This view was set out clearly on 14 March 2000 in a joint statement by Clinton and Blair (heads of the Governments of the two countries whose scientists were responsible for roughly two-thirds and one-third of the sequencing, respectively): “To realise the full promise of this research, raw fundamental data on the human genome,

including the human DNA sequence and its variations, should be made freely available to scientists everywhere. Unencumbered access to this information will promote discoveries that will reduce the burden of disease, improve health around the world, and enhance the quality of life for all humankind. Intellectual property protection for gene-based inventions will also play an important role in stimulating the development of important new health care products.”

Underlying this statement is the fundamental principle that the raw sequence data, as such, is discovery and thus not patentable, whilst subsequent elucidation of the structure and function of specific genes, and development of products from this understanding, is invention and thus patentable. Not only does this accord with basic patent law as seen by most experts, but it also has important benefits both for scientific advance and for commercial development: the pace of scientific advance has always been favoured by free and open exchange of basic discoveries; commercial inventions based on subsequent explicit elucidation of the workings of particular genes will have clear commercial protection as the intellectual property of the investor.

There is also, in my opinion, a moral dimension to this argument about the human genome. But I rest on the essentials of patent law, along with the advantages to science and commerce.

However, as most readers will know, there are current attempts to claim intellectual property rights over bits of sequence data whose function remains undetermined. Such attempts (unanimously characterised as “sleazy” by an expert panel at the World Economic Forum in Davos) rest, in essence, on the grounds that computer searches have tentatively identified some such sequence fragments as having superficial similarities to other fragments whose coding functions have been determined. Supporting the Clinton–Blair statement in arguing against the validity of such claims, the Presidents of the US National Academy of Sciences, Bruce Alberts, and the UK Royal Society, Aaron Klug, have written: “In our opinion, such a [computer-search based] discovery should not be rewarded with a broad patent for future therapies or diagnostics using these genes when the actual applications are merely being guessed at.” Apart from anything else, the result is likely to be that, once the function of a full gene sequence has been properly understood, and a specific application developed, the individual or institution doing the real work could be besieged by co-claimants for intellectual ownership. Good news for the lawyers, but very bad for the sound and speedy development of tomorrow’s biotechnology.

In summary, I have ridden this hobby horse because I join many others as seeing these issues as being much more than ego-driven squabbles on the frontiers of genomics, but rather as deep questions for the future of an emerging industry which could, *inter alia*, transform great swathes of Chemical Engineering.

4. Science and engineering in society

Science has expanded more in the past half-century than in the sum of all previous human history. Engineering has translated this understanding into applications, in both developed and developing worlds, which create wealth and improve the quality of life. Trite though this mantra may sound by now, we should remember that — as George Orwell emphasised — clichés are usually compact phrases which ring true. Increasingly, however, we recognise unintended adverse consequences from our well-intentioned actions: witness climate change and loss of biological diversity. More regionally, we fret about the ethics of, and/or the risks from, new technologies such as the GM crops, cellular phones, therapeutic uses of stem cell cloning, or xenotransplants.

In the UK, and more generally, every week seems to bring a new committee, debate, or report on “science and society”. And a very good thing too. I believe we need to do a better job of deliberately asking what kind of world we want — subject to the opportunities offered by scientific advances and the constraints that science clarifies — rather than just letting things happen.

There is much misunderstanding of public worries about new technologies, which are too often attributed to scientific ignorance, to be cured by better “public understanding of science”. In fact, well-designed EU studies show that those countries whose citizens score best on substantial tests of scientific literacy are exactly the countries where ambivalence about the benefits of scientific advance is greatest. A recent poll shows that 84% of Britons think that “scientists and engineers make a valuable contribution to society”, and 68% think that “scientists want to make life better for the average person”. But the nub, as the same poll showed, is that roughly 50% thought the pace of current scientific advance was too fast for government to keep up through effective oversight and regulation. In short, the belief I set out in the preceding paragraph seems to be fairly widely shared.

So, how best to conduct the dialogue, as old as democracy itself, between government policymakers and the public in complex scientific areas, in a way that fosters trust? Perhaps chauvinistically I begin with the principles set out by the UK Office of Science and Technology, and recently reaffirmed both by a House of Lords committee on Science and Technology and by the Phillips Inquiry into the history of Bovine Spongiform Encephalopathy (BSE): consult widely and get the best people, but also make sure dissenting voices are heard; recognise and admit uncertainty; and above all, be open and publish all advice. Try to separate risk assessment from risk management, and aim at management that is proportional to the risk involved. Wherever possible, make the facts and uncertainties clear, and leave it to individuals to choose.

All this is, of course, easier said than done. Even when risk can be assessed, people's subjective views may be different (people feel that cars are safer than trains, even though they are more than a hundred times more dangerous). And often the questions are outside the envelope of known science, and the risks can only be guessed at. This

is especially awkward for a public that experiences science — in school, in university, and on TV quiz shows — as the crisp certainties of established knowledge, not the unknown terrain at or beyond the frontiers. It is easy to say “let all voices be heard”, but many will bring other agendas to the debate, and the resulting babble of voices is uncomfortable for a civil servant used to confidential, anonymous, and consensual advice to a minister. However, these admitted and awkward costs of wide and open consultation, and of open admission of uncertainty, are outweighed by their trust-promoting benefits. And anyway, the world that deferred to authority, advised by confidential cabals, has gone. I do not mourn its passing.

Many of these themes are developed in more detail by Robin Batterham later in this book. The essential idea is clear: we need more explicit and open debates about the world we wish to create from the opportunities scientists and engineers are offering us. These are debates about values, beliefs, feelings even. Scientific authority has no special voice in these value-laden debates. Where the voice of science is, however, crucial is in clarifying what the choices and constraints really are; in excluding cloud-cuckoo land from the range of viable options. The essential ideas of this process may be clear, but obviously many devils lurk in the details. And we are still low on this learning curve.

One thing is sure. Many among the dazzling array of advances and potential benefits which are on show at this 6th World Congress on Chemical Engineering will have difficulty in being realised if general public assent is not secured through thoughtful and open discussion. And this is how it should be. Tomorrow’s world will be better for it. Unfortunately, the most difficult technical problems of Chemical Engineering look slight beside the difficulties of conducting such socio-political debates engaging heart with head, democratically reconciling values — often passionately held values that come from the heart — within a coldly rational framework of what the scientific facts and uncertainties are.

Reference

- [1] F. Narin, K.S. Hamilton and D. Olivastro, *Res. Pol.* 26 (1997) 317.

Chapter 2

Chemical Engineering — the First 100 Years

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1. Introduction

In attempting to construct a set of visions of the future, it helps to understand how chemical engineering came to be. The objective of this chapter is to outline the development of the discipline and profession of chemical engineering starting from origins in the last part of the eighteenth century.

Five periods will be discussed. In the first, some initial conditions will be established. The one hundred years to 1880 saw the emergence of a substantial chemical industry, and of the new science of chemistry.

By 1910, people calling themselves ‘chemical engineers’, some of whom possessed a university qualification in the subject, existed, and the American Institute of Chemical Engineers had been formed.

By the close of the Second World War, chemical engineers had proved their worth, and an independent academic discipline of chemical engineering with a substantial body of codified knowledge underpinning it had been established.

In the 1950s and 1960s, chemical engineering expanded around the world. Many university departments of chemical engineering were founded during this period.

In the modern era, beginning in the 1970s, the profession has faced many challenges arising from the maturation of our traditional industries and from societal pressures. At the same time, chemical engineers have come to the realisation that their unique combination of knowledge and skills equips them to address a very broad range of important opportunities.

2. 'Initial conditions' (1780–1880)

In a sense there has always been a chemical industry. For many centuries, people have wanted 'chemical products' such as soaps, dyes, medicines and poisons. Such things were traditionally made on a small scale and were of little general significance. However, the arrival of the industrial revolution in Northern Europe in the last decades of the eighteenth century boosted activities such as soap-making, glassmaking and textiles production, and brought with it a significant growth in the production and consumption of chemicals. Some figures for Great Britain illustrating this growth are shown in Table 1.

The Lead Chamber process for the manufacture of sulphuric acid was developed in the 1740s by John Roebuck, then based in Birmingham. Production of this key commodity rose steadily. By the 1820s, British annual production had reached 10,000 tons of 100% acid. By 1900, Britain was producing one quarter of the world's output with an annual production approaching one million tons.

Demand for alkalis for glassmaking and soap-making, for textile dyes and for bleach was growing rapidly in the second half of the eighteenth century, and it became clear that existing sources would not be sufficient. In response to a prize established by the *Académie des Sciences*, Nicholas Leblanc had devised by 1791 a method for converting common salt into soda ash, which was to become the central operation of the world alkali industry for about one hundred years.

In parallel with these industrial developments, the conceptual basis of the science of chemistry was being established. Lavoisier, in his *Traité Élémentaire de Chimie* published in 1789, enunciated the principle of conservation of mass: 'Nothing is created. . . and one can set a principle that in every process there is an equal amount

Table 1
Growth of chemicals production in Great Britain during the 19th century

Year	1801	1841	1881
Consumption of raw cotton ('000 tons)	24	195	638
Production of soap ('000 tons)	22	70	215
Production of major chemicals ('000 tons)			
Sulphuric acid (100%)	4	150?	780
Alkali	–	100?	480
($\text{Na}_2\text{CO}_3 + \text{NaHCO}_3 + \text{NaOH}$)			
Bleaching powder	0.1	10	132
Synthetic dyestuffs	–	–	2

From [1].

of matter in the beginning and at the end of the process' [2]¹. The atomic theory was developed in the first half of the nineteenth century by John Dalton, Jöns Jakob Berzelius and others. By 1850, chemical scientists had at their disposal workable assumptions regarding the structure of matter, and laws to describe observed chemical phenomena.

With the emergence of the science of chemistry and of a burgeoning chemical industry, the most appropriate education and training of technical personnel became an issue for countries in Northern Europe and in North America during the nineteenth century. Different nations adopted different approaches to this issue, depending on a whole variety of cultural and other factors.

France was the first of the European nations to institute technical education on a large scale, building up its system of *Grandes Écoles* throughout the nineteenth century. The most prestigious of these, and a model for further developments both in France and elsewhere, was *École Polytechnique* founded during the French revolutionary period in 1794. Several of these *Grandes Écoles* graduated engineers with the title *ingénieur chimiste*². To what extent the French system represented an effective way of providing appropriately trained manpower for the emerging chemical industry was a source of debate both at the time and since (Guédon, 1980). On the one hand, the existence of programmes in 'applied chemistry' both in the *Grandes Écoles*, and later at the *Facultés des Sciences* established in a number of cities in France, would seem to provide a strong base. On the other, it has been argued that the emphasis on theory and analysis in the *Grandes Écoles* mitigated against the proper development of chemistry, and of applied chemistry in particular, in the French education system.

The situation in Germany was rather different, and by the end of the nineteenth century came to be regarded as a model of good practice both in France and in Britain. By that time, an extensive system of well-funded technical education existed alongside the universities. Further, the ability of the German chemical industry to make use of the output from these institutions was quickly established on a scale unknown elsewhere. However, it is possible that the characteristics of the German chemical industry which facilitated the strong relationship with the education system also discouraged the early growth of modern chemical engineering as a separate discipline in Germany. A heavy chemical industry did not develop in Germany to any great extent during the nineteenth century, because it proved difficult to overcome older and better established competition in other countries, most notably Britain. Instead, an industry relying on a high level of scientific input, first in synthetic dyes and later

¹Lavoisier's contribution to the principles of chemical engineering has been claimed by some to go beyond this. For example, Villiermaux [3] credits him with anticipating the concept of 'unit operations' in an address to the National Convention of the French Revolution in 1793.

²For example, Gustave Eiffel was a student at *École Centrale* in the 1830s, where his family background (in the vinegar trade) was instrumental in his decision to take in his final year the speciality of *chimiste*. I am grateful to the current Deputy Director of *Centrale*, Daniel Grimm, for providing me with this information.

in other complex products such as pharmaceuticals, developed. As a result, the importance of knowledge of chemistry was emphasised, and it was widely believed that an education in that subject should not be ‘diluted’ through addition of elements of engineering. A strong advocate of the division of labour between chemists and engineers was Carl Duisberg, a leading figure in the German chemical industry (Duisberg, 1896, quoted by Guédon [4]):

‘In opposition to many of my friends I place myself ... on the standpoint ... that the chemist does not require [engineering] as a necessity. Nothing, in my opinion, is worse than to make of a chemist an *ingénieur-chimiste* as is done in France, or a chemical engineer as is very often done in England. The field of chemistry which the chemist has to master is at present so enormous that it is practically impossible for him to study at the same time mechanics which is the special field of the engineer. Division of labour is here absolutely necessary. I leave to the engineer and to the chemist their respective sciences, but I desire that both work together.’

Although the cradle of the Industrial Revolution, Britain had not capitalised on its leading position to put in place systems of technical education capable of fuelling further developments. By the 1860s, this lack had become a source of concern; for example, a significant number of Royal Commissions were set up and reported on the issue (Guédon identifies ten separate inquiries between 1868 and 1900!). In Britain, engineering was by tradition a craft to be learned as an apprentice in the factory. This tradition contrasted sharply with that in France and Germany where the engineer had become a professional with a long training in basic science and technology. The manpower needs of the chemical industry were considered in the latter part of the nineteenth century within a context involving often unflattering comparisons with continental competition.

Nineteenth century chemistry programmes at universities in the United States often included courses dedicated to the description of advances in industrial practice [5]. There was a recognition that the US was developing as an industrial nation, and that education ought to take account of this. Rensselaer Polytechnic Institute was founded in 1824 ‘for the purpose of instructing persons, who may choose to apply themselves in the application of science to the common purposes of life’. The formation of the Massachusetts Institute of Technology in 1865 had the specific aim of establishing a new kind of independent educational institution relevant to an increasingly industrialised America. However, as late as 1880, the US chemical industry was a negligible force. This situation was to change rapidly over the next three decades, as the national economy as a whole grew, and high tariffs restricted imports of most chemical products [1].

Overall, the position in 1880 could be characterised as follows. France, having played a leading role in the development of chemistry and chemical technology in the last part of the eighteenth century, had lost ground, most notably to Great Britain, and was increasingly looking to Germany as a model for the future. Germany had not developed a significant heavy chemical industry, but was instead establishing a

very strong position in the manufacture of more complex molecules, first synthetic dyes and later pharmaceuticals. Having established itself as the leading supplier in the world of alkali based on the Leblanc system, Britain was by 1880 beginning to suffer the consequences of a large investment in what was becoming increasingly outdated technology. There were also concerns about the lack of an organised system for technical education in that country. The US chemical industry was very small by world standards in 1880. However, changes in US economic policy were to drive huge growth over the next three decades. Further, a comparatively young education system was responsive to the needs of US industry.

It is against this background that a number of pioneers began to argue for the recognition of a new kind of professional properly equipped to meet the needs of the chemical industry. The main engine room for these developments was the United States, although earlier developments in Britain made a significant contribution. Thus, the next chapter of our story begins in the North West of England.

3. Origins of chemical engineering (1880–1910)

The chemical industry in the North West of England had achieved considerable success by the mid-nineteenth century [6], but by 1880 the industry was changing. The successful operation of the Solvay process by the Brunner Mond Company in Northwich showed the potential advantages of continuous processes, and threatened to make the Leblanc system uneconomic. The development of reliable dynamos enabled electrochemical processes to be introduced. The small but highly profitable synthetic dyestuffs industry, which had developed in Manchester based on discoveries made at the Royal College of Chemistry in London by Perkin, was coming under increasing threat from the rapidly expanding German chemical industry.

To facilitate discussion of the problems facing the industry, industrial chemists and manufacturers in the region began to seek some sort of society. (There had been a tradition of local organisations where matters of general technical or commercial interest were discussed: the Newcastle Chemical Society was founded in 1868, the Tyne Social Chemical Society in 1873 and the Faraday Society based in several towns in the North West in 1874.) A series of meetings to discuss the formation of a new body was held between 1879 and 1881. Notable in the proceedings of these meetings was a concern to focus the organisation on chemical engineering. At a meeting held at Owens College, Manchester in April 1880, the title ‘Society of Chemical Engineers’ was proposed for the new society. The proposal was carried unanimously, and the name was later ratified at a meeting in December 1880, and used in communications to the press, with the further comment that [7]:

‘It may afterwards prove desirable to found a distinct branch of the Engineering Profession.’

A key figure in these developments was George E. Davis. Davis was born in Eton in 1850 and educated at the Slough Mechanics Institute and the Royal School of Mines, although there is no record of him having secured a formal qualification at the latter. From 1871, he was employed in the North West, first as an analyst but taking increasing levels of responsibility for manufacturing as he moved from factory to factory. In May 1878 he was appointed to the Alkali Inspectorate, a body set up in 1864 to conduct the official inspections of chemical plant to curb excessive pollution required under the 1863 Alkali Act. After his resignation from the Inspectorate in 1884, Davis set up a successful chemical engineering consultancy practice. He died in 1907.

By the time of the inauguration of the Society in April 1881, the title had been changed to ‘Society of Chemical Industry’ (SCI), apparently at the suggestion of Davis, who had been Honorary General Secretary of the Faraday Society and became the first Secretary of the new Society. Davis later gave the reason for this change as an expedient to retain the interest of a number ‘of the professorial type’ that might be ‘left out in the cold’ by a Society of Chemical Engineers. The Society’s interest in chemical engineering was retained in one of its two primary aims:

‘To promote the acquisition and practice of that species of knowledge which constitutes the profession of chemical engineering.’

In an initiative to address the lack of suitable technical education in Britain, the London Livery Companies had founded in 1878 the City and Guilds of London Institute, which had two objectives. One was to provide a system of qualifying examinations in technical subjects. The other was to establish in London a ‘Central Institution’ which would offer a new and more advanced form of technical education. The Central Institution was opened on a site in South Kensington in June 1884, and full-time courses started in February 1885. Professor H.E. Armstrong had been appointed Professor of Chemistry, and he established a three-year course leading to a Diploma in Chemical Engineering, which was publicised in the Chemistry Department’s first prospectus [8]. Armstrong’s course has been discussed in detail by Tailby [9], who concludes that the course ‘was not chemical engineering but a mixture of mechanical engineering and chemistry’. (A similar observation could perhaps be made about many of the early courses [5], including the famous Course X at MIT initiated by Norton in 1888, see below). In any case, by 1887, the Central Institution had resolved that the graduates from this course would not after all receive a Diploma in Chemical Engineering, but in Chemistry.

Almost a century earlier, in 1797, an institution for education in applied science was set up in Glasgow as the result of the bequest of John Anderson, Professor of Natural Philosophy at the University of Glasgow [10]. The institution became in 1828 ‘Anderson’s University’, in 1887 the ‘Glasgow and West of Scotland Technical College’, in 1912 the ‘Royal Technical College, Glasgow’, and much later (1964) the University of Strathclyde. In 1870, the president of Anderson’s University, James

Young, decided to endow a Chair of Technical Chemistry and to fund a new building for a Department of Applied Chemistry at the university. The first choice of incumbent for the new chair was W.H. Perkin (the original developer of coal tar dyes), but he never actually took up the position and was succeeded after only one year by G. Bischoff (1871–1875) and then by E.J. Mills (1875–1901). Mills was born in London in 1840, and studied at the Royal School of Mines, obtaining bachelor's (1863) and doctoral (1865) degrees in science from the University of London. Elected as a Fellow of the Royal Society in 1874, he joined Anderson's College in 1875 [11]. During his tenure of the Young professorship, Mills '*...devoted his attention to developing sound courses of instruction*' [12].

A sample syllabus (from 1888–1889) is given in Fig. 1, which shows that by that year Mills was using the title 'Chemical Engineering' for his course of 24 lectures covering 'the construction and use of chemical plant'. A three-year diploma course in 'Chemical Engineering' was also offered by the Glasgow and West of Scotland Technical College from 1887 [10]. It is interesting to note that the Society of Chemical Industry had a very strong branch in Glasgow, and that Mills was an active member, for example serving on the Glasgow Section committee for a number of years.

A widely recognised event in the development of chemical engineering was the course of lectures given by George E. Davis in Manchester in 1888. These lectures on chemical engineering at the Manchester Technical School were claimed by Davis to be 'the first course of lectures on the subject that have been delivered in the native tongue to the English-speaking race'. (This might be arguable given other developments around that time.) Some of the lectures were published in that year in the *Chemical Trade Journal*, a periodical which Davis himself had founded in 1887. The entire series was not published until 1901 as the first edition of Davis' *Handbook of Chemical Engineering*, and later in the second and enlarged edition of 1904.

In his lectures, Davis analysed the processes of the contemporary chemical industry, presenting them as a series of basic operations. He recognised that 'the chemical processes could be regarded as combinations or sequences of a comparatively small number of procedures'. In the opinion of Warren K. Lewis [13], Davis should 'be given full credit for the initiation of the modern chemical engineering profession'. Davis had recognised that the problems facing the industry were engineering problems, and that the way to train professional leaders is not to emphasise the details of specific industries, but rather to ground the student in relevant scientific principles and how to use them.

Also in 1888, the first course called chemical engineering in the United States was initiated. Lewis Mills Norton, professor of organic and industrial chemistry in the Chemistry Department at MIT, developed, organised and ran the course until his untimely death at the age of 38 in 1893. The course was the tenth to be offered at MIT and so was labelled Course X. Norton had studied chemistry at MIT and completed a

THE "YOUNG" CHAIR OF TECHNICAL CHEMISTRY.

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Fee for the Course—£2 11.

Chemical Engineering.—A course of twenty-four Lectures will be delivered on Wednesdays and Thursdays, at Three p.m., commencing on October 3rd. They will deal mainly with the construction and use of chemical plant, and will comprise the following among other subjects:—

1. Gaseous, liquid, and solid fuel: the conditions and mode of their application. Raising and carrying steam. Preparing water for chemical operations.
2. Open steam, steam coils, and steam jacketed plant.
3. Refrigerators.
4. Open evaporators and their efficiency. Closed evaporators. Stills of various kinds, including stills for fractional distillation.
5. Modes of employing an air-current.
6. Stirring and mixing machinery. Grinding. Squeezing. Crushing.
7. Precipitation. Floating. Washing. Filtering.
8. Sublimation.
9. The materials to be used in the construction of plant to hold chemical liquids of different kinds and at varied temperatures and pressures.
10. Manipulation of large volumes of gas. Apparatus employed in the generation, heating, cooling, scrubbing, and filtration of gases. Impregnation of gases with vapours. Governors.
11. Tanks, cisterns, vats, and tuns.

The Lectures will, as far as possible, be illustrated. The following industries will be referred to:—Distillation of tar and liquor and obtaining of tar products. Brewing. Spirit manufacture. Gas manufacture. Aerated waters. Pigments. Soap. Paraffin oils, scale, and candles. Purification, boiling and storage of vegetable and animal oils. Alkali manufacture.

Fee for the Course—£2 11.

Fig. 1. A syllabus from Glasgow and West of Scotland Technical College, 1888–1889³.

PhD at the University of Gottingen in Germany in 1879. He returned to the US first to join Amoskeag Manufacturing Company. After two years, he joined MIT as a faculty member, where his research was oriented largely towards practical applications.

³I am grateful to Professor Colin Grant of Strathclyde University for his help in providing information on Mills and his courses.

Norton's experience caused him to recognise the engineering problems faced by the chemical industry. He stated the objective of his new curriculum in chemical engineering as to give the students 'general training in mechanical engineering and at the same time to devote a portion of their time to the application of chemistry to the arts, especially to those engineering problems which relate to the use and manufacture of chemical products.' Most of the instruction was given in subjects already offered in the chemistry or mechanical engineering curricula. However, one course, given throughout the final year, was only given to the chemical engineering students. Called 'Applied Chemistry', it presented 'a discussion of the appliances used in manufacturing and applied chemistry, considered from an engineering point of view'. Warren K. Lewis' [13] view was that this course represents 'the first course in unit operations ever incorporated in an organized curriculum in chemical engineering.'

Several other chemical engineering courses were established in the USA before the end of the nineteenth century (University of Pennsylvania 1892, Tulane University 1894, University of Michigan 1898, Tufts 1898). As it happens, all of these courses were established in Chemistry departments, although later, courses also emerged from other existing disciplines, e.g. from Mechanical Engineering, University of Colorado 1904; Electrical Engineering, Wisconsin 1904; 'Sugar Engineering', Louisiana State University 1905 [5].

By the early 1900s, the complexion of the US chemical industry had changed significantly in comparison with that of 1880. Further, its character was different to its European competitors, either through its focus on high volume products (in comparison with Germany and France) or through the use of more modern manufacturing processes (cf. Britain) [14]. This rapid growth led to an increasing need for a class of professionals.

Personnel with the appropriate skills for the rapidly expanding, high volume American industry were initially unavailable. The education and training of those traditionally employed by the industry: industrial and applied chemists, were widely criticised in the early years of the twentieth century. For example, M.C. Whitaker complained in 1904 that the chemist was 'generally not a man who is capable of transmitting from a laboratory to a factory the ideas which he has developed'. At the same meeting, J.B.F. Herreshoff complained that chemistry students left college 'not knowing of mechanical engineering and were totally unfit to take positions as works managers or wherever it became necessary to apply chemistry in a large way.'

In October 1905, R.K. Meade published an editorial in his newly founded journal '*The Chemical Engineer*' asking 'Why not the American Society of Chemical Engineers?'. Meade argued that a discipline of chemical engineering had been slowly emerging with several colleges offering courses with that title. He estimated that there were at least 500 chemical engineers in the United States. A professional society might help convince manufacturers that chemical engineers should design and operate their plants and would promote the exchange of ideas to mutual advantage. Meade reprinted this editorial in March 1907, and followed it up with a letter to 50 chemists

and chemical engineers seeking support for the formation of a professional society for the emerging discipline. Encouraged by the response, Meade took responsibility for organising a meeting to discuss the subject.

This meeting took place in June 1907; eleven participated including Meade himself. The major outcome of the meeting was the formation of a six-man committee to consider further the advisability of forming a society for chemical engineers, to correspond with interested parties, and establish membership criteria. This committee sent out 600 questionnaires during 1907, and received 187 responses. Seventy per cent of respondents favoured formation, and 87% considered that high membership requirements were desirable. Despite this very positive response, the committee felt unable to move to formation of a society on its own. Instead, 50 chemists and chemical engineers (including some known to be opposed to the idea) were invited to serve on a committee to consider the formation of a society.

The new committee (or at least 21 of its members) met in New York in January 1908. Records of the meeting indicate that there was a lively discussion of the issues with strong views for and against being expressed. Leading the opposition was M.T. Bogert, then President of the American Chemical Society. Bogert presented ACS' plans to set up a Division of Industrial Chemists and Chemical Engineers as well as to found a Journal of Industrial and Engineering Chemistry. On the other side, the need for an intermediate discipline lying between chemistry and mechanical engineering was expressed, as well as for engineers qualified to design and operate large-scale manufacturing facilities in the chemical industry. J.C. Olsen, who acted as secretary to the committee, argued that the new ACS Division was too broad and therefore could not accomplish the same goals as a society 'composed of men who can be called strictly engineers'.

Given the strength of opposition expressed at the meeting, it was deemed appropriate to ballot the entire membership of fifty. Thirty-six people chose to vote in the ballot — 22 in favour, 7 against, with 7 neutral votes. Armed with this positive outcome, the Committee of Six decided to proceed to a meeting to set up a new American Institute of Chemical Engineers. Over one hundred invitations to the meeting were issued, but only nineteen attended in Philadelphia in June 1908. Nevertheless, a constitution was approved, and officers elected. The first President was Samuel Sadtler, and John Olsen was elected Secretary, a post he was to hold until 1927.

Thus, by 1910, the use of the term 'chemical engineer' had acquired a certain currency both in Britain and in America. Courses had been set up at universities in North America⁴, although there were not as yet very many independent Departments of Chemical Engineering (Wisconsin, formed in 1905, Toronto in 1908 and Purdue in

⁴Courses in chemical engineering were established in the early years of the twentieth century in Canada [15]. The 1902–1903 calendar for the School of Mining affiliated with Queen's University includes a four year BS programme; this course produced its first graduates in 1906. The University of Toronto made a similar announcement in 1904.

1911 could claim to be the first.) The rapid expansion of the US chemical industry had exposed the need for a new kind of professional properly equipped to deal with large-scale chemical manufacturing. After careful deliberations, an American Institute of Chemical Engineers had been set up to promote the cause of the new profession.

4. Defining a new profession (1910–1945)

A major focus of the early work of the new Institute was *education* [14]. In his keynote address to the founding meeting of AIChE in June 1908, Charles McKenna declared:

‘But the noblest aim before us, gentlemen, the one which most amply justifies us before all the world, is our ambition for the enlightenment and ample equipment of our successors: that is for the improvement of the training of the chemical engineer of the future.’

A Committee on Chemical Engineering Education was established at the first regular meeting of AIChE in Pittsburgh in December 1908. It was charged with determining just what the education of a chemical engineer should include. It proved difficult to reach a consensus on this issue, however. Reporting on its work in December 1913, the Committee noted that opinions expressed were ‘varied and often apparently mutually antagonistic’. As a result, the Committee felt unable to bring forward specific recommendations for a curriculum in chemical engineering, but instead expounded some anodyne general principles which should guide the construction of such a curriculum. They also proposed that a study of all existing courses in chemical engineering should be undertaken by the Institute. However, owing to competing priorities in a young and small organisation (the AIChE had only about 200 members at the time) and the impact of the First World War, this project was deferred for five years.

Another effect of the War was an acceleration in the growth rate of the American chemical industry, in response to the unavailability of products traditionally imported from Germany. In the wake of this expansion, the number of universities offering chemical engineering courses, and the number of students studying chemical engineering, increased significantly. In 1910, 869 students were enrolled in chemical engineering courses; by 1920, enrolments had reached 5743 [13]. So, when a revitalised Committee under the chairmanship of Arthur D. Little began to survey universities, it found a much larger and more diverse provision than that prevailing in 1914.

Little was a consultant who had formed in 1900 in Boston the firm of Little and Walker, later to become Arthur D. Little, Inc. Although not a faculty member at MIT, he was an influential alumnus (having graduated from the chemistry course in 1885) and a close associate of William Walker, who played a key role in the establishment of chemical engineering at that institution (see below) [16]. He served as President of AIChE in 1919.

Little is credited with first coining the phrase ‘unit operations’ in a report to the President of MIT prepared in 1915:

‘Any chemical process, on whatever scale conducted, may be resolved into a co-ordinate series of what may be termed “Unit Operations”, as pulverising, dyeing, roasting, crystallising, filtering, evaporation, electrolysing, and so on. The number of these basic operations is not large and relatively few of them are involved in any particular process. The complexity of chemical engineering results from the variety of conditions as to temperature, pressure, etc., under which the unit operations must be carried out in different processes, and from the limitations as to materials of construction and design of apparatus imposed by the physical and chemical character of the reacting substances.’

The unit operations approach sharply delineated the domain of chemical engineering and clearly distinguished it from industrial or applied chemistry and from mechanical engineering. Industrial chemistry had focussed on products, applied chemistry on the individual reactions employed in manufacturing and mechanical engineering on machinery; none had a focus on processes or recognised the operations common to a whole variety of products, reactions and machinery. As such, the concept of unit operations was key in the efforts to establish an independence for the fledgling profession and academic discipline of chemical engineering.

Little’s Committee conducted a very thorough survey of existing chemical engineering courses, and by the end of 1920, 78 institutions offering courses in chemical engineering had been identified. Their findings indicated a ‘bewildering’ number of subjects being required in chemical engineering curricula, ‘great variations’ in the relative weight given to courses, and ‘little evidence’ of anything like a standard course. Little concluded that a radical change in courses and teaching methods ‘appears to be desirable if not imperative’ [14]. Little’s final report on his committee’s work was presented to the Institute in 1922. The report declared:

‘Chemical engineering... 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 co-ordination constitute a chemical process as conducted on the industrial scale.’

The committee recommended reduction in the multiplicity of subjects included in existing curricula, the avoidance of specialisation by industry, standardisation of nomenclature, and the provision of a strong foundation in chemistry, physics, mathematics and chemical engineering to students.

The Little report was enthusiastically received by the Institute, who immediately sought mechanisms to encourage the implementation of its conclusions. After a successful discussion meeting with educators held in May 1922, a new Education Committee was set up charged with continuing to study chemical engineering curricula, with persuading institutions to accept the conclusions of the Little report, and with publishing from time to time a list of those institutions whose programmes in chemical engineering were considered satisfactory.

Reporting on its work in 1925, the Committee listed fourteen schools meeting its standards, and recommended that a permanent standing committee be established to

take forward the accreditation activities of the Institute. This recommendation was accepted, even though the decision generated a fair measure of controversy [14]. AIChE accreditation standards emphasised the importance of unit operations as the core of chemical engineering curricula, and favoured the establishment of independent departments in engineering schools rather than sub-departments within chemistry departments. As a result, pressure was brought to bear on those involved in the provision of chemical engineering courses throughout the US to promote the position of chemical engineering as an independent discipline.

The growth in chemical engineering education brought with it the need for textbooks expounding the principles of the subject. A number appeared in the early 1920s both in North America, and in Britain where education in chemical engineering was reviving, albeit on a part-time basis, after earlier false starts [17]. Notable in the latter were contributions by Norman Swindin, who had worked closely with George E. Davis from 1901 until the latter's death in 1906 (for example taking a leading role in the preparation of the second edition of the *Handbook*), to a book series called the *Chemical Engineering Library* published by Benn Brothers [7]. The series consisted of some three dozen small books and was edited by Hugh Griffiths then responsible for chemical engineering courses at Battersea Technical College⁵ [18].

However, the most significant of these early texts in terms of establishing chemical engineering as a separate discipline and profession was Walker, Lewis and McAdams' *Principles of Chemical Engineering*, first published in 1923. The book was based on the curriculum that had developed at MIT. William Walker received a bachelor's degree in chemistry from Pennsylvania State University in 1890 and a PhD at Göttingen in 1892. After two more years at Penn State, Walker became an instructor in analytical chemistry at MIT. In 1900 he resigned to join Arthur D. Little in the consulting firm of Little and Walker. Two years later (in 1902) he was recalled to MIT to look after the chemical engineering course, and 'immediately started the transformation of the chemical engineering curriculum. His first objective... was to focus, not on the equipment and current methods of industrial production, but on the underlying principles, mastery of which would put the engineer in a position to transform existing methods and to develop progressively more effective techniques. His second objective was to make the treatment quantitative' [13]. Warren K. Lewis had entered MIT as a student in Mechanical Engineering in 1901, but a year later transferred to the Chemistry Department to study chemical engineering under Walker. After completing a PhD in Germany, and a brief period in industry, Lewis returned to MIT in 1910 as Assistant Professor in Chemical Engineering. When Chemical Engineering became a separate department in 1920, Lewis was appointed as its first head, a position he held until 1929. William McAdams completed an MS in chemical engineering

⁵A course of evening lectures in chemical engineering had been initiated by J.W. Hinchley at Battersea in 1909. When Hinchley was appointed to a full-time position at Imperial College in 1917, Griffiths took over responsibility for the Battersea course.

at MIT, following qualifications in chemistry from the University of Kentucky. After a year in industry and a year of military service, McAdams returned to MIT as a faculty member in 1919 [16,19]. Walker, Lewis and McAdams' book 'set the course for chemical engineering' [18]. In the preface to the first edition, the authors set out their objectives for the book:

'In this book we have attempted to recall to the reader's mind those principles of science upon which chemical engineering operations are based and then to develop methods for applying those principles to the solution of such problems as present themselves in chemical engineering practice.

...So far as is now possible the treatment is mathematically quantitative as well as qualitatively descriptive.'

In the next two decades, a significant number of texts were published. In the USA, McGraw-Hill launched its Chemical Engineering Series in 1925, under the auspices of an Editorial Advisory Committee which included Lewis, Little and Walker, and Wiley followed suit soon after [20]. Almost all these texts were concerned with the physical operations of transport processes and solids processing. While the first edition of Hougen and Watson's 'Chemical Process Principles' was published in 1930, it did little to restore this balance. It was to be more than 20 years before a book dealing specifically with reactor design would appear treating the subject as Walker would have wished, applying principles of science to the solution of problems in a quantitative fashion. As Freshwater [17] has noted, 'it is remarkable but true that as late as the 1950s one could graduate as a chemical engineer without knowing anything about chemical reactor design'.

The role of AIChE in helping to develop and promote the profession of chemical engineering particularly through its educational activities has been discussed. In the years immediately following the First World War, chemical engineers in Britain also sought to set up organisations better able to promote the cause of chemical engineering [7]. The supply of chemical munitions had been central to the waging of the war, and eventually well over one thousand technical personnel with chemical and engineering backgrounds were mobilised in Britain to work on satisfying the demand. As a result, the potential importance of professionals able to design and operate large-scale chemical manufacturing facilities received greater public recognition, and gave renewed impetus to campaigners promoting chemical engineering.

The first attempt in this period to establish a more effective organisation to help the cause in Britain was the formation of a 'Chemical Engineering Group' (CEG) under the auspices of the SCI. We have seen that the SCI had been formed in 1880, partly: 'to promote the acquisition and practice of that species of knowledge which constitutes the profession of chemical engineering.' In July 1918, seventy SCI members attended a meeting to discuss the formation of a group devoted to chemical engineering as a specialism. One of the leading campaigners was John Hinchley, who became the first chairman of the CEG. Hinchley had studied at the Royal College of Science and the Royal School of Mines in London in the 1890s. After periods of employment



Fig. 2. Membership of chemical engineering organisations (all grades) (from [7], p. 298).

both in England and overseas, including a spell as technical head of the Siamese Mint, where he was instrumental in establishing the Royal Engineering Society of Siam, he returned to London late in 1907 [21]. He set up as a consultant, and delivered evening lectures in chemical engineering at Battersea Technical College. Within two years he was also delivering a substantial course at Imperial College [9]. In 1917 he was appointed to the staff of that institution as a Lecturer, but it was not until 1926 that he became the first professor of chemical engineering at the College.

The CEG was formally constituted in 1919, and by the end of that year could boast some 510 members, whilst AIChE reported a membership of 306 for that year. However, in contrast to AIChE whose membership continued to grow, CEG membership numbers remained static, as shown in Fig. 2.

While the new group was successful in focussing interest and promoting the technical aspects of the subject, it was impotent in developing a professional presence for chemical engineers in Britain's difficult post-war economy. Members of the Group continued to agitate for the formation of a separate Institution. In November 1921, Hinchley organised a meeting, attended by approximately one hundred people who unanimously carried motions agreeing: the desirability of an Institution of Chemical Engineers, the formation of a provisional Institution and the election of a Provisional Committee. Hinchley was elected Convenor of the latter, and was to be Honorary

Secretary of the IChemE when it was formally incorporated in December 1922 until his death in 1931 at the age of sixty.

To celebrate the twenty-fifth anniversary of its foundation, AIChE published in 1933 *Twenty-five years of chemical engineering progress* [22], a volume documenting the developments in the chemical and allied industries in the first part of the twentieth century, and the contributions of chemical engineers to those developments. Chapters covering a number of sectors of the chemical industry, but also petroleum refining, pulp and paper, food, paints, plastics, glass and water demonstrated that the young profession of chemical engineering was spreading rapidly, and having a significant effect on industrial practice.

In the following year, the first edition of Perry's *Chemical Engineer's Handbook* appeared. Both the editor and his assistant, W.S. Calcott, were chemical engineers working for the DuPont company. DuPont had in 1929 set up a chemical engineering group at the Experimental Station in Wilmington, Delaware under the direction of T.H. Chilton. The group was charged with providing authoritative information for the design of process equipment and selection of materials of construction. The *Handbook* was one major outcome of this development. The preface states that

'This handbook is intended to supply both the practicing engineer and the student with an authoritative reference work that covers comprehensively the field of chemical engineering as well as important related fields. To ensure the highest degree of reliability the co-operation of a large number of specialists has been necessary; this handbook represents the efforts of 60 contributing specialists.'

Most of the thirty sections dealt with unit operations. Approximately one third of the contributors were based in universities, one third were DuPonters and the remainder represented other industrial concerns [23].

Efforts to codify a discipline of chemical engineering also occurred in Germany in the inter-war years [20]. *Chemische Ingenieur-Technik*, a 2200-page treatise displaying attributes of both a textbook and a reference work, was published in 1935. Its 24 authors were drawn mostly from industry. By the time of its publication, its editor, Ernst Berl had transferred to the Carnegie Institute of Technology in Pittsburgh, where he played a part in the development of chemical engineering [24].

Der Chemie-Ingenieur, a twelve volume encyclopaedia of chemical engineering was published between 1932 and 1940 under the editorship of Professor Arnold Eucken of Gottingen and, before he too departed for the USA, Professor Max Jakob of Berlin. The first eight volumes give a scientific treatment of unit operations. Subsequently, physicochemical and economic aspects of chemical reaction operations are treated, including important contributions from Damkohler.

Overall, the situation in Germany in the inter-war years has been well summarised by Scriven [20]:

'So it was that although chemical engineering was *practiced* very well within segments of German industry, and the *discipline* had been compiled in fine scientific form, it could not

propagate without an academic base, nor could a *profession* emerge without an industry that wanted it, or journals for its voice, or a society for its organisation.’

Chemical engineering education became established in a number of countries during this period. In Britain, postgraduate diploma courses were set up in three colleges of the University of London — Imperial College (1910), University College (1924) and Kings College (1928). Imperial and University Colleges introduced undergraduate programmes leading to a BSc degree of the University of London in 1937. A four-year undergraduate programme was offered at the Royal Technical College in Glasgow as early as 1923, but there were only three graduates from that course before 1939.

The term ‘chemical engineering’ had been employed by colleges offering professional education in South Africa since the early years of the twentieth century [25], and a Diploma in Chemical Engineering was offered by the South Africa School of Mines and Technology in Johannesburg as early as 1910. When the University of South Africa, a federal degree-granting institution, was founded in 1918 the former diploma course became a course leading to the Bachelor of Science degree, and this qualification was granted retrospectively to some 100 diplomates. The School of Mines eventually became in 1922 the University of the Witwatersrand with the power to award its own degrees. The first degree in chemical engineering at Cape Town was awarded in the same year.

Pioneers in chemical engineering education in India succeeded in establishing a course with that title as early as 1921 at the Bengal Technical Institute [26]. Both the professor in charge, Hira Lal Roy, and his assistant, Baneshwar Das, had trained in the USA — Roy at Harvard in Chemistry, and Das at Illinois where he had obtained a BS in Chemical Engineering. By the close of the second World War, a confusing variety of courses were in existence, including five year stand-alone undergraduate programmes, two-year postgraduate courses, and courses offered as part of an Applied Chemistry degree.

A chemical industry in Japan developed comparatively late, and was initially dependent on foreign technology. By the 1930s however, a need for chemical engineers was being increasingly felt [27] as a result of the expansion of chemicals in Japan and the Far East. After the outbreak of World War II, it became imperative for the Japanese to develop increased self-sufficiency since it could no longer count on imported technology. As part of a government initiative to address this, the Ministries of Education and Finance and the Japanese parliament approved the formation of two chemical engineering departments at Japanese universities, one at Kyoto and the other at the Tokyo Institute of Technology. Both opened officially on 1 April 1940.

Overall, in the period from 1910 to 1945, there was huge progress in the development of the discipline and profession of chemical engineering, as well as in the chemical industry. Capitalising on an explosive growth in chemical engineering courses in response to the needs of a rapidly growing American chemical industry, the AIChE

led a successful campaign in the USA for a distinctive and independent discipline of chemical engineering. Unit Operations, originally proposed by George E. Davis in the 1880s, but fully developed and promoted aggressively by Little and Walker in the US, became the key element in the conceptual basis of the new discipline. A substantial body of knowledge in support of education in chemical engineering and of practising professionals, also emerged during this period. While the volume of activity was greatest in North America, the need for chemical engineering was also recognised in other countries through the establishment of university courses and departments, and in Britain the formation of the Institution of Chemical Engineers.

5. Sustained growth (1945–1970)

The period following the Second World War was one of sustained and increasingly global growth in academic chemical engineering. New university departments of chemical engineering appeared in increasing numbers, both in countries having a long tradition of education in the subject, and in places where chemical engineering as an academic discipline was a new venture. In Britain, for example, industrial donations played an important part in the expansion of existing departments (Imperial, Kings and University Colleges London), and the establishment of new departments in Cambridge (1945), Leeds (1945) and at Sheffield, Newcastle, Swansea, Edinburgh and Nottingham in the 1950s [7]⁶. In addition, a government committee in the immediate post-war period estimated that in excess of 1200 new chemical engineers would be required before 1950. As a result, the British government decided to invest in a rapid expansion of chemical engineering teaching, resulting in a doubling of the number of institutions offering courses ranging from part-time diploma courses to degree programmes. Similar post-war expansion occurred in Australia⁷, in Canada [15], in South Africa [25] and in Japan [29], for example.

The first institutions in France specialising in modern chemical engineering were also established in the immediate post-war period. Originally founded in 1887, the *Institut Chimique*, part of the University of Nancy, became in 1946 the *École Supérieure des Industries Chimiques*; Professor R. Gibert was appointed to the first chair in chemical engineering at that university in 1952. Meanwhile, in 1949, under the leadership of Professor Cathala, the *École Nationale Supérieure d'Ingénieurs de Génie Chimique de Toulouse* was founded. This development presumably forms the basis

⁶The development of chemical engineering education in the Netherlands was also boosted in the post-war period through a large grant from Shell to the University of Delft [28].

⁷There are records of educational activities in chemical engineering in Australia as early as 1915 at Sydney Technical College, where R.K. Murphy, an American, was the lecturer on a diploma course in 'industrial chemistry and chemical engineering'. Professor T.G. Hunter was appointed to the first chair in chemical engineering, at the University of Sydney, in 1948.

for Cathala's assertion that Toulouse was the first French institution in the field of chemical engineering, or *Génie Chimique* [30].

An entertaining account of the development of academic chemical engineering in Italy is given by Astarita [31]. Astarita argues that Italian chemical engineering developed during the 1950s and 1960s from a tradition firmly rooted in Industrial Chemistry to a leading position in modern chemical engineering through a combination of the efforts of pioneering leaders, notably Natta at Milan and Malquori at Naples, and government intervention.

The post-war development of chemical engineering, with support both from industry and from governments, provides concrete evidence that the early campaigners for a new profession better equipped to meet the needs of the chemical industry had been successful in their goals. By the late 1940s, chemical engineering had become established as a profession and key to the future success of the rapidly growing chemical industry, and both industrial and public investment was forthcoming to try to ensure an adequate supply of future practitioners.

During the first half of the twentieth century, the academic discipline of chemical engineering had been concerned with the development of a body of knowledge based on the concept of unit operations. However, by the late 1940s, it became clear that the scientific principles underlying the analysis of unit operations could be useful objects of study in their own right, and the Chemical Engineering Science (CES) movement emerged to define a new 'era' [32] or 'second paradigm' [33] of the discipline.

In a sense, CES was not a paradigm shift, but a natural development of the concerns of the early pioneers at MIT. Their goal had been to develop and illustrate 'those principles of science upon which chemical engineering operations are based' [34]; the chemical engineering science movement sought to develop and organise those principles, but in a more general context than unit operations.

Key to these developments was the realisation that a more substantial knowledge of the fundamentals of momentum, heat and mass transfer might enable chemical engineers to formulate and solve a wider variety of problems in new areas of activity [32]:

'For 40 years it had been recognised that a scientific approach to the basic principles of the transfer of heat, mass, and momentum applicable to chemical engineering was lacking in scientific and mathematical development. ... With the unlimited number of systems involving thousands of molecular species in chemical processing, it became logical that a theoretical approach be undertaken based upon molecular concepts and transport properties. ... It was also recognised that the separate unit operations each involve a combination of the same basic principles in the transfer of heat, mass and momentum. A scientific approach to chemical engineering should be acquired through these principles. ...'

The publication in 1960 of *Transport Phenomena* by Bird, Stewart and Lightfoot was an important milestone in the establishment of the chemical engineering science approach. Bird and Lightfoot had joined the staff of the Chemical Engineering Department at Wisconsin in 1953. Bird had just spent a summer at the Du Pont Experimental Station in Wilmington, where he had been exposed to a 'large number

of problems in the polymer industry which were difficult to solve, partly because of gaps in the traditional chemical engineering training'. Lightfoot had extensive experience with Pfizer in biochemical processing. Stewart joined the department in 1955, following a doctoral degree with Mickley at MIT (on heat and mass transfer in boundary layers) and six years' experience with Sinclair Research dealing primarily with catalysis and reactor design [35].

The book was the basis for a new course in Transport Phenomena developed at Wisconsin by the three authors in the late 1950s. In the Preface to the book, the authors declare:

'Because of the current demand in engineering education to put more emphasis on understanding basic physical principles than on a blind use of empiricism, we feel that there is a very definite need for a book of this kind.'

As implied by this quote, this group at Wisconsin was part of an international trend to develop a more scientific approach to engineering education and research, not only in chemical engineering, but in all branches. Another important contribution to developments in chemical engineering was that made by Amundson and his group based at Minnesota [36]. Amundson had obtained bachelors and masters degrees in chemical engineering from Minnesota before completing a PhD in the Mathematics department at the same university. By the mid-1950s he had launched a research programme whose objective was to use mathematics to understand the behaviour of many diverse chemical engineering systems, including separation processes and chemical reactors. In reviewing *The Mathematical Understanding of Chemical Engineering Systems — Selected papers of Neal R. Amundson*, John Davidson expressed the view that 'no-one has made greater contributions to chemical engineering science than N.R. Amundson' [37].

Transport Phenomena excited widespread praise and enthusiasm, as well as being a focus for the critics of the Engineering Science approach both at the time and later. In a famous review of the book, T.K. Sherwood (a sufficiently eminent chemical engineer to have a dimensionless group named in his honour!) offered the following [38]:

'This is probably the most important textbook on chemical engineering to appear in many years. . . The book is timely because there is currently a great enthusiasm for the analytical approach, and a helpful text has been wanting. . .

In a sense this is a dangerous book, for it is so well done that it will accelerate the trend towards emphasis on analysis in chemical engineering curricula. The danger stems from the current situation in engineering education, and is in no way attributable to the authors. Process design and conception generally are difficult to teach, but analysis is of no use until there is something to analyse. If perspective is lost through enthusiasm for scientific and mathematical analysis, the engineer will be less effective in industry. The book poses a challenge for someone to produce an equally good text dealing with the *engineering* aspects of chemical engineering.'

Sherwood made his own attempt to provide such a book, when he published in 1963 *A Course in Process Design*, but a more concerted reaction to CES was to

emerge during the 1960s as Process Systems Engineering (PSE) [39]. In contrast to the analytical approach of CES, process systems engineers concern themselves with the synthetic elements of chemical engineering, with the conception and design of process and control systems, and with the effective operation of complex plant and processes.

As with CES, the PSE movement was part of a larger engineering trend in Systems Engineering, which arose from a post-war recognition that engineers were becoming increasingly concerned with the design and operation of complex systems of interacting components. The increasing availability of automatic computers opened the possibility of the use of mathematical analysis and computers as aids to the conception and understanding of these complex systems. In addition, PSE pioneers were concerned to equip students of chemical engineering with modern tools and techniques to help them to design and operate chemical and other process plant.

A major contribution to the development of teaching materials based on a systems approach to design and operation was made by Professor Dale Rudd, also of Wisconsin. Rudd led the development of two fine textbooks addressing the need for a conceptual framework for a systems approach to chemical engineering. The first of these, *Strategy of Process Engineering* was published in 1968. Freshwater, in his appreciation of the literature of chemical engineering, describes the achievement of this book in the following terms [17]:

‘It was the first book to recognise (a) that design was not something picked up by experience but was a formal procedure with its own rules which could not only be learnt by students but could be taught in a rigorous manner and (b) that the chemical engineer needed to know about a whole range of techniques outside the narrow ever more scientific approach of chemical engineering science. Here is a book that truly reflects the practice of the profession in industry far more than any other published in the same time period. Hence... it is a very significant book and will be seen as such in the future.’⁸

Not content with this one pioneering achievement, Rudd was involved in the production of a second significant contribution five years later. *Process Synthesis* [40] appears to be the first text entirely devoted to setting out a conceptual framework and to providing methods to help students to engineer new processes from scratch. The motivation of the authors is made clear in the book’s Preface:

‘Since World War II, engineering education has moved strongly toward analysis, with courses dealing with individual process operations and phenomena. Transport Phenomena, Unit Operations, Process Control, Reaction Engineering, and other engineering science courses greatly strengthened engineering education by showing how things are and how they work. Unfortunately, there was not a parallel development of courses dealing

⁸Freshwater has been a strong critic of the engineering science movement, and his comments should be seen in that light. To what extent his prediction of the value placed on Rudd and Watson’s text by future practitioners has turned out to be true is arguable. The book was certainly influential within the PSE community, but it is almost certainly not as widely known or appreciated today as *Transport Phenomena*.

with synthesis... This deficiency has been recognized for years, but the remedy awaited the development of sufficiently general principles of synthesis about which to organize educational material.'

The tension between analysis and synthesis is key to the health of any engineering discipline, and the existence of the complementary views of chemical engineering in CES and PSE helped ensure the vigorous international development of academic chemical engineering in the 1960s and beyond.

While the expansion of chemical engineering in the post-war years was driven by the potential and problems of the petrochemicals industry (for example polyethylene demand increased by a factor of six between 1954 and 1960), other opportunities were developing during this period. Notable among these was the field of Biochemical Engineering, capitalising on the opportunities to apply chemical engineering knowledge and skills to the development of the growing number of processes for manufacturing chemicals based on biological operations. While there are examples of such processes throughout the twentieth century (e.g. the Weizmann process for the manufacture of acetone and butanol from starch had been in operation during the First World War), it was the Second World War that revitalised the development of biochemical processes and enabled chemical engineers to demonstrate the potential of their contribution to that development.

A major success story was Penicillin [41], whose active ingredient was first isolated by Florey's group at Oxford University in 1940. By 1942, plans for production of this antibiotic in Britain and the US were at an advanced stage. In contrast to the approach taken by British scientists, who replicated the original protocol based on growing mould in a vast number of shallow bowls, the American engineers succeeded in developing a process based on deep stirred tanks of corn steep liquor aerated by oxygen. While some suggested that the manufacturing equipment should emulate the gentle shaking of laboratory flasks in order not to damage the growing mould, engineers from Merck experimented with vigorous mixing under high shear conditions, thereby doubling the yield from the process. As a result of this innovative approach, the USA was able to supply ten times as much penicillin to the UK in 1944 as could be produced by indigenous firms.

On the basis of these and other developments in the mid-1940s, Sidney Kirkpatrick made in an editorial in *Chemical Engineering* in May 1947 'The Case for Biochemical Engineering' in the following terms [42]:

'For almost the first time, the pharmaceutical manufacturers have been faced with the opportunity to use the well-developed techniques and equipment that characterise efficient chemical engineering production. ... They want now to apply the same methods and equipment to other products, but they tell us that they are handicapped by a lack of engineering manpower with fundamental knowledge and experience in biology — particularly bacteriology and biochemistry. ...

... Perhaps we have been too slow in recognising the need for better training of chemical engineers in the border sciences of biology.'

The piece provoked an immediate response from Olaf Hougen, who was then chairman of the chemical engineering department at Wisconsin [43]. Hougen's letter reported on an experimental five-year programme in Biochemical Engineering which was already running at Wisconsin and had 'originated as a result of persistent demands from industrial groups within the state'⁹. Later in the same year, the magazine's Award for Chemical Engineering was made to Merck, in recognition of its development of an industrial fermentation process for the antibiotic streptomycin [22].

Biochemical engineering continued to develop through the 1950s. In Britain, for example, M.B. Donald, appointed the fourth Ramsay professor of chemical engineering at University College London in 1951, had established a collaboration with the biochemist E.M. Crook. By 1958, the reputation of the group was such that the Guinness Company funded the establishment of a lectureship in biochemical engineering and the development of a new postgraduate course in the subject suitable both for graduates from engineering and from the biosciences [44]. In the same year, a course in 'biological engineering' was launched by the chemical engineering department in Birmingham [45]. In the US, five graduate programmes in biochemical engineering had been established by the mid-1960s (Columbia, Cornell, MIT, Minnesota State and Pennsylvania State).

The organisers of the 1965 Fall meeting of AIChE chose as a major theme the application of chemical engineering to biological processing [46]. A continuous stream of sessions throughout the conference programme covered Biological Catalysts, Chemical Engineering and Protein Processing, New Developments in Bioengineering (Growth Cells, Processing of Natural Products), and Cryogenics in Food Processing. In an article designed to promote the conference, a 'New Era' of Bioengineering was foreshadowed, where not only would chemical engineering be exploited in the manufacture of bio-products, it would also be used as a means of 'inquiring into the nature of biological systems themselves' [47]. Such thoughts had been enabled by the CES movement, and were to become increasingly common as the belief of the chemical engineering research community in the uniqueness and power of its toolkit grew.

6. New challenges (1970–)

The twenty-five years following World War II represented a period of sustained growth in industrial production by the process industries, and we have seen that academic chemical engineering developed strongly over the same period. However, subsequent decades brought to light a number of threats to the traditional prosperity of

⁹I have not been able to find information on the subsequent development of this course. Interestingly, it does not feature in Hougen's paper 'Seven decades of chemical engineering' [32]. However, this could be a manifestation of his view that biochemical engineering was not a branch of chemical engineering, but a distinct discipline.

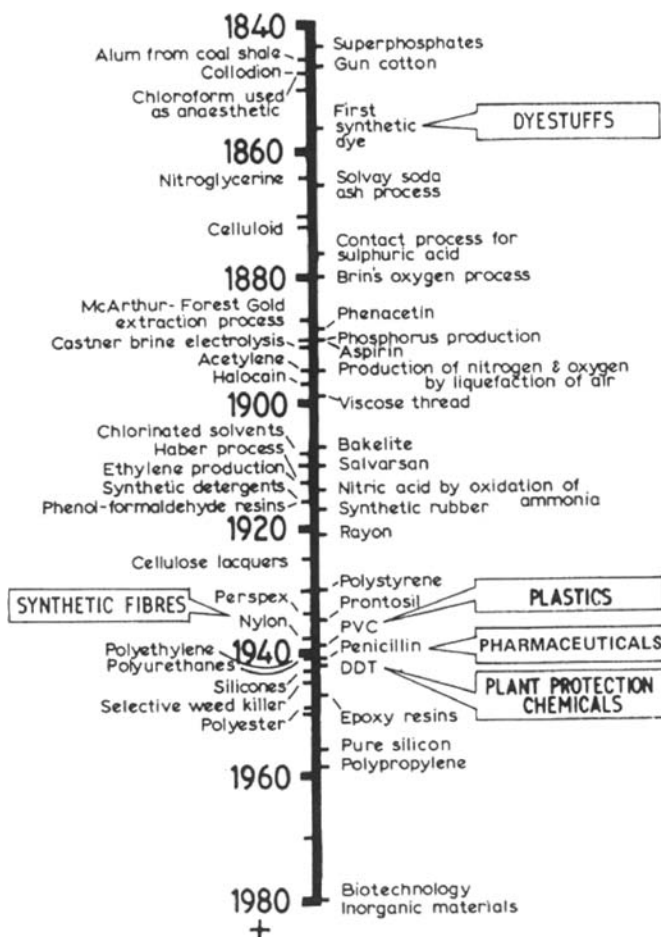


Fig. 3. Major chemical innovations 1840–1980 (from [48]).

the industry, and the resulting challenges impacted on the profession as well as the discipline of chemical engineering.

The post-war growth in chemical engineering had to a large extent been stimulated by the needs of a rapidly growing chemical industry. A retrospective analysis of this growth [48] characterised it as being ‘fuelled by the almost explosive burst of innovations in the period 1935 to 1950 followed by vigorous exploitation of these new fields’. The perception of a lack of major innovations since 1950 is illustrated in Fig. 3. A timeline of major chemical innovations is presented, showing essentially a drying-up of new chemical products since 1960. Whether this analysis is correct in substance or in detail, it represents a widely held perception of the ‘traditional’ chemical industry in the 1970s and beyond.

Adding to the uncertainty about the future was the instability in energy and feedstock costs induced by the price increases and embargo of the Organisation of Petroleum Exporting Countries in 1973–1974. Between 1950 and 1973, energy and feedstock prices had been declining in real terms. It was recognised that this trend could no longer be expected to continue, and as a result, the need was felt to be *‘for unique, high-technology products which were less capital intensive and less dependent on the cost of feedstock and energy’* [48]. In that context, it is interesting that biotechnology and new materials were identified (see Fig. 3) as promising new sectors.

Public concerns about the safety and environmental impact of large-scale chemicals manufacturing facilities have also come to the fore in the modern era. The explosion of the Nypro chemical plant at Flixborough in the UK on 1 June 1974 caused the loss of 28 lives, devastation of the plant and extensive damage to three nearby villages. This and other incidents impacted on the reputation and confidence of the profession, and safety and loss prevention became a subject attracting greater attention in their aftermath. For example, in addition to increasing its learned society activities in the safety area (organising conferences, publishing proceedings and monographs) the IChemE modified its Model Degree Scheme in 1982 to require that safety be a mandatory element in any degree course accredited by the Institution. Further, demonstration of adequate training and experience in safety matters became a compulsory element of applications for corporate membership.

While concerns about the impact on the environment of increasing industrialisation existed from time of the Industrial Revolution (we have already noted the British Alkali Act of 1863 as an early attempt to legislate to control the environmental impact of industry), from the 1960s public concern grew noticeably [49]. One manifestation of this has been the formation of large numbers of non-government organisations (or NGOs), set up to campaign for greater attention to be paid to environmental questions. Also, from the late 1960s, new legislation was introduced, such as the US Clean Air Act (1970) and West Germany’s Emission Control Act (1974). Regulatory bodies were set up to monitor society’s environmental performance, for example the US Environmental Protection Agency (1970), and the French Ministry for the Protection of Nature and the Environment (1971). There has been a growing awareness that many of the issues in this area are global in their impact, and regulations seeking to control emissions to individual media might merely cause environmental problems to be transferred from one place to another. Again, the 1863 Alkali Act provides a striking early example; a reduction in air-borne acid gas quickly led to an increase in water pollution as the liquid effluent from absorption towers was discharged into rivers. Acid rain in Northern Europe provides a more modern and more geographically extended example. Problems of this sort have given rise to the concept of Integrated Pollution Control, enshrined in the 1990 Environmental Protection Acts of both Britain and Sweden. The idea is that the environmental impacts of all pollution control measures should be assessed in an integrated way. As well as consideration of extended spatial effects and interactions, the time dimension has been

Table 2

1960s	1990s
Homogeneous materials	Composite and structured materials
Inexpensive, low performance	High value, high performance
Commodity chemicals	Specialties & biochemicals
Synthesis	Formulation by design
Macroscopic	Microscopic
Large-scale processing	Smaller scale and flexible
Continuous processing	Batch and flexible/continuous and flexible
Process emphasis	Product and process emphasis
Cost competition	Quality competition
Efficient	Rapid innovation and commercialisation
Capital intensive	Information intensive
National	Global
Manufacture	Service and manufacture too!
Short term payoff	Longer term investment
Intradisciplinary	Interdisciplinary
Understanding of macroscale	Understanding microscale and nanoscale and mesoscale

Industry trends (adapted from [50]).

introduced through the concept of Sustainability, where the impact of current activities on the quality of life of future generations is explicitly considered. The response from chemical engineers to these developments has been many-faceted. Chemical engineering researchers have recognised that the complex interactions involved in a proper consideration of environmental issues represent an opportunity to apply the broad science base and systems thinking of chemical engineering to develop an improved understanding. Further, with a growing recognition from industry that more environmental friendly products and processes are just good business, there has been a need to develop new technologies for manufacturing and new approaches to design. The profession has come to embrace its key role in developing a sustainable future, for example through the London Communiqué of 1997, signed by eighteen societies committing professional chemical engineers around the world:

‘To use our skills to improve the quality of life, foster employment, advance economic and social development, and protect the environment.

This challenge encompasses the essence of sustainable development.

We will work to make the world a better place for future generations.’

Against this background, the modern era has been a time of careful reflection about the future of the discipline of chemical engineering. In the USA, the National Research Council published in 1987 its report *Survey of Chemical Engineering Research: Frontiers and Opportunities* [50]. Recognising the underlying trends in the process industries (see Table 2), the so-called Amundson report (named after the chairman of the committee) represents a call to the discipline to realise its potential

Table 3
Research frontiers identified in the Amundson Report [50]

Impact-oriented
Energy and natural resources processing
<i>Critical in long-term; established but needs sustained research</i>
Biochemical and biomedical engineering
<i>Emerging technology; interdisciplinary, glamorous research area</i>
Advanced engineering materials
<i>Emerging technology, interdisciplinary; still specialised, spotty</i>
Electronic, photonic and recording materials and devices
<i>Emerging technology, fast growth, strong competition; attractive opportunities</i>
Environmental protection, safety and hazardous materials
<i>Great public concern, tough challenges; needs concerted research</i>
Cross-cutting
Surface and interfacial (i.e. microstructure) engineering
<i>Ubiquitous, diverse, interdisciplinary; research payoffs in novel processes and products</i>
Computer-assisted process control and process engineering
<i>Fast-advancing technology; core chemical engineering; research payoffs</i>

as ‘the most broadly based of engineering disciplines’ [51], resulting from a deep involvement with chemistry in addition to the application of physics and mathematics common to all engineering.

The research frontiers identified in the Amundson report (see Table 3), confirmed by other contemporary studies (e.g. from the Chemical Industries Association in the UK, and from the AIChE [50]), serve to emphasise the broad scope of chemical engineering, and set a research agenda for the discipline which will keep us occupied for some time to come!

7. Conclusions

The early pioneers of chemical engineering in the last two decades of the 19th century were concerned to establish a new profession to support the needs of a rapidly growing chemical industry. We have seen that their recognition that this new industry faced problems of an essentially engineering nature, and therefore that existing education and training based on chemistry or mechanical engineering would not completely

satisfy industrial requirements, led to the development of a new profession and an independent academic discipline to support it.

This discipline and profession developed as the industry itself grew rapidly, in response to a growing demand from society for the products of the chemical industry. We have seen that the early practitioners of chemical engineering, emerging from university courses in the early years of the 20th century, quickly found employment not only in those sectors of the chemical industry that had originally served to define the need, but also in other parts of the process industries. By the 1930s in North America, the footprint of chemical engineers in industry was already surprisingly broad, and chemical engineers had had a significant impact on practice across a wide range of industries. It is interesting to note that, because of its origins, chemical engineering has always been a graduate profession.

The early conceptual basis of chemical engineering, based on ‘unit operations’, enabled the burgeoning discipline to establish itself as distinctive from courses in industrial or applied chemistry and mechanical engineering. However, in the post Second World War period, a desire to place the discipline on a more fundamental foundation and to broaden its applicability even further, led to the emergence of the Chemical Engineering Science movement, together with Process Systems Engineering to provide a synthetic counterbalance. The confidence engendered by these strong scientific fundamentals combined with systems thinking has enabled chemical engineers to move into an even broader range of activities in the post war years, as well as to identify a bright future for themselves.

The challenge for the future will be to try to ensure that chemical engineering realises its full potential as the broadest and most scientific of the engineering disciplines. The threat is one of ‘opportunity overload’, that we will lose focus, and contact with our distinctive roots, as we try to deal with an ever-growing range of challenges. I hope that this history will give an encouraging message to our profession as it strives with these issues. We have demonstrated an ability to grow and adapt in the past without compromising our essence. This fact should make us optimistic about the future!

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Chapter 3

The Future Shape of the Process Industries

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1. Introduction

Since its emergence the chemical industry has made a considerable contribution towards fulfilling many of our day-to-day needs. We seldom notice many of the everyday products that originated from innovations in the chemical industry because, in the meantime, we have become so used to them. There are many things that we now simply take for granted, such as

- Drugs for humans and animals are products from the chemical industry. They are manufactured by the pharmaceutical industry by means of chemical processes. Even when certain drugs are based on natural active ingredients they have to be prepared into a marketable form by chemical processes.
- From the outside, few people buying a modern car realize the extent to which plastics contribute to the good power to weight ratio and low fuel consumption that we have grown to expect. In the future we can expect to see car bodies completely made of plastic.
- Our most important construction material, cement, becomes water- and weather-resistant through admixtures, not just through steel reinforcement. These admixtures also come from the chemical industry.
- Lacquers, paints and protective coatings are used whenever materials are to be protected from the weather or from wear. Again these products are developed and produced by the chemical industry.

This chapter focuses on the future trends and shape of the chemical industry. Although chemical manufacture is only part of the process industry as a whole, the basic trends also apply to other areas such as minerals, oil, water and food processing.

1.1. *Industry development of the past*

The technological-scientific developments that have taken place in the chemical industry over the years have seen small pioneering production units grow into complex, large-scale conglomerates. Based on the necessary access to raw materials, these small trailblazing factories have developed complete value-added chains for a large number of different products addressing many different applications. The main concern was to develop the products and only then did the companies concentrate on developing the associated markets. From the 1920s we have seen the growth of integrated chemical companies producing a wide range of products as the standard organizational model of the chemical industry. Examples of this are Du Pont and Dow in the US, ICI in the UK, Rhône-Poulenc in France, Swiss based major players in Basel and I.G. Farben, and its successor companies BASF, Bayer and Hoechst in Germany.

1.2. *Restructuring of the chemical industry*

However, since the beginning of the 1990s this picture has experienced a dramatic transformation. The initial spark was the split of ICI in 1993. The pharmaceutical, agricultural and specialty chemicals activities of ICI were separated from the traditional plastics, fertilizer and basic chemicals business and formed into a separate company bearing the new name of Zeneca. In 1999, Zeneca itself experienced a further cell division when the specialty chemicals business became independent under the name of Avecia and the pharmaceuticals division merged with the Swedish company Astra to form AstraZeneca. In the meantime, the remaining ICI has divested itself of almost all of its traditional industrial chemicals business and, since acquiring the chemical activities of Unilever in 1997, is attempting to define its profile as a provider of specialty chemicals even more markedly.

Cell division began in the Swiss based chemical industry in 1995 with Sandoz. It spun off its specialty chemicals business under the name of Clariant, which later merged with Hoechst's specialty chemicals activities. In 1996 we saw the merger of Ciba-Geigy and Sandoz to form Novartis, which focused exclusively on pharmaceuticals and crop protection agents. This was followed by the spin-off of Ciba specialty chemicals, as it no longer fitted in with the life sciences concept.

In the USA, Dow is focusing on industrial chemicals, having handed over its pharmaceutical business (Marion Merrell Dow) to Hoechst in 1995. In 1999 Dow merged with Union Carbide. Monsanto went in the opposite direction, spinning off its chemical business in 1997 under the name of Solutia and focussing entirely on crop protection with genetically modified seeds. Finally, in 2000, Monsanto merged with the pharmaceutical company Pharmacia & Upjohn, forming Pharmacia. The activities in the area of crop protection remain a part of Pharmacia under the name of Monsanto.

In Europe, the Dutch company Akzo merged with the Swedish-based Nobel in 1994 to form Akzo Nobel, which then spun off its fiber business in 1999 under the

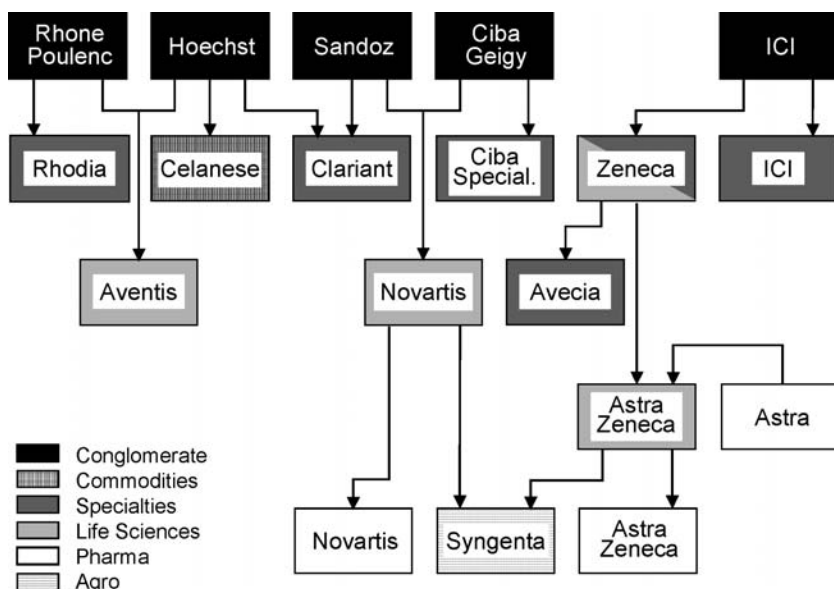


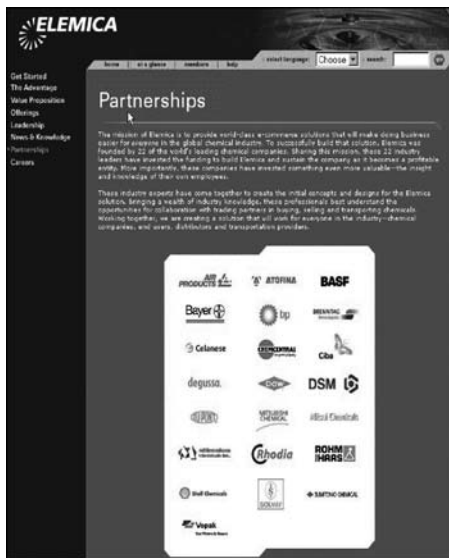
Fig. 1. Development of some major companies in the chemical industry [1].

name of Accordis. In Germany the restructuring of Hoechst had far-reaching effects. This began with the sale of its specialty chemicals division to Clariant in 1995 and culminated in 1999 with the company spinning off its remaining industrial chemicals business under the name of Celanese and the merger of its life science activities with French Rhône-Poulenc, forming the new company Aventis. Rhône-Poulenc had already positioned itself to focus on pharmaceuticals and crop protection agents in 1998 by spinning off its Rhodia chemical activities. Degussa-Hüls, which was formed in 1999 from the merger of Degussa and Hüls, merged with SKW in 2001 to form Degussa, a company that now focuses on specialty chemicals.

But there is no end in sight to these developments, some of which are illustrated in Fig. 1. For instance, companies involved in life sciences have started to divest themselves of their agricultural chemicals business in order to concentrate on pharmaceuticals. Astra Zeneca and Novartis spun off their agricultural business in 2000, merging them into Syngenta.

1.3. Reasons for change

But what are the reasons for these developments at breakneck speed? In 1989 the Iron Curtain fell. The opening of the borders and the collapse of the old Socialist systems were responsible for dramatic changes worldwide. Globalization could begin. Besides the fall of national trade barriers, which was probably only the trigger, decisive communication barriers were removed. Advances in telecommunications, the



(Source: www.elemica.com)

ELEMICA

- Global, neutral marketplace for the Chemical Industry
- Founded by 22 of the leading chemical companies
- Objectives:
 - Bring together chemical industry, end users and distributors
 - Increase process efficiency for product and information flow
 - Reduce supply-chain costs

Fig. 2. E-commerce changes business processes, e.g. ELEMICA.

triumphal march of the personal computer and developments on the Internet led to a broad and open flow of information. Previously closed markets were opened up and there was a dramatic increase in competitive intensity.

For example, in the course of globalization, virtually all of the European and parts of the US textile industry shifted to South East Asia to take advantage of the lower wages paid there. These developments naturally had an effect on the chemical fiber industry. The new development of very large polyester capacities in South East Asia led to overcapacities throughout the world, resulting in deep restructuring upheavals in the traditional locations of the old industrial countries. Similarly, textile dye manufacturers, the nuclei of many chemical companies, were affected. They were also forced to follow their customers and commit themselves increasingly in South East Asia.

However, these changes were observed not just on the customer's side, there were also changes in the competitive environment on the provider side. In particular in India and China a chemical industry grew that was able to penetrate and gain considerable market share in the traditional domain of the European suppliers of intermediates, for coatings, pigments, crop protection agents and pharmaceuticals. Traditional intermediates such as resorcinol and β -naphthol could no longer be produced competitively in Western Europe. Many formerly high-priced specialty chemicals were "commoditised" and put under considerable price pressure.

Currently, trading on the Internet (e-business, e-commerce) is becoming increasingly important, resulting in changes in many companies' business processes. For

instance, in September 2000, 22 of the largest chemical companies founded the on-line marketplace ELEMICA (www.elemica.com), which went online on January 1, 2001 (see Fig. 2). ELEMICA is a global, neutral marketplace on the Internet that concentrates on contract-based transactions in the area of chemical products and bringing buyers and sellers together. The objective is to process global flows of products and information relating to chemicals trading more efficiently and more cost-effectively and thus reduce supply-chain costs. The potential market volume is currently estimated to be approximately €500 billion per year. However, the Internet is creating a much greater market transparency, which in turn intensifies global competition.

1.4. Trends for future developments in the chemical industry

In order to be able to survive in the global competition, companies must develop promising strategies, wherein attention should generally be paid to the following trends

- In many respects, the chemical industry is a mature industry. Many basic patents will soon expire. The fundamental manufacturing technologies will become purchasable. In future, most commodities will be ubiquitously available. Thus, most of the differentiation characteristics that were decisive in the past will no longer play a role.
- The markets for chemicals are well developed. In industrial countries, which have a high purchasing power, people's needs in fields like health, nutrition, communication and mobility are covered to a great extent. The markets are reaching their respective growth capacities. Instead of technological innovations, pure marketing strategies are increasingly significant for the success of selling a product.
- Globalization leads to toughening competition. But the free flow of information and the removal of bureaucratic barriers have not just globalized the market for chemical products and intensified competition. There is also a high level of competition for the decisive production factors of capital and personnel amongst chemical companies as well as the most attractive companies from other industries.

2. Business models of the future

In order to survive in this intensified competitive environment, chemical companies have to specialize and concentrate on their core competencies. The limited capital and personnel resources of a company and the considerable expenditure for future investments which are necessary for a stable and promising competitive position do not permit an equal promotion of all the traditional business operations. Only by concentrating on the most promising operations in the portfolio of a chemical company will it be possible to deploy the limited resources in a targeted fashion in order to improve the company's competitive position.

In the strategic assessment of the different business operations, criteria such as market attractiveness, market size and growth rates, the market position that has been achieved, the technological position, profitability and the strategic fit to other operations, all play a role. Consistent application of these criteria produces an assessment sequence for the individual activities in the company portfolio. This provides management with a basis for investment and divestment decisions. Business activities that no longer belong to the company's core business are divested. Management can then look towards strengthening those activities that are thought to be promising.

In addition to the trend towards specialization and concentration, there is a very noticeable upward trend in size. To be able to play a decisive role in the expanded global markets, individual markets must be developed in a targeted manner. Only companies with sufficient critical mass have the financial resources necessary for this. Even more important, the size factor is highly significant for the company's market and competitive position. Only those companies that are at least number 3, better still number 2 or the absolute market leader can actively compete from a strong position. It is absolutely vital for a company to have a leading market position if it is to achieve stable earnings. In the long term this can be achieved by means of internal growth or, in a much shorter time, by merging with companies that are active in the same field.

The business model of the future will no longer be the broadly diversified chemical company of the past, but rather a provider focussing on the special products of its (few) business operations that have a leading global market position. Depending on the product portfolio, a distinction can be made between various categories of providers (see Fig. 3).

Basically, a distinction can be made between the Molecule Suppliers and the Problem Solvers. Molecule Suppliers include manufacturers of commodities and fine chemicals; the Problem Solvers are companies supplying functional chemicals for technical applications and manufacturers of pharmaceuticals and agricultural active ingredients in the field of life sciences. Both fine chemistry and functional chemistry are utilised in the area of so-called specialties. But what distinguishes these specialties from commodities? In general, commodities are associated with large quantities and small margins, with a high level of cyclicality, while specialties are produced in lower quantities with higher margins, less market cyclicality and higher growth rates.

The Boston Consulting Group has given a more precise definition of the specialties business [2]. According to this group, it is not the method of production, the produced quantity or the necessary applications technological service that is decisive, but rather two other factors. These are, on the one hand, the substitution cost and risks faced by a customer if he chooses a different manufacturer for a specific product and, on the other hand, the absolute cost reduction that could be achieved by the customer in the case of a reduction in the product's purchase price. Thus, specialty chemicals are those where the customer is facing both high change cost and a high risk as well as only low cost savings if he were to substitute the product with a cheaper one. In the

Traditional chemical conglomerates and diversified groups restructure into four types of focused companies:

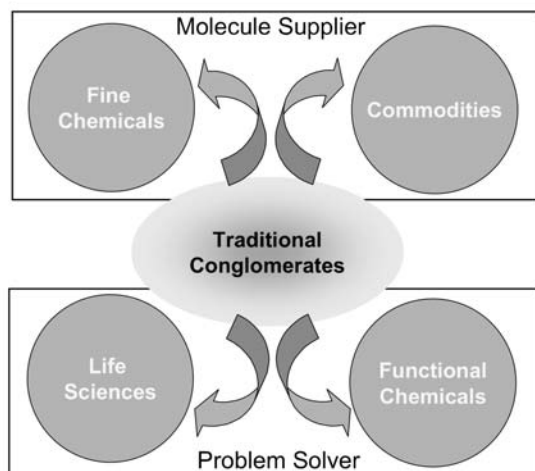


Fig. 3. Business models of the future.

Specialties have a low ratio of purchase cost savings to associated substitution cost for the customer

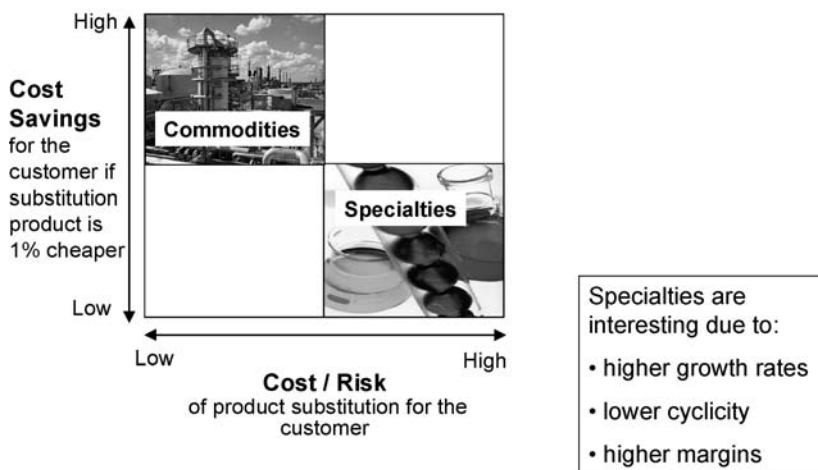


Fig. 4. Definition of specialty chemicals.

case of commodities the cost and risk associated with a product substitution by the customer are low and the cost savings that could be gained by lowering the purchase

price are high. Figure 4 illustrates this distinction graphically, using a system of coordinates based on the purchasing cost savings, and the cost and risks of change. This allows the degree of specialization of a chemical to be estimated.

2.1. Strategic success factors for suppliers of commodities

In the case of these products it is virtually impossible to make a differentiation in the market through product properties. The degree of purity that has already been achieved is very high and adequate for nearly all applications. For a product such as acetic acid, price and availability are the decisive selling points. Therefore, in order to have a good competitive position, a manufacturer of commodities must have cost leadership through leading technology in its manufacturing processes. This requires constant improvement of existing processes and the development of new manufacturing processes. The most cost-effective access to raw materials, and savings in material and energy cost are important factors in achieving cost leadership. These factors require large sites with interlinked processes to give integrated production systems. In addition, it is necessary to develop and optimize a worldwide logistics concept utilizing modern communications as well as information networks (Internet) and to have a presence in the global market.

For companies active in the area of commodities, the following are thus the strategic success factors which determine the product portfolio:

- Sophisticated process technology.
- Utilization of economies of scale in large plants.
- Access to a cost-effective supply of raw materials.
- Energy and material-saving by interlinking of various manufacturing processes in sites with an integrated production system.
- Excellent development of logistic systems for large quantities of materials.

It can be assumed that this concentration process in the area of commodities will result in just a small number of large international groups able to implement the necessary strategic success factors.

2.2. Strategic success factors for suppliers of fine chemicals

In future, intermediates that — in comparison to commodities — are typically manufactured in relatively small quantities will no longer be sold on the basis of their product properties but more and more on the basis of price and availability. Suppliers of fine chemicals will be able to avoid the effects of this “commoditisation” by aligning themselves more towards providing services. The provision of special molecules for the synthesis of specialty chemicals or active ingredients will increasingly be operated as a special service, and the manufacturer of specialty chemicals will begin cooperating with its customer in the research stage. “Custom Manufacturing”

and “Exclusive Synthesis” are the key words used to characterize this trend. Strategic success factors in this business are:

- Strategic development partnerships with the relevant customers.
- The ability to develop complex, multistage organic syntheses fast and efficiently.
- A broad technology portfolio in the key synthesis methods.
- Certified pilot scale and production plants.
- Reputation and image as a competent and reliable supplier.

2.3. Strategic success factors for suppliers of functional chemicals

In the future functional chemicals will play a much more significant role in the chemical industry. Functional chemicals are complicated systems and formulations consisting of various components, which sell because of their application-relevant properties. As opposed to commodities and fine chemicals, the customer does not purchase molecules, but rather an application-relevant effect; the product performance is achieved by means of a targeted design of molecule systems. As a result of this development, the customer is provided with a “high impact additive” which has a very good price-performance ratio and which provides the essential component of his product.

The customer’s requirements dictate the development of products and therefore very special customer-specific solutions will be developed in close cooperation with the customer. Because of this, functional chemicals can be described as problem solvers. The products that are developed cannot simply be substituted by competitors’ products; in other words, in line with our previous definition of specialty chemicals, the cost and risks associated with product substitution are high for the customer. Decisive for the successful marketing of the products is the technology applied, and the implementation of targeted development of a problem solution for the customer.

2.3.1. The concept at Degussa

Our concept at Degussa is to focus on such “High Impact Additives”, which we call “Magic Ingredients”. Our “Magic Ingredients”

- provide a well understood application-relevant effect for the customer,
- are indispensable for the customer’s application,
- are designed in close co-operation with the customer (e.g. strategic alliance),
- are tailor-made for the customer,
- are difficult to be substituted,
- have a good price–performance ratio.

This concept of Magic Ingredients can be illustrated with the following examples

1. Carbon blacks, silicas and silanes from Degussa’s Coatings & Advanced Fillers Division are used in tires to reduce rolling resistance, which reduces the fuel con-

Carbon blacks, Silicas and Silanes as advanced fillers for tires



The Green tire:

- Lower rolling resistance (~ 30 %)
- Less fuel consumption (~ 5 %)
- Improved wet grip
- Better winter performance
- Good abrasion resistance

Fig. 5. The green tire as an example of the magic ingredient concept.

Probiotic Cultures as a major component of Yogurts



Their use is communicated by:

- List of ingredients
- Co-branding on the packaging (e.g. Bioghurt®)

Fig. 6. Probiotic cultures as an example of the magic ingredient concept.

sumption in cars by up to 5%. These so-called green tires thus make an active contribution towards reducing the emission of environmental pollutants (see Fig. 5).

Examples of Magic Ingredients from Degussa

Special Polymers control flow and curing properties of self compacting high-performance concrete

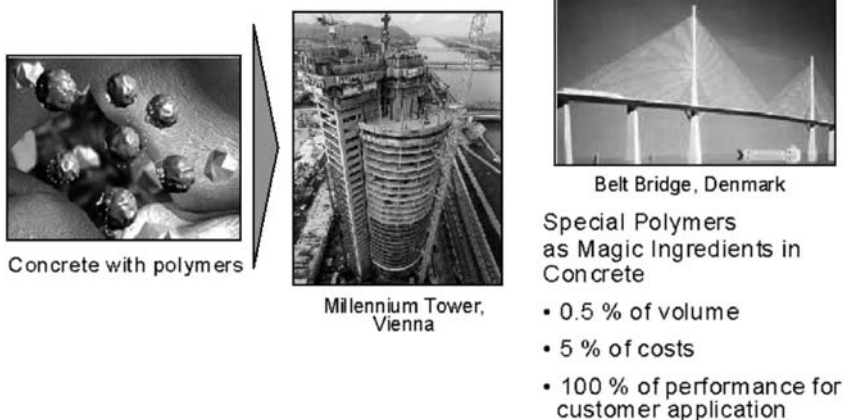


Fig. 7. Special polymers as an example of the magic ingredient concept.

2. Yogurts made with probiotic cultures can have positive effects on the microbiological status of the human digestion system and support the demand of the customer in terms of wellness and healthy nutrition. The Degussa Business Unit BioActives provides the dairy industry with the starter cultures for these products (see Fig. 6).
3. Special polymers from the Construction Chemicals Division of Degussa control flow and curing properties of self-compacting high-performance concrete. This permits concrete constructional elements to be made with a complicated geometry and high level of durability. In this case the polymers — the magic ingredients — only make up 0.5% of the volume of the product and are only responsible for 5% of the cost, but they are absolutely essential for the effectiveness of high-performance concrete (see Fig. 7).

2.3.2. General implications

The strategic success factors for the manufacturers of functional chemicals can be summarized as follows:

- Intensive market knowledge in regard to the customer requirements.
- A number of “magic ingredients” in the portfolio, i.e. products that are decisive for the function of the customer’s system in small quantities.
- Very good technological understanding of the customers systems (“know more than the customer himself”).
- Broad-based, flexible technology.

In terms of focussing on core competencies, manufacturers of functional chemicals will no longer produce all the chemicals of their system solutions themselves in the future, but they will have to reduce their value-chain instead and partly restrict themselves to formulating bought-in molecules in a product system for customers' application.

2.4. Strategic success factors for manufacturers of active ingredients

Due to the high development cost, sustainable business successes can be achieved in the area of pharmaceuticals and agricultural chemicals only during the life-time of patents covering the products, before generic providers appear on the scene looking for market entry through lower prices. Suppliers of Life Science drugs therefore have to concentrate on research, for example clarifying the biomolecular causes of diseases, and pursuing the patentable discovery of specific active ingredients. Then, after long and expensive periods of development, immediately after the completion of clinical trials that statistically prove the effectiveness of their preparation and after its approval by the regulatory authorities, they have to start a very effective global sales and distribution campaign so as not to lose any time in tapping the markets. This is needed in order to recoup the high development cost as quickly as possible before the term of the patent expires.

The strategic success factors for the manufacturers of active ingredients are as follows:

- Clarification of the biomolecular causes of a disease, and a targeted search for a pharmacological effect
- Development of an effective active ingredient (high throughput screening, discovery and optimization of the basic structure, clinical development)
- Patent protection
- Efficient sales and distribution organization.

From a strategic point of view, the traditional chemical production of active ingredients and the associated intermediates plays a subordinate role and is increasingly being handed over to efficient providers from the areas of fine and specialty chemicals. The company's own production facilities are thus available for the manufacture of the end stage of new drugs or they are shut down. For example, a company such as Aventis purchases approximately 500 intermediate stages for its drugs from specialty chemicals companies and about 20% of the active ingredients are manufactured by external companies. By using this strategy the company is able to reduce costs and increase the rate of return on investments. The specialty chemicals companies have discovered a lucrative market as suppliers and problem solvers for the manufacturers of active ingredients. In the next few years (to 2004), annual growth in this area is expected at a rate of about 8%, higher than the growth in the global pharmaceutical market itself.

Restructuring Principle Are Different Strategic Success Factors

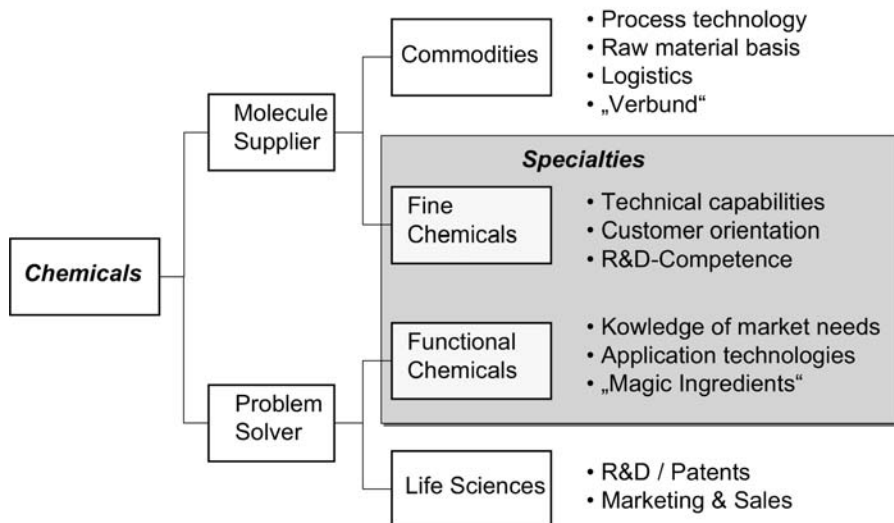


Fig. 8. Business models and their strategic success factors.

2.5. Summary of the business models

Figure 8 summarizes the business models and their strategic success factors.

3. Innovation fields

In order to be able to keep up with the structural changes that are already taking place, a company must deal with the innovative driving forces in a differentiated manner. However, there is a distinction between the Molecule Suppliers and the Problem Solvers in the focus of their innovation fields. As a rule, all innovations are in a three-cornered relationship between the specific technology developments (technology push), market conditions (market pull) as well as social demands (see Fig. 9). None of these three components can act on its own today, and innovation only advances in a network-like system of interaction. In retrospect, the current balance of these components has only been formed in the last 15 to 20 years, and it will change continuously in the future as new technological and social trends emerge.

3.1. Innovation fields for molecule suppliers

The innovation fields for Molecule Suppliers and the technological development pressures on them lie in the interaction of the chemical industry with process and engineering technology. This interaction will lead to new process technologies, which

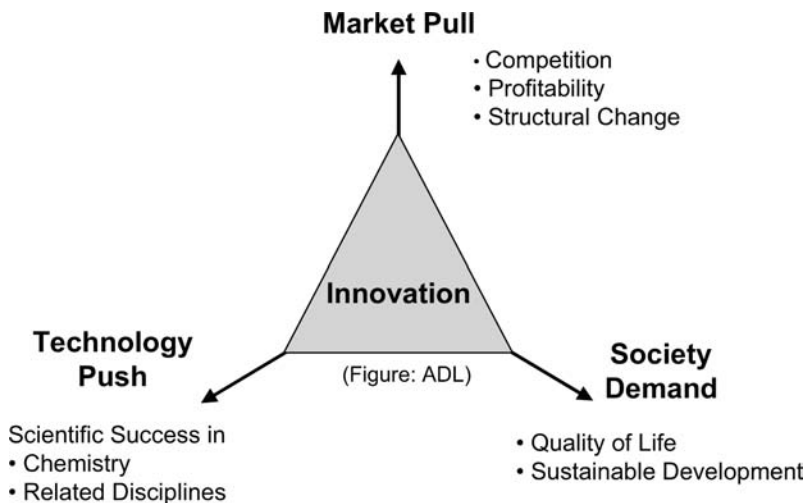


Fig. 9. Driving forces for innovation.

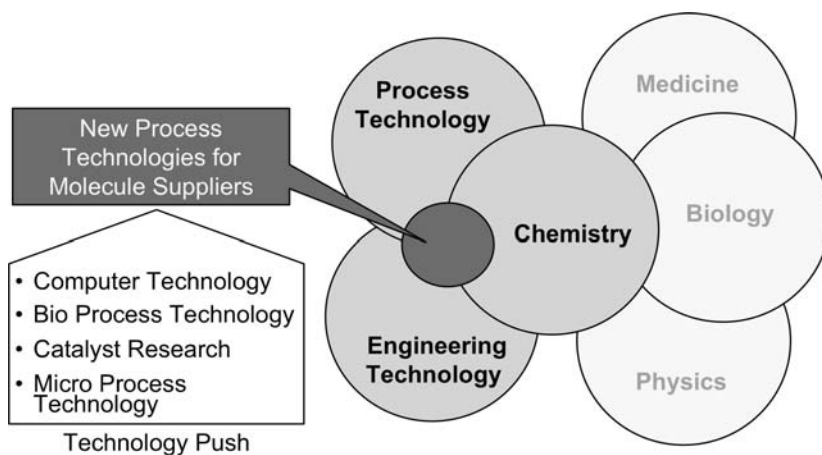
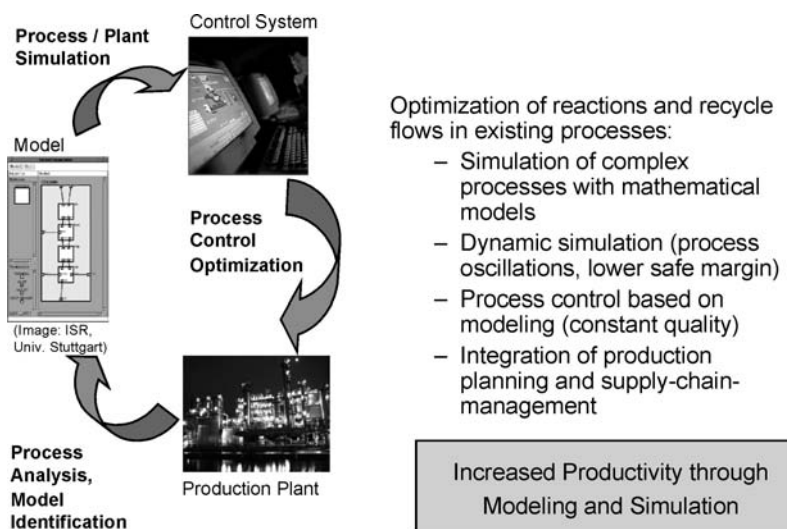


Fig. 10. Innovation fields for molecule suppliers.

will be better optimized than before and work with new manufacturing processes and improved catalysts. This will be supported by micro-process technology using chip laboratories, because this can keep development expenditures to a minimum. In the following paragraphs trends in process technologies emerging from Technology Push effects (see Fig. 10) will be discussed in more detail.

3.1.1. Computer technology

To optimize chemical reactions and the increasingly important process and regeneration cycle systems, computers are employed for simulation and modeling purposes.



(Figure based on FhG-Institute IPK, Berlin)

Fig. 11. Modeling and simulation.

These can calculate the optimum solution without any great material or financial expenditure. In this way, complex processes can be simulated and optimised dynamically. They can be started up and shut down in a cost, time and energy saving fashion. The key process parameters can be calculated from the model and applied in practice to produce a more even quality in the end products. Computer programs are now so sophisticated that, in order to increase productivity, many operational functions from production planning to supply-chain management to energy management can be coordinated with one another at a minimum cost (see Fig. 11).

3.1.2. New production processes

Another technological trend relates to new production processes. In this respect considerable cost savings can be achieved by Molecule Suppliers even in the area of bulk chemicals by changing to cheaper, readily available raw materials:

- Ethane or butane derivatives.
- Prevention of so-called co-products by direct synthesis, for example of propylene oxide or hydrogen peroxide.
- Process simplification such as oxidative dehydration of ethane to ethylene without a steam cracker and without the release of carbon dioxide and nitric oxides.
- New catalytic processes with optimized catalysts.

Innovations in the production of fine chemicals require a different approach. In this case, the molecular functions demanded by the market play the major role. As they

Bulk Chemicals:

(Image: Celanese)

- Change to cheaper readily available raw materials (e.g. ethane or butane derivatives)
- Prevention of co-products by direct synthesis (propylene oxide, hydrogen peroxide)
- Catalytic processes

Fine Chemicals:

- Chiral molecules
- Basic intermediates produced from renewable raw materials (biotechnology)
- Biotechnological production of proteins as active ingredients for medicine and nutrition

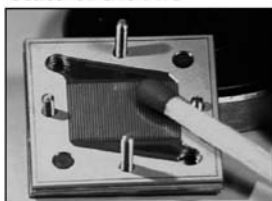
Fig. 12. New manufacturing processes for bulk and fine chemicals.

are dependent on molecular structure, companies are increasingly employing chiral structures. Chiral compounds consist of the same atoms, but their structures are arranged in a mirror-inverted manner. They are no longer optically identical and form enantiomers which can be right- or left-handed. In biological systems generally only one of these enantiomers has the desired effect. To avoid dangerous side effects and to minimize spreading of chemicals in the biosphere there is an increasing demand for pure chiral structural units as active ingredients.

As nature mainly works with chiral molecules, raw materials that can be manufactured using biotechnological processes and also renewable raw materials will increasingly be used as the main source for the production of fine chemicals. The future-oriented market of proteomics, proteins as active ingredients for medicine, for nutrition or enzymes as biocatalysts, will be highly demanding, requiring completely new biotechnological production technologies.

3.1.3. Combinatorial catalysis

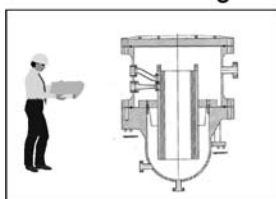
Combinatorial catalyst research will help satisfy the demands placed on new process technologies. As 90% of all production processes work with catalysts to ensure efficient, cost-effective conversion, they have a key role to play. In future, combinatorial research will generate what was once mainly acquired empirically. With combinatorial methods, many possible design variants can be tested very reliably and within a short time, to locate their optimum behavior. The information gathered includes the type and structure of the required catalyst carrier as well as catalytic conversion rates. To achieve this, modern machines with a very high throughput/screening rate

State of the Art

Micro Heat Exchanger
(Institute of Mikrotechnik Mainz)

Micro structuring of process components

- Very intensive heat and mass transfer (Process intensification)
- Reduced hold-up of hazardous components

Current R&D at Degussa

Concept large scale micro reactor

Possible Applications

- High-Throughput-Screening
- Model examinations (reaction kinetics) and benchmarking
- Development of syntheses (time to market)
- Decentralized production
- Large scale production (low scale-up risk!)

Fig. 13. Micro-process technology.

are employed. In this way optimized basic structures can be created with low development, design and testing cost. Together with comprehensive process simulation, researchers will quickly be able to produce ready-to-use process models without the need for time- and cost-intensive laboratories or pilot plants. The method can yield practice-relevant basic parameters for the subsequent process control.

3.1.4. *Micro-process technology*

In micro-process technology, micro-structured process components such as heat exchangers, mixers or reactors are being developed in which very intensive heat and mass transfer can be realized. In many cases, under defined conditions, this allows process intensification with drastically reduced residence times for the reacting components and simultaneously a considerable increase in selectivity and yield. Due to the low degree of hold-up, hazardous components can be handled safely, even under extreme pressure and temperature conditions.

Micro-process technology can be used in the laboratory in high throughput screening and modeling research, such as in the determination of reaction kinetics. In the development of industrial-scale syntheses, process variants can be tested with a low expenditure so that they can be implemented as fast as possible and new products can be introduced to the market quickly (time to market). Process intensification in micro-process technology also provides interesting prospects in the area of decentralized production of small quantities. As a rule, to provide the required capacity a

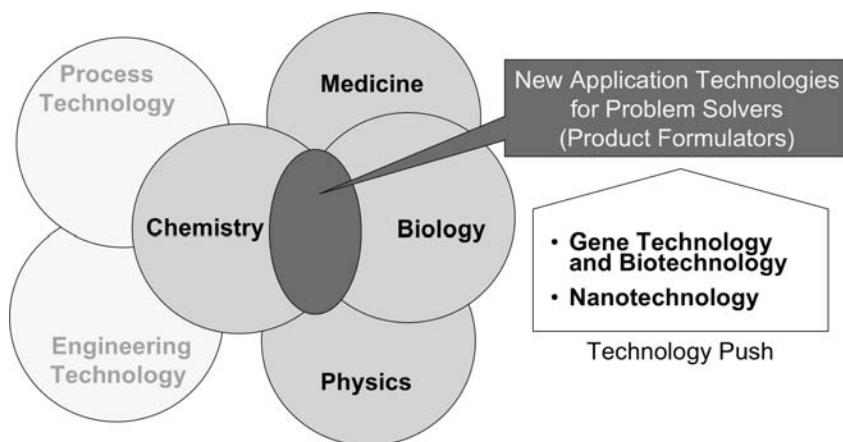


Fig. 14. Innovation fields for Problem Solvers.

limited number of micro-reactors are connected in series, which is why this process is called numbering-up.

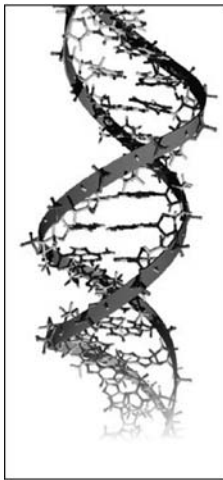
Degussa's current research work in cooperation with partners from industry and universities is concerned with the development of innovative industrial-scale micro-structured reactors, which can principally be used in the liquid and gaseous phase up to the range of large tonnage products. The aim of this new concept is to make the exceptionally interesting potential of micro-process technology available for a wide range of chemical processes, in particular for many of our processes in the area of fine and specialty chemicals, and at the same time to circumvent the traditional problems of scaling-up.

3.2. Innovation fields for Problem Solvers

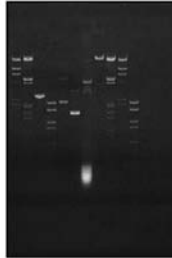
As shown in Fig. 14 the innovation fields for the Problem Solvers (Product Formulators) lie in the interaction between chemistry, medicine, biology and physics. In addition to these modern working technologies, they utilize research results from gene technology and molecular biology. Here, chemistry plays a role as an interdisciplinary science. However, the innovation fields will also utilize knowledge from biotechnology and nanotechnology.

3.2.1. Gene technology and biotechnology

The key driver is the rapid progress being made in determining the human, animal and vegetable genomes. Knowledge of genes theoretically opens up access to all proteins, cell hormones and enzymes as well as controlling messengers of all life forms. As a result great hope is being placed in the discovery of new therapies addressing basic causes — first for hereditary diseases, but soon followed by all other diseases.



(Image: H.-J. Hecht in
www.dhgp.de)



(Image:
www.fvdhgp.de)

- Human genome project identifies and characterizes structure and function of human genes
- Identification of molecular mechanisms of diseases
- Extension to animal and vegetable genomes begins

Objectives

- New targets for more effective drug development (causal therapy)
- Genetic engineering of transgenic plants (pest resistance, metabolic pathways)

Fig. 15. Gene technology and biotechnology.

Pharmacological research into active ingredients has already started searching for the targets. With the aid of gene testing a trend will develop towards personalized medical treatment. By examining the patient's genes, any side effects caused by specific hereditary dispositions can be prevented. In this way drugs can be used in a targeted fashion and a "personal pill" can be developed for specific patients. This new field of research is described as pharmacogenomics. "Genetic Engineering" is most advanced in the area of research into cultivation, to create new resistant useful plants and subsequently also new breeds of domestic animals. Gene technology and molecular biology in a wider sense are also reflected in genomics, or more accurately in proteomics, as the functions of the proteins determine the control chains of genetic reactions as well as all metabolic reactions.

Today, more than 117 approved drugs come from red gene technology (the application of gene technology to medicine) and more than 350 preparations are being clinically tested in the U.S. [3] (see Fig. 16). Medical and veterinary diagnostics have hundreds of new systems based on biotechnology at their disposal, which can provide fast and simple diagnoses without the need for special laboratories. Laboratory chips will prove their worth in this area as they can be produced cheaply in large numbers. Problem Solvers are developing these systems and also producing the respective reagents. With the discovery of stem cells, medicine now has completely new possibilities of tissue transplantation while the pharmaceutical industry has entirely new ways of administering drugs and "tissue engineering" using cell culture technologies. For instance, stem cells might replace dead insulin-creating island cells and cure patients of diabetes, or repair damaged cartilage, bone and even nerve tissue.



(Image: www.fvdhgp.de)



(Image: Monsanto)

Pharmaceutical Industry:

- More than 117 drug products approved by U.S. Food and Drug Administration
- More than 350 drug products in human clinical trials in the U.S.

Diagnostics:

- Hundreds of medical diagnostic tests

Agriculture (resistant plants):

- About 50 products on the market

Industrial Applications:

- Hundreds of enzymes as biocatalysts

Fig. 16. Status of biotechnology [3].

The agricultural industry is currently reaping the benefits of green gene technology with the availability of more than 50 resistant species of useful plants as well as plants with enriched or modified constituents. In future, plants will take over industrial functions and work as bioreactors: for instance, the fatty acid content and type of fatty acid in rape, sunflowers, peanuts and soy has been increased or modified. The durability and the aroma of tomatoes, peppers, bananas and pineapples have been improved by gene technology. Work is even being carried out to equip fruit and vegetable plants with antiviral and antibacterial active ingredient genes to simplify mass inoculations by using them as nutraceuticals. Cotton is given improved fiber and dyeing properties. Potatoes have a higher concentration of starch. Tree species have been developed with a lower lignin concentration to enable more environmentally friendly, cheaper manufacture of paper than has previously been possible. There are now hundreds of enzymes from red and green gene technology available for the food and detergent industries as well as for textile finishing. There would appear to be no end in sight to the fast pace of these developments.

3.2.2. Nanotechnology

Another area of technology with an enormous application potential is nanotechnology. Currently, nanotechnology is developing at a dramatic rate as atomic force spectroscopy provides it with instruments to model atoms and molecules and also to control them. Because of their enormous specific surface area in relation to their volume, particles as small as a millionth of a millimeter have different chemical and physical

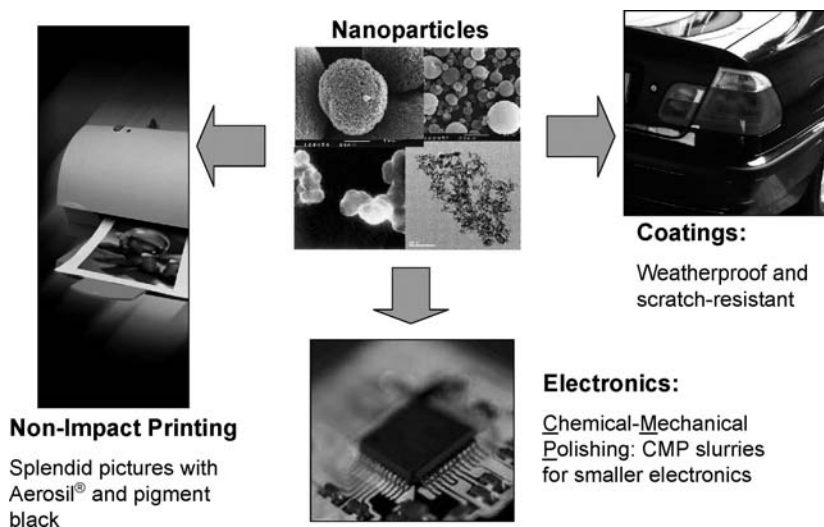


Fig. 17. Nanotechnology: tailor-made nanoparticles.

properties: they melt at lower temperatures, react faster at lower temperatures and pressures and possess different optical and electrical characteristics.

Molecule and product suppliers complement one another in their implementation of nanotechnology in order to equip nanoparticles with functions that could not have been achieved with the technologies available to us in the past. For instance, the principle of self-organization in the nanometer range is based on functional molecule groups that form weak, non-covalent interactions. This allows an automatic formation of new functional structures without any large energy expenditure.

The Lotus Effect® is based on microstructured functional surfaces, in the same way that biocompatible material surfaces are adapted to the surrounding tissue structures. Application-technological effects that can be created with nanoparticles are, for example deep black, matt coatings made from nano-scale carbon black and silica particles, scratch-resistant and transparent surfaces such as laminate flooring and sun screen with a high light protection factor and a high degree of transparency, made from fine titanium dioxide.

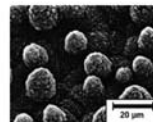
The Lotus Effect simulates the properties of the lotus flower in nature, by microstructured hydrophobic protrusions which enable surfaces to clean themselves by water in motion. By making use of innovative technologies, the Lotus Effect can be used on many different products. For example, self-cleaning surfaces could be used for self-adhesive films, injection moulded parts or painted components in the construction industry, for façade elements or window frames, for traffic facilities such as road signs, and not to forget cars themselves.

Nanotechnology also allows the manufacture of nanoporous layers, which can be used to regulate diffusion processes. Due to their pore size in the light wavelength



Lotus Plant

- non-wettable completely self-cleaning leaves due to:
- nanostructured rough surface with wax crystals



Design of self-cleaning surfaces for technical applications: **Lotus-Effect®**

- e.g. in form of self-adhesive films, coatings
- Architecture: windows, roofs, facades
- Advertising / street signs, cars

Fig. 18. The Lotus Effect.

range, they can act as light filters or light insulators in photonic materials. The field of optics embraces nanomaterials with non-linear optical properties, used in applications for optical data transmission and data processing. New laser systems are being created with “optical” band gaps.

This technology push has a high degree of dynamism. The chemical industry now has the opportunity to implement many new findings and research results in new products, to the benefit of economic and technological progress. The examples shown here serve to illustrate some of the emerging opportunities.

4. Methodological change in R&D

The restructuring of the chemical industry and its focus on core competencies also leads to changes in research and development methods. Before the structural change in the industry, innovations were aimed at creating new products for applications. Nowadays the application requirements and the developing markets are the first priority, and only when these are established is a targeted product synthesis tackled. This method corresponds to the procedures used in pharmaceutical research when developing new active ingredients, but it is not restricted to this area alone; it can be transferred to all performance chemicals. It is unimportant here whether these compounds are of an organic or inorganic nature.

Research is faced with the task of first clarifying the mechanisms of application-technological effects on a molecular basis before selecting the molecules and then

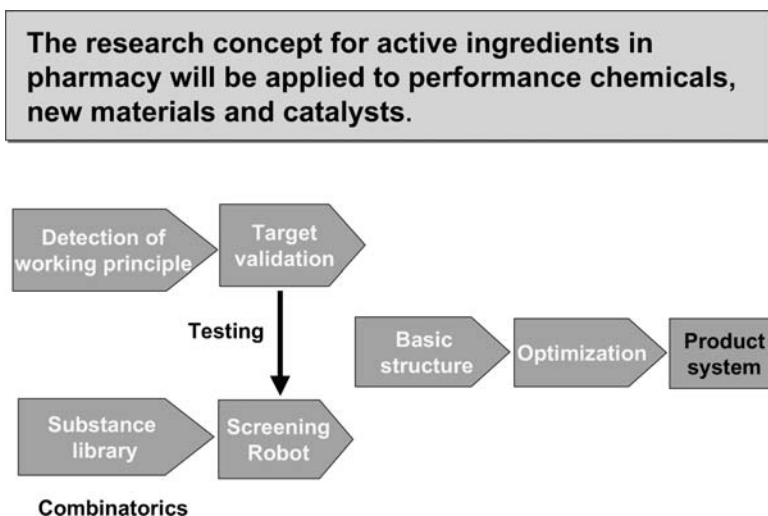


Fig. 19. Methodology change in R&D.

carrying out the synthesis. Effect mechanisms are inseparably linked to the molecular structure and reactive atom groups, and the type of bonding — strong or weak chemical, or molecular bonds, as well as ionic or metallic bonds. New principles have come from molecular biology through combining suitable structural elements — the key and lock principle such as with enzymes, antigens and antibodies. This is where most pharmacologically active ingredients attack: as a target an enzyme loses its catalytic effect when its “keyhole” is blocked. Antibiotics fulfil their function by means of blocking reactions such as this in the metabolism of microorganisms.

When effect mechanisms and targets have been identified, combinatorial screening methods using substance libraries fish out the molecules from the thousands of possible molecule combinations. The best molecule then serves as the basic structure, which can be further optimized and finally synthesized at large scale.

5. Consequences for chemical engineers

Restructuring of the chemical industry also has had consequences for the prospects of chemical engineers. We will consider these — the typical areas of work for a chemical engineer in the chemical industry being manufacturing, research and development, engineering, site management and technical marketing and sales.

5.1. Manufacturing

The increasing trend to outsource the manufacturing of active ingredients and intermediates in life science companies has led to a drop in the number of chemical engi-

neers that are required in this area. The specialty chemicals industry is benefiting from this trend by taking over this manufacturing business. In addition, a constant stream of new products is being developed, which, of course also have to be manufactured. However in the area of fine and specialty chemicals, apart from niche products, there is a constant danger of commoditisation and in many cases manufacturing is limited to the final formulation stages. Still the required products have to be purchased from commodities or fine chemicals companies. Therefore we can assume that there will be no change in the number of chemical engineers that are needed in this industry.

In the case of commodities, one of the essential success factors is the cost-effective manufacture of large product quantities. Here in particular the skills of engineers are required in the manufacturing area, so that the prospects in this field can be regarded as positive.

5.2. *Research and development*

With regard to research and development, life science companies offer the opportunity of career development for chemical engineers in areas such as the automation of laboratory processes where high throughput screening methods for active ingredients are employed. However, this is a relatively new area of employment for chemical engineers, in which they still have to develop a reputation.

In the field of specialty chemicals, engineers are still required for process development, because the companies are taking over many manufacturing processes for life science companies. The focus will shift from large-scale continuous processes towards developing smaller discontinuous multi-purpose plants. As opposed to the other areas, in the field of specialty chemicals chemical engineers will also be deployed in product development, as application technology requires a good knowledge of the customers' production processes. As a whole, the prospects for chemical engineers in this area are excellent.

In the commodities industry, process development plays a very important role, as even small improvements in large production facilities — which tie up a large part of the company's capital — become profitable very quickly. The development of completely new alternative processes is less pronounced, as, due to the very high investment cost, this is only worthwhile in the case of a real quantum leap in process technology. However, in general the prospects for chemical engineers in this area are good.

5.3. *Engineering*

In the area of engineering in the chemical industry there is a general trend towards outsourcing, as this is no longer regarded as a key function and can be purchased on the open market. However, this only applies where the core competencies of a company are not affected. Particularly with regard to so-called front-end engineering,

the company must retain a core competency. In principle, engineering in the chemical industry is being reduced to the extent that front-end engineering is carried out by contracting companies, who can also be used (if controlled and monitored) for other tasks, such as projects aimed at de-bottlenecking and maintaining existing facilities. But engineering jobs that are lost in the chemical manufacturing companies will be created in contracting companies that specialize in engineering.

5.4. Site management

The outlook for careers in site management in the chemical industry remains unchanged. In this area, the job entails supplying utilities such as electricity, water and steam, logistics, telecommunications and workshops. At large sites where several independent companies may be present, each with production facilities, companies are formed that specialize in site management.

5.5. Technical marketing and sales

Technical arguments do not play a role in sales of commodities or life science products. However, in the field of specialty chemicals chemical engineers are increasingly being integrated into the areas of technical marketing and sales. As the sale and marketing of a product plays an increasingly important role, technical support from engineers is becoming more and more significant. The prospects for chemical engineers in this area are very good.

Working area \ Industry sector	Life Sciences	Specialties	Commodities	Supportive Branches
Manufacturing	↓	→	→	↑ Consulting
R & D	↑	↑	→	↑ Start ups
Engineering (within Chemical Industry)	→	→	→	→ Contractors
Infrastructure & Maintenance	→	→	→	→ Site Manag.
Tech. Marketing & Sales		↑		

Fig. 20. Prospects for chemical engineers in the chemical industry.

5.6. Overall perspectives for chemical engineers

Figure 20 summarizes the situation. With regard to the future expectations of chemical engineers in the chemical industry it should be said that industry expects highly qualified staff with an interdisciplinary training. Due to the innovation fields that are forming, knowledge of disciplines close to process technology such as chemistry, biology, medicine and computer science are becoming increasingly important. Work in a company is a continuous learning process aimed at expanding one's personal abilities. Key factors for a successful career are international mobility and an intercultural way of thinking, required for the new globalised markets.

6. Summary

This chapter deals with the structural changes in the chemical industry, and the business models of the future which result from these changes, with their strategic success factors. Differentiating companies as Molecule Suppliers and Product Formulators or Problem Solvers and identifying their fields of activity as commodities, fine and specialty chemicals and life sciences provides a useful overview. There are different innovation fields for the different business models and there is also a general change to be observed in the methodologies of research and development. The prospects for chemical engineers in the individual areas of the chemical industry are assessed.

In spite of its long tradition and the existence of several rather mature areas, the chemical industry will remain a motor for innovation in research and industry and play a decisive role in the design and development of new industrial branches. These innovations will result from the ever-closer interactions of all scientific-technological disciplines. Research in the industry is tending to concentrate on the application properties of its products. The chemical industry has always worked to satisfy the general public's needs with regard to health, nutrition, wellness, communication and mobility and will continue to do so.

The author is grateful to many sources for supplying statistical and other information for this paper.

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Chapter 4

The Chemical Engineer and the Community

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1. Introduction

The pace of change is increasing at an exponential rate. In his opening address, Lord May indicates “science has expanded more in the past half-century than in the sum of all previous human history” and there is no issue more public today than science and its impact on society. Stem cell research and the debate on use of embryonic cells, potential implications of the hydrogen cell, use of nano-technology, not to mention the developments in fibre optics and computer processing capabilities are all very current issues. 15% of power consumption in the USA is used to power the internet (compared with close to zero 9 years ago). The digital power is there and people are using it — the ability to disseminate information and share knowledge is driving continuous innovation at amazing speeds. A revolution is occurring — some refer to the digital revolution (which is the process), the knowledge revolution is the outcome.

So, what does this mean for society? The original, more traditional lines of communication were hierarchical in nature. People trusted companies and governments to disseminate information down through fixed channels. This can be referred to as the ‘hub-and-spoke’ method of communication, where information disseminates from a central core through fixed lines projected radially. Some people may have been sceptical of the news they received, but the means of questioning the information, gaining evidence to support their position, proving possible discrepancies and letting others know their concerns was not so straightforward. The new way information flows is less hierarchical, more interlinked. The mechanisms are available to easily access information on the same topic from more than one source. The framework is networks and they are reshaping the way people communicate and changing the way we live and work. Increasingly, we are relying on networks for our knowledge. And the knowledge gained is driving innovation and creating needs, which the technology network supplies. In this context, how is the chemical engineering profession adapting? And, more to the point, why is it important that they do?

Society, through networking and information flow, is interacting more directly with the profession, becoming increasingly more vocal in the debate on environmental, safety and ethical issues associated with the types of work that chemical engineers do. A community motivated and inspired to action is a force that cannot be ignored — nor should it be. All professions operate within the context of general acceptance by the community. That is to say, it is society (the community) which provides our licence to operate. Relationships with the community need to be rooted in notions of mutual respect. To not listen to the public is dangerous.

There has not been much in the way of change yet in terms of the way in which the chemical engineering profession interacts with the community. The current focus is on meeting forced (regulatory) compliance. Where we do interact with the community, it tends to be reactive — such as in response to community concerns over environmental emissions. This is often not constructive — with community in outrage and the profession on the defensive. The profession needs to be more proactive with regard to setting the agenda for its interaction with the community. More active engagement needs to take place by, for example, taking the initiative in informing the public of actions and outcomes and addressing the issue of science literacy.

This is general stuff, but let's be more specific: to what extent should we be engaging proactively and in what direction?

Chemical engineers and the societies and institutions that represent them already hold positions within the community (such as on advisory panels to governments and NGOs). This is not enough, but how close to enough is it? Do we need to step things up incrementally or substantially? Given the exponential pace of change as outlined above, it follows that it needs to be the latter. So, in what direction? In the last twenty years, the catch-cry was 'the environment', and we sat up and took note and responded accordingly — tighter regulations on contaminant levels in water, air etc, focus on responsible rehabilitation of old industrial sites. And it was within a structured framework of regulations and accountabilities (forced interactions).

The catch-cry for the new century is 'sustainability'. It is the bigger picture, taking 'environment' to the next level. It is a logical extension of current community concerns — looking after the planet and still maintaining a comfortable lifestyle. This is set against a background of less defined interactions, where the regulatory framework is not a clearly defined set of forced interactions, and with a shift to self-regulation and the abandonment of detailed prescriptive guidelines.

The chemical engineering profession needs to develop a strategic framework that fits with the current world in which we operate — flexible, proactive, engaging, communicating. Sustainability is a new concept for a new century. The elements of sustainability are more like the network (multi-faceted interactions) than the 'hub-and-spoke'. Sustainability offers a framework for proactive interaction with the community by the chemical engineering profession. This chapter seeks to explore this concept and to outline what such a framework might look like.

2. Framework of chemical engineers' interaction with the community

What defines the profession?

'I am, and ever will be, a white-socks, pocket-protector, nerdy engineer — born under the second law of thermodynamics, steeped in the steam tables, in love with free-body diagrams, transformed by Laplace, and propelled by compressible flow... dedicated to doing things better and more efficiently' [1].

2.1. *Subject matter*

Chemical engineers develop, operate and optimise chemical and physical processes that take raw materials and transform them into products that are either feedstocks for the domestic market or have direct application in it: refining of petrol, production of acids or alkalis, processes to produce foods and medicines. They must simultaneously understand the micro (chemistry, physics, mathematics) and macro (engineering) elements. The ability to make the link between the two is expanding the horizons of chemical engineering into areas of new technology, particularly those with a biotech focus.

There is an expectation from the community that we supply the products they need and/or desire and that these products are safe to use and produced with minimum impact on the environment. It is the application of the 'doing things better and more efficiently' which brings chemical engineers into contact with the community in a manner which can have significant impact on the communities where we operate and the way in which we operate.

2.2. *The profession*

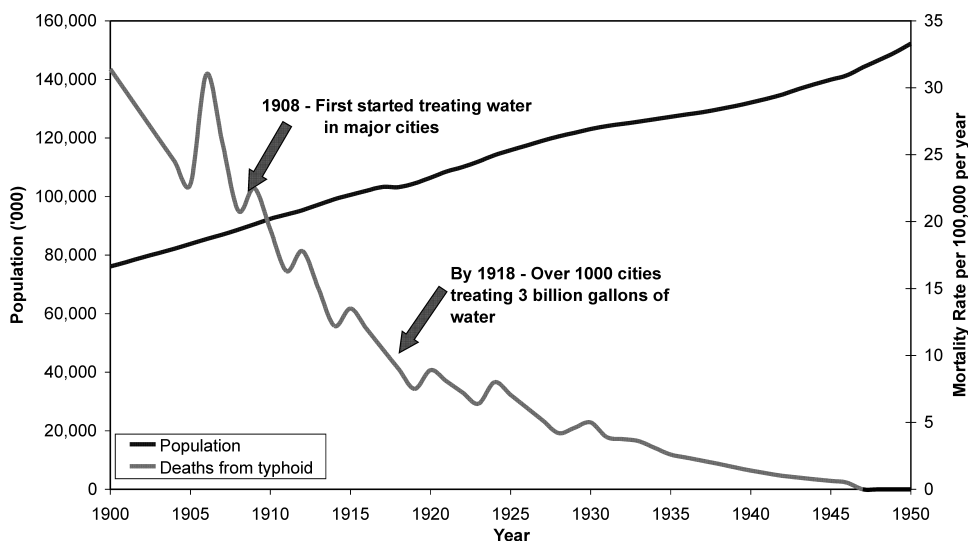
Societies and institutions represent the corpus of chemical engineers and the subject matter of the profession. Chemical engineers look to their professional societies and educational institutions to set the standards and framework for their conduct as professionals. Our societies, institutions and professional bodies play an important role in supporting the profession in its engagement with the community. There is a direct role through recognised positions within the community — e.g. advisory role to government, provision of educational material to schools, production of public publications and developing and maintaining websites. Indirectly, these organisations oversee the individual chemical engineer's engagement with the wider community through the codes of conduct they set and formal processes such as accreditation of course and certification of practising professionals.

In this chapter, by chemical engineering, we mean the corpus of practising chemical engineers and the societies and institutions that represent them. We are not talking about companies or industries.

2.3. Historical contributions to the community

The nature of chemical engineering is in using basic scientific principles to solve practical problems. In looking back over the last hundred years at how the profession has contributed to the community, it is at a practical level. The USA's National Academy of Engineering in marking the turn of the century, acknowledged what it believed to be the twenty greatest achievements of the 20th Century. Number four on their list was technologies that purify and deliver safe and abundant water, which significantly improved living standards (as an aside, lasers and fibre optics, which transformed the rate of information flow, is ranked 18th). The NAE, in determining the twenty greatest achievements, acknowledged contributions based on impact to society. Clearly, contributions with a more direct, measurable, impact are in the outcomes based stuff than the process stuff (such as fibre optics). This method of ranking also reflects where society is focused when it comes to valuing science and engineering.

Chemical engineers contribute at a practical level — the above example of safe water supply is a good one. Figure 1 shows the decrease in incidents of typhoid in the United States once open sewers in back lanes were done away with and adequate plumbing installed. There are numerous others examples of technologies developed by chemical engineers assisting to improve living standards — food processing, large-scale manufacture of medicines etc.



Source: Armstrong et al, "Trends in Infectious Disease Mortality in the United States During the 20th Century" JAMA / volume:281 (pg61-66), January 6, 1999

Fig. 1. USA: population and incidence of major water-borne diseases.

It is not just in the practical implementation of technologies that the profession contributes. More recently, chemical engineers have taken active roles in organisations such as Greenpeace and on advisory panels to governments.

In the work we do, it is vital to always consider the outcomes and implications. Sustainability is all about this, and, as such, makes a good framework for our interaction with the community. Before considering a new framework, it is necessary to look at the current modes of interactions between the chemical engineering profession and the community.

2.4. *Community interaction and the licence to operate*

Chemical engineers practise their profession within communities — there is constant interaction. But, what form does that take? There are legal requirements for environmental compliance, government regulations regarding where we can build our processing plant etc. So, at one level, the current framework for interaction is set by government and legal process. In a broader context though, as mentioned earlier, the profession also requires the general acceptance of the community in order to function. That is to say, the licence to operate is given by society.

Prescribed legislation and regulation exist for a reason. Protection for the environment is one reason, but more importantly it is for the health and safety of the individual (members of society who make up the community). Society did not sit passively by and wait for a higher authority to put that legislation in place — campaigns for safer working conditions, controls on pollution, the 8 hour day, eliminating child labour are all examples of community intervention driving change. Today, companies who choose to build their factories in countries with relaxed labour laws in order to improve their profit margins have a poor public image and are targeted by an outraged community. Our licence to operate may be regulated through legal channels, but it is given by society. It is important not to lose sight of this. It is not by chance that companies are beginning to discuss the concept of having an ‘implied’ contract with their communities.

Two parallel modes of interaction with the community are emerging: forced and voluntary. Forced interaction is that fixed in legislation, with clear legal requirements and defined penalties for non-compliance. Voluntary interactions are more about implied ethics and social responsibility.

2.5. *Forced interactions*

As discussed above, there are laws and regulations which dictate where and how we build and operate our process plants. These vary between countries. It is necessary to meet the legislative requirements of the country in which we operate.

Accreditation of chemical engineering courses allows those who graduate to be acknowledged as a professional and accepted into the societies and industry associa-

tions which stipulate the requirements to be a certified practising chemical engineer. Again, the requirements for accreditation and certification vary across borders.

Even though different countries have different legislative requirements, our "...right to practise... is, and must continue to be, based... upon our competency and accountability" [2]. This is over-arching, regardless of the country in which you work.

Legislation sets the framework for safe operation of our plants. There are prescriptive regulations regarding occupational health and safety, though again the exact structure and extent varies across borders. And, embodied in all of this legislation, there are clearly defined penalties for non-compliance — penalties not only directed at the companies, but also targeting the individual. A chemical engineer in a line management role is personally responsible for the safety of those that work for him/her.

2.6. *Voluntary interactions*

Not prescribed in legislation are the unwritten codes of conduct, the ethics that govern our interaction with the community. This is about doing what we see as right and appropriate, as well as what is required by legislation. It is about meeting the most stringent standards for environmental emissions when operating in a location with the most relaxed legislation. It is about going above minimum requirements for health and safety. This is becoming more important as we operate globally — across borders, and across varied levels of regulatory requirements.

The interaction of the profession with the community it seeks to serve can be seen from the perspective of a licence to operate to companies first, but less directly, to the profession itself. However, unless this is placed in an historical context, the message may appear apologetic.

An early mover in voluntary initiatives was that of Responsible Care[®] begun in Canada in 1987 to develop the principles on which the chemical industry could base its product development from laboratory to disposal, to improve its health, safety and environmental performance (see Table 1). That was taken up by the International Council for Chemical Associations in 1991 and now covers 87 per cent of global chemical production in 42 countries. Mainly adopted by the larger multi-nationals, the Responsible Care[®] concept needs to be extended to more small and medium sized enterprises [3].

2.7. *Balance between forced and voluntary interaction*

The lines between forced and voluntary interaction are becoming more blurred, with greater overlap taking place. Companies and the professions that service them are operating globally. There is a move to self-regulation but the community is being more proactive in its expectations. All these factors contribute to the overlap, but that overlap is still not fully grasped by the profession.

Table 1
Objectives of Responsible Care®

Responsible Care®
1. To seek and incorporate public input regarding our products and operations. 2. To provide chemicals that can be manufactured, transported, used and disposed of safely. 3. To make health, safety, the environment and resource conservation critical considerations for all new and existing products and processes. 4. To provide information on health or environmental risks and pursue protective measures for employees, the public and other key stakeholders. 5. To work with customers, carriers, suppliers, distributors and contractors to foster the safe use, transport and disposal of chemicals. 6. To operate our facilities in a manner that protects the environment and the health and safety of our employees and the public. 7. To support education and research on the health, safety and environmental effects of our products and processes to foster the safe use, transport and disposal of chemicals. 8. To work with others to resolve problems associated with past handling and disposal practices. 9. To lead in the development of responsible laws, regulations and standards that safeguard the community, workplace and environment. 10. To practise Responsible Care by encouraging and assisting others to adhere to these principles and practices.

The abandonment of detailed and prescribed regulation in favour of self-regulation sees the lines between forced and voluntary interaction with the community — in terms of looking after the health and safety of individuals — becoming blurred. Desired outcomes are set through codes of practice aimed to assist employers, but these are not mandatory.

In exploring dimensions of self-regulation versus prescribed regulation, a couple of key issues are evident. Respect for governments and their role in control the regulatory environment is changing (this is explored later) and there is a focus on the rules applying to individuals, rather than companies. These issues came to light in the Longford case, illustrated in Fig. 2. This is a local, Melbourne, example but there are plenty of others around the world.

There is a need for the chemical engineering profession to work with the community, rather than leave it to the government and regulatory bodies to dictate the level and extent of accountabilities. A united approach between the profession and the community is more effective. Whatever the dimensions of regulation and self-regulation, interdependence of chemical engineers with the wider community must be recognised. That interdependence is not power-based but rather one that attempts to satisfy mutual needs.

Lessons from Longford and the issue of self-regulation

On the 25 of September 1998, an explosion ripped through the Esso gas plant at Longford, Victoria, Australia. The Longford incident received a significant amount of attention from the community — not surprisingly as it left Melbourne, a city of 3 million people, without gas supply for 10 days. This is a city where the majority of residents rely on gas for heating their water and houses and for cooking. In a month where overnight temperatures averaged 8°C, us softies used to a comfortable lifestyle were not so keen on cold showers in the morning. This was a small price to pay, compared to those who lost their lives or who were seriously injured at the plant, but it got the government's attention and resulted in a royal commission.

The Royal Commission into the Longford incident ruled that 'operator error is not an adequate explanation for major accidents' and 'front-line operators must be provided with appropriate supervision and backup from technical experts' [4] — i.e. the responsibilities and accountabilities expected of the chemical engineer. The practising chemical engineers were seen as having a responsibility for the operators performance and hence the impact of plant and production on the wider community.

Fig. 2. Lessons from Longford [4].

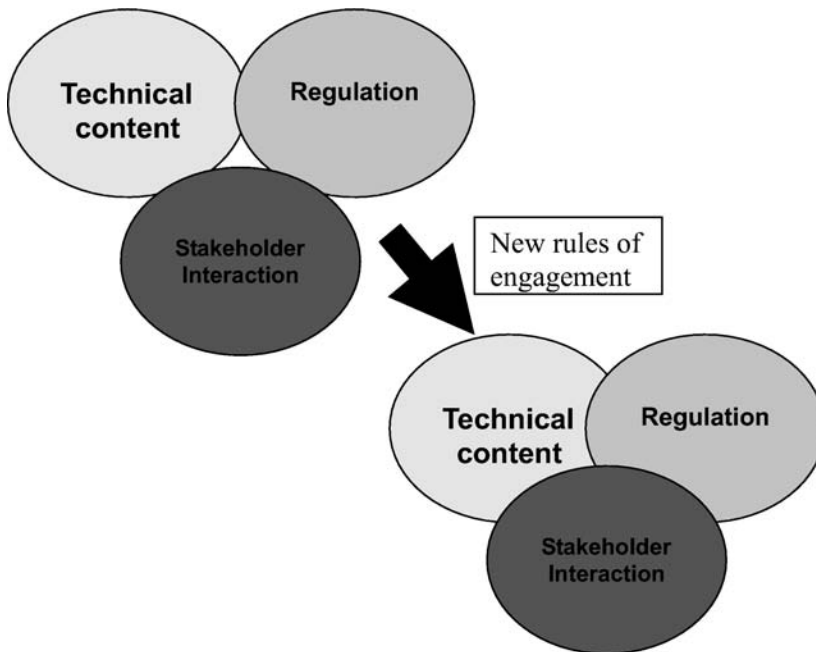


Fig. 3. The new rules of engagement.

2.8. *The pace of change driving a shift*

What was once voluntary is becoming the forced position (see Fig. 3). For the chemical engineering profession, the components of technical content, regulation and stakeholders interaction have all expanded and overlap to a greater extent than in the past.

In the past, chemical engineers have operated within a comfortable framework of technical content and prescribed legislation. On the technical side, the laws of thermodynamics, the continuity equations, McCabe-Thiele diagrams and, when you cannot quite remember the required formula off the top of your head, go to Perry/Levenspiel/Bird, Stewart and Lightfoot. On the legislative side, HAZOP analysis, classification of hazardous substances, requirements for PPE, rules for confined space entry. Nowadays, there is greater interaction with the community by individual chemical engineers, their societies and institutions and this interaction falls outside the areas of technical content and prescribed legislation with which we are comfortable.

There is a need to shift the framework, and to be proactive in doing so or society will do it for us. To step outside the old framework (with no form-guide to help us) takes the traditional chemical engineer outside their comfort zone. But, it is becoming a necessity if we wish to maintain our licence to operate. How much should societies and institutions acknowledge the shift? We pose that, in a rapidly changing society, they need to address the shift by being proactive in developing a framework for community interaction.

3. Society is changing

Welcome to the 21st Century. You are a Netizen (a Net Citizen), and you exist as a citizen of the world thanks to the global connectivity that the Net makes possible. You consider everyone as your compatriot. You physically live in one country but you are in contact with much of the world via the global computer network. Virtually you live next door to every other single Netizen in the world. Geographical separation is replaced by existence in the same virtual space [5].

3.1. *The world is changing and society with it*

The external factors that drive and encourage community behaviour and interactions are changing at an exponential rate. Consider the pace of change in digital infrastructure. John Seely Brown illustrates this by describing Digital Power as a function of

- computing power (Moore's law — a doubling every 18 months),
- communication (fibre law (bandwidth), doubles every 9 months),
- storage (disk law, doubles every 12 months),
- content (community law, which is 2^n , where n is the number of people).

Couple this with the exponential increase in power consumption that can be attributed to the internet. In the United States alone, current estimates are that 15% of all electricity consumption is used to power the internet (from a base of 0% 9 years ago). From 0% 20 years ago, and 5% in 1992, roughly 20% of US electricity consumption is used to power computers [6]. The ability to disseminate information rapidly and globally has seen a breakdown in traditional forms of communication. With the explosive development of the internet neither companies nor professions have complete influence on, or control of, the communications process between themselves and consumers.

The internet is mandating unprecedented global transparency. Now with access to the internet and mobile phones, communities feel empowered to challenge developments that are contrary to an established agenda. They have the access to a support and information network that can, and will, assist them in this challenge. An Australian company working in Turkey spent 18 months negotiating an agreement for mining with the central government while evaluating an old mine near an established community. On reaching agreement in Ankara, the company turned its attention to developing the mine only to find that the local community had organised themselves to reject the project [7]. It is no longer possible to ignore the influence of the community as a stakeholder.

The next generation of the internet is the “evernet”, where broadband, wireless protocol and the growing range of internet devices intersect. The “evernet” applies not only to the World Wide Web but also the universal connection of domestic and industrial units to the internet, such as that much written-about refrigerator that can order its own replacement food. It is an ‘always on’ instant internet that is rather quickly becoming a reality, able to further intensify and revolutionise the dissemination of information.

Consumers, stakeholders and employees will each be rapidly informed of company activities and performance. In addition, the community can be aware and monitor action taken. As a consequence communities across the world can be empowered to challenge developments given the support and information networks that can, and will, assist.

It is not surprising that people’s approach is changing. With the traditional ‘hub-and-spoke’ lines of communication all but dissolved and a global communication network at their fingertips, there is a heightened sense of awareness in the community. There is a fall-off in trust in authority and hierarchical responses because information is available from other sources. The challenge for the chemical engineer is that the changing content of technology is also seeing a change in the content of the corpus of chemical engineering. An example of this is the new areas of genomics-based chemical engineering, described by Lord May in his opening address, which will see an increased emphasis on the development of processes utilising bacteria.

The community is just as vocal in traditional areas of clash with science and engineering, such as health, safety and environment. But, with the changes to the content

Table 2

DNA-free food? [8]. “Ordinary tomatoes do not contain genes but genetically modified ones do”. True or false?

	True	Don't know	False
Canada	15	33	52
USA	10	45	45
Austria	44	22	34
Finland	29	27	44
France	29	39	32
Germany	44	20	36
Ireland	29	51	20
Italy	21	44	35
Netherlands	22	27	51
Spain	26	46	28
Sweden	30	24	46
UK	22	38	40

of engineering, new areas for concern are emerging. The individual chemical engineer, in his/her interaction with the community, needs a broad knowledge base while retaining a deep working knowledge of one or two particular areas. This position is important when dealing with a public who can be ignorant of scientific detail, particularly in emerging areas. The rapid advances in science and technology, particularly in the biotechnology area, are bringing about changes and potential changes that are being questioned, such as GM foods, but sometimes with little understanding of the basic science. The example in Table 2 demonstrates misconceptions relating to the existence of genetic material in plants — people know the rhetoric, but there is a lack of science literacy.

Being overwhelmed by information and conflicting arguments can lead to swings and outrage. The anti-globalisation protests around the world are an example.

3.2. *How are chemical engineers responding?*

In view of these pressures, it is important to consider how chemical engineers are responding, and why it is important that they do. The current situation is reactive and the consequences, when they come, can be extreme, resulting in drastic swings. The approach is frequently ad hoc — is this desirable?

Being reactive has a long history of landing us in the soup. Consider Love Canal.

In 1978 New York State officials began something that has long haunted America. What they did led to a Presidentially ordered, complete ‘emergency’ relocation of the residents of Love Canal, a small community in Niagara Falls, NY. From 1942 to 1952 some 21 000 tons of various chemical wastes were dumped in a 70 acre site. In 1953 the landfill was sealed. Subsequently an area close by was extensively developed and

problems with odours and residues, first reported in the 1960s continued into the 1970s.

Worried by headlines concerning an earlier industrial waste site in the area, the residents then clamoured for government intervention. As a result of the Presidential order, some 950 families were evacuated. Laws determining how to dispose of unwanted chemicals began to be introduced. But in the post evacuation scientific inquiries, researchers did not find any evidence of an abnormal incidence of cancers or other maladies among the former residents. They did, however, find evidence of indirect psychological damage traceable to sensational media reports.

The Environment Protection Agency's Science Advisory Board, noting the presence of dioxins, advised the only human disease with a known connection to dioxin was chloracne — a skin disorder that Love Canal residents never had.

In 1980 *Science* magazine stated that while adverse physical consequences had been rare, the series of events known as 'Love Canal' had engendered "deep and abiding mistrust" of authorities.¹ Subsequently, remediation continued into the 1980s and 1990s.

Love Canal set the scene for massive intervention as well as the sheeting home of costs to all users of a site, not just the polluters. To not be proactive can prove costly, not just financially for the companies involved, but also for the reputation of the profession. Love Canal had a long history. By being proactive in looking ahead at the implications for new technologies, we can develop a strategic framework for addressing issues.

In looking to the future, consider the recent advances in stem cell research that indicate the potential to turn embryonic stem cells into blood cells, with the possibility of creating inexhaustible blood banks [9]. How might the community react to the first process plant for blood production? What is the ethical position of the chemical engineering profession with regard to synthesising blood cells from embryonic stem cells? Do we need one? Governments around the world are putting frameworks and regulations in place to address the implications of stem cell research. If the community shows outrage at large-scale synthesis of blood cells, then it is the chemical engineers who operate the plant who will be in the firing line. The societies that represent the profession need to be proactive in educating the community, addressing their concerns, and setting the ethical framework for such an activity, or the licence to operate can be withdrawn.

Doing nothing is not smart. Being proactive is effective if strategic. Other professions have been proactive. In the medical and health sciences area, Research!America, a not-for-profit membership supporting a public education and advocacy alliance, has been active for over 10 years. The mission of Research!America is to make medical and health research a much higher national priority. The organisation received a 3-year, US\$ 5.5 million grant to build national support for prevention

¹ See: <http://www.prioritiesforhealth.com/1004/lovecanal.htm>

and public health research and is quoted by The Wall Street Journal as “the driving force behind the huge 15% increase in the NIH budget”.

Being proactive enables greater direction in setting the framework for interaction, ensuring it is a framework within which the profession can reasonably be expected to operate, and that it does take cost–benefit analysis into account.

3.3. *Communication, engagement and discussion*

Communication, engagement and discussion are key to any framework for interaction with the community. The ability to communicate information and ideas rapidly and to a broad audience is the common thread linking social and technical change. Network communication channels are seeing diminishing powers of governments to regulate interactions, a lack of trust in authorities and an expansion of what comprises the group of stakeholders in a given situation. These elements support the argument to be more proactive.

The engagement process for the profession and for individual engineers can be considered in the light of stakeholder theory. The theory considers the relationships between an organisation and its stakeholders in terms of a manager acting as a caring person wishing to help the myriad local organisations, in its region, in all ways. A firm and its stakeholders are now no longer considered in either terms of power or contractual relations. Rather they are related to each other as part of their very existence; a firm’s relationships constitute part of the firm. The question now to be asked by the manager is “What can we do to help you prosper, to act on our caring for you?”. While contracts require consideration of reciprocity, caring relationships do not. In a world of essential relationships all groups are interdependent.

The balance between forced and voluntary interactions with the community, in the light of stakeholder theory, defines our licence to operate. Nowadays, the number of stakeholders is drastically increasing. The example given below illustrates this multiplicity of interactions.

In 2000 in South Australia an announcement was made about a proposed new magnesium development. While it did not proceed, reactions in the press and on radio highlighted the views, often conflicting, of the different community sectors.

- The *local aboriginal community* indicated it had not been consulted (nor, presumably offered compensation or part of the action).
- The deposit to be mined was in a national park — *environmental groups, and the park ranger service*, opposed mining in the park as it would impact on its sensitive ecology; they suggested that there were plenty of places outside the park to mine!
- The *SA Government* welcomed the development, as it would have created much-needed jobs; it wanted to stay in office.
- The *Port Pirie Council*, where the smelter was to have been located also welcomed the development; it would have benefited employment and added wealth to a depressed area.

- The *Australian community* should have welcomed it because it would have resulted in reduction in vehicle fuel consumption as a result of lighter cars.
- The *Federal Government* would have welcomed it because of export income and potential greenhouse-friendly production.
- The *world community* would have benefited from lighter cars, reduced fuel consumption and reduced greenhouse gas emission.

In the context of a changing society, chemical engineers need to be more attuned. They need to take advantage of the networks to pick up on community concerns and then be proactive in responding. The profession has embraced ‘the environment’, but that was in the last decade (an old framework). With the new century, ‘sustainability’ is the catch cry.

3.4. Sustainability offers a framework

Sustainability is a framework that is being embraced, that sits well with the concerns of the community and where society is heading in the 21st century. In the profession’s second century, sustainability is not just about integrating environmental considerations with the bottom line. Sustainability is about making best environmental practice, product stewardship, partnership and transparency integral to the bottom line. In this changing society, sustainability is also about people’s expectations and aspirations, the framework in which they operate and their understanding of risks and rewards.

A proactive position is needed because society is changing. This position is required to prevent the chemical engineering profession being caught by extreme swings.

4. Sustainability as a framework for proactive community interaction

We are now transforming the biosphere — depleting the oceans, poisoning the air, levelling mountains and altering the composition of the atmosphere — and we are doing it in a mere instant of geological time. In the nearly four billion years that life has existed on Earth, no species has possessed this capability for changing the biophysical makeup of the planet and thus affecting every other species on Earth. From an Australian perspective the effect of 200 years of European methods of agriculture now require us to replant 75 per cent of our now cleared agricultural land so as to ensure our cities have a continued supply of potable drinking water [10].

In Australia, European farming practices led to native vegetation being replaced with crops and grasses with shallower roots and different growth patterns. Native vegetation evolved to make the best use of available rainfall. Imposing foreign methods of agriculture has resulted in a major water imbalance in many catchments. Water is no longer used at the same rate, with the unused portion migrating to lower soil depths and causing a rise in the water table. As the water table rises, stored salts are

mobilised and brought near to, or reach, the surface, leading to widespread land and environmental degradation. As well as causing problems for agriculture, with land becoming unusable for growing crops, salinity damages downstream aquatic ecosystems and biodiversity and can affect urban infrastructure due to damage to building foundations from shallow, saline water [11].

The salinity issue in Australia is the result of agricultural practices that are unsustainable. Finding ways to redress the balance and implement sustainable farming practices is a matter of necessity receiving significant attention from scientists, engineers and the wider community.

4.1. *Sustainability is on the agenda*

There is widespread interest in the elements of sustainability. It is not simply a fashion and is certainly not a Luddite reaction against new technologies. As an example, recycling is now widespread and common practice. A common feature across a number of countries, seen and supported by the community, is the recycling of waste paper, aluminium cans and household garbage. Not so visible to the wider community are the large changes that have taken place in manufacturing, such as the changes in metal forming techniques to minimise waste and the looming of copper wire in cars so that it can be easily removed in one piece when recycling vehicle components.

Sustainability itself has been adopted by some countries. In Sweden, The Natural Step Framework (discussed later in this section) has received strong support from business and political leaders and has been adopted by a number of council municipalities and corporations (such as IKEA and Electrolux).

As a strategic framework for the chemical engineering profession, sustainability builds nicely upon the traditional framework of mass and energy balances. At the most practical level, it offers concepts easily grasped by the classically trained chemical engineer. Also, sustainability and its key elements such as life cycle analysis, require teamwork and a multi-disciplined approach. Strong interaction with all stakeholders is necessary, making it a good framework for community interaction.

4.2. *Technical innovations enabling sustainability*

Technical innovations are leading us towards a more sustainable society. With today's technology we are learning to take care of much of the waste we produce. We recycle waste water, plastics and aluminium cans, re-manufacture discarded tyres and use garbage as a source of electricity. A number of organisations are seeking to develop a no-waste strategy by 2010. This is built on the increasing levels of success we have achieved in new waste reduction strategies over the last twenty years.

Most recently, 'Green Chemistry' focuses on modifying intrinsic chemical properties of substances to reduce or eliminate their hazardous nature. The implementation of green chemistry technology has potential to offer environmental benefits that

propagate throughout the life cycle. Waste minimisation is at the core of a process that seeks to not only promote clean technologies and reduce the environmental impacts of the energy sector but also to stimulate ecologically conducive consumption patterns. By developing processes to assist remediate past pollution the profession can work to preserve the landscape. With redesign, investments in efficiency yield expanding rather than diminishing returns.

Taking advantage of the technical innovations that enable a move towards sustainable processing has occurred in incremental and revolutionary steps throughout the 20th century. The example of technologies that purify water (discussed earlier as example of practical contribution to the community and illustrated in Fig. 1) was a first step towards sustainability — how do you sustain an increasing population without a process for treating sewerage and providing a clean water supply?

“Chemical engineers will be central to solving water shortages... increasing the efficiency of use, reducing demand by rethinking systems for treating and recycling water and designing and overseeing the construction of reverse osmosis plants.” [12]

4.3. *The role of societies and institutions*

Societies and institutions have a key role now in setting the context for the sustainable practice of chemical engineering.

The misunderstanding regarding genes in tomatoes has been discussed earlier. Perceptions can be made with lack of understanding, but if people respond according to what information is available, then what more can we expect? Our societies and institutions have a role to educate the profession. They also represent the profession in its interactions with the community. Therefore, they also have role to educate the community with regard to profession.

Our societies and institutions have been active in the past in revamping the profession. Certified practice, and the requirements that go with it set a standard for professional behaviour. Societies have been instrumental in defining the code of conduct — particularly with regard to matters of health and safety. Certification is becoming an ever more rigorous process as the community's expectations of what engineers can deliver is rising: “Ensuring that engineering skills are practised competently is essential for safeguarding the health and prosperity of our nation. It is our competency, together with our accountability that defines us as a profession” [2].

Examples of initiatives by the professions societies with regard to sustainability include:

- (a) Future Life Report by IChemE, released in 1997 [12]. The report sets out ideas on how chemical engineers might contribute to sustainability. In particular, the report addresses the following questions:
 - Can we quench our thirst for water?
 - Can we break the link with carbon?

- Are miniaturised factories the way forward?
- Can we reduce the amount we produce?

These are all issues that need to be addressed in order to sustain our community into the 21st century and beyond and they are issues that will require engineering solutions.

- (b) More recently, IChemE has become part of a consortium of chemical industry organisations in the UK — the CRYSTAL Faraday Partnership — which has come together “to improve and develop the UK science and technology base by providing a virtual centre of excellence in low cost, sustainable (‘green’) manufacturing technologies and practices”.
- (c) Center for Waste Reduction Technologies (CWRT), established by AIChE in 1991. Technologies and management tools supporting sustainable growth, environmental stewardship, and Responsible Care[®] CWRT’s mission: To benefit industrial sponsors and society by leveraging the resources of industry, government, and others, to identify, develop and share non-proprietary technology and management tools that measurably enhance the economic value of sponsor organizations while addressing issues of sustainability and environmental stewardship.

An example of a recent CWRT project is the use of their previously developed Sustainability Metrics to establish a methodology for determining practical minimum energy requirements for chemical processes.

There has also been commitment by individual companies, such as Alcoa who has set very clear waste reduction targets over the next 10 years:

- SO₂ — 60% reduction in emissions by 2010.
- Volatile organic compounds — 50% reduction in emissions by 2008.
- NO_x — 30% reduction in emissions by 2007.
- Mercury — 80% reduction in emissions by 2008.
- Landfill waste — 50% reduction by 2007.
- Process water use and discharge — 60% reduction by 2008.
- GHG — 25% reduction by 2010 (potential to achieve 50% with use of new inert anode technology).

“This set of goals will be milestones along the way to the ultimate vision of a company where all wastes have been eliminated, where products are designed for the environment, where the environment is fully integrated into manufacturing, where the workplace is incident free, where protecting the environment is a core value of every employee and where all stakeholders recognise Alcoa as a leader in sustainable development.”

In considering sustainability as a framework for the chemical engineering profession, the London Communiqué was an ad hoc step in the right direction. The 1997 London Communiqué (Fig. 4) acknowledged the need for chemical engineers to minimise their adverse impact on the environment more so than to use the profession’s

We, the representatives of 18 societies representing chemical engineers worldwide and acting here in our personal capacities, subscribe to the following statement:

THE KEY CHALLENGE FOR OUR PROFESSION IN THE TWENTY-FIRST CENTURY IS:

To use our skills to improve the quality of life: foster employment, advance economic and social development, and protect the environment.

This challenge encompasses the essence of sustainable development. We will work to make the world a better place for future generations.

SPECIFICALLY, CHEMICAL ENGINEERS WILL:

Design processes and products which are innovative, energy-efficient and cost-effective, make the best use of scarce resources and ensure that waste and adverse environmental impact are minimised.

Achieve the highest standards of safety in making and using products of all kinds.

Provide the processes and products which give the people of the world shelter, clothing, food and drink, and which keep them in good health.

Work with other disciplines to seek solutions.

Engage in honest and open dialogue with the public on the challenges presented by manufacture of the products which the public requires.

Promote research to allow the profession to respond fully to global demands.

Encourage the brightest and best young people into the profession, and promote lifelong professional development.

Therefore we must co-operate together and recognise each other's efforts in striving to meet this challenge.

We acknowledge that this challenge cannot be met by our efforts alone, but this does not lessen the responsibility to pursue it.

Fig. 4. The London Communiqué.

skills in systems design to achieve good social outcome. It cited honest and open dialogue with the public, but did not refer to a partnership between the profession and the community in which it operates.

This communiqué is a marvellous start in that it is a concerted effort by the leaders across the profession. It is a long way however from a code of practice. It is a statement of intent and an encouragement to the profession, but not a commitment.

The London Communiqué, the efforts of IChemE through the Future Life report and the CRYSTAL Faraday Partnership, the commitment of AIChE to sustainability through the CWRT Industry Alliance, the efforts of individual companies such as Alcoa, are all positive steps but they may not be proactive enough.

Proactive commitment is possible. This can happen by our societies and institutions adopting a strategic framework whereby

- Practising chemical engineers must commit to the London Communiqué in order to retain their licence to operate.
- Courses to be accredited base teaching on a strategic framework for sustainability.
- The profession (and in particular the societies and institutions) are proactive in communicating with the wider public.
- A commitment is required — implemented within a framework, supported and promoted by the societies and institutions that represent the profession.

4.4. *What are the options for a strategic framework?*

A strategic framework for chemical engineers is required, as for example suggested by The Natural Step² (a good example) or the Global Reporting Initiative (GRI)³. As a structured framework, the Natural Step is about the science, life cycle analysis (see Fig. 5).

One concern regarding The Natural Step is that the goals are too broad, with targets for chemical engineers a long way from where we are now. A better approach could be through initially targeting reduction of wastes within a set timeframe or adopt a current strategy being used. The CWRT project to determine minimum energy requirements for certain chemical processes may be a good start in specific areas of process engineering.

A further framework for consideration is the Global Reporting Initiative (GRI), which is about indicators for measuring economic, environmental and social impact — regulatory in nature, but a voluntary exercise (Fig. 6). The GRI is in the process of establishing a global presence and a credible guidelines-setting process for environmental reporting. Early in 2001 the GRI circulated its members and interested friends to engage those able to offer the resources, legitimacy, technical excellence and global standing to achieve its mission in the long term. Their aim is to establish the GRI as a permanent, independent and international institution in 2002.

The concern raised by some with regard to the GRI is that it does not offer directions on how to go about improving underlying systems and processes in order to achieve sustainability. Also, that it is not sufficiently focused on active community interaction.

Engaging in strategic initiatives such as the Global Reporting Initiative is one process. Another is to engage with the community more directly. A good example of effective direct community interaction is the recent initiative of BHP Cannington. This BHP-Billiton mine in Australia engaged the North Queensland Conservation Council (an independent community-based environmental advocacy group) to create a robust external environmental appraisal of their operation. “This innovative partnership brought together for the first time in Australia (and probably the world) both

²See: <http://www.naturalstep.org>

³See: <http://www.globalreporting.org>

The Natural Step Cyclic Principle (www.ozemail.com.au/~natstep)

Basic science and the precondition of our lives lead to the cyclic principle. This means that waste must not systematically accumulate in Nature, and that reconstitution of material quality must be at least as large as its dissipation. Consequently, all matter must be processed in cycles. This avoids a systematic shift in environmental parameters and enables the continuing diversity of Nature and human activity.

From the cyclic principle, four conditions for the maintenance of quality in the whole system can be deduced.

There should be no systematic increase of:

(1) Concentrations of substances extracted from the Earth's crust.

This means substituting certain minerals that are scarce in nature with others that are more abundant, using all mined materials efficiently, and systematically reducing dependence on fossil fuels.

(2) Concentrations of substances produced by society.

This means systematically substituting certain persistent and unnatural compounds with ones that are normally abundant or break down more easily in nature, and using all substances produced by society efficiently.

(3) Degradation by physical means.

This means drawing resources only from well-managed eco-systems, systematically pursuing the most productive and efficient use both of those resources and land, and exercising caution in all kinds of modification of nature.

In a sustainable society:

(4) Human needs are met worldwide.

This means using all of our resources efficiently, fairly and responsibly so that the needs of all people on whom we have an impact, and the future needs of people who are not yet born, stand the best chance of being met.

Fig. 5. The Natural Step.

sides of the traditional mining/environmental divide to jointly develop a sound and portable methodology for assessing sustainable development in mining operations. This project has shown the way for other such partnerships around the world.”⁴

This proactive approach to community interaction is increasingly necessary when the rules of engagement change and wild swings are observed as communities seek solutions to their concerns that may border on uneconomic idealism. There is potential to shape the language of public debate through educating the community in the concepts of risk analysis — the cost–benefit trade-off in green and clean production strategies and other such processes.

⁴AMEEF — 2001 Awards, Community Award finalist, see: <http://www.ameef.com.au/awards>

The GRI aims to help organisations report information:

- in a way that presents a clear picture of the human and ecological impact of business, to facilitate informed decisions about investments, purchases, and partnerships;
- in a way that provides stakeholders with reliable information that is relevant to their needs and interests and that invites further stakeholder dialogue and enquiry;
- in a way that provides a management tool to help the reporting organisation evaluate and continuously improve its performance and progress;
- in accordance with well-established, widely accepted external reporting principles, applied consistently from one reporting period to the next, to promote transparency and credibility;
- in a format that is easy to understand and that facilitates comparison with reports by other organisations;
- in a way that complements, not replaces, other reporting standards, including financial; and
- in a way that illuminates the relationship among the three linked elements of sustainability — economic (including but not limited to financial information), environmental, and social.

The GRI's Sustainability Reporting Guidelines encompass the three linked elements of sustainability as they apply to an organisation:

Economic: Including, for example, wages and benefits, labour productivity, job creation, expenditures on outsourcing, expenditures on research and development, and investments in training and other forms of human capital. The economic element includes, but is not limited to, financial information.

Environmental: Including, for example, impacts of processes, products, and services on air, water, land, biodiversity, and human health.

Social: Including, for example, workplace health and safety, employee retention, labour rights, human rights, and wages and working conditions at outsourced operations.

Fig. 6. The Global Reporting Initiative (<http://www.globalreporting.org/>).

There is no doubt that a strategic framework for community interaction, which focuses on the elements of sustainability, is required by the chemical engineering profession. There is not currently an ‘off-the-shelf’ framework that is a universal good fit. We need to work on it.

4.5. Sustainability as a framework for proactive community interaction

Issues in sustainability that fall within the ‘control’ of chemical engineers include the core elements of The Natural Step and GRI — Life Cycle Analysis and criteria for monitoring performance. These core elements fit well with elements that are

- *In the teaching of the profession:*
A greater emphasis on life cycle analysis and sustainability as the key element in all subjects. Also, training in stakeholder engagement.
- *In the activities of our professional societies:*
Proactive in promoting sustainable practices within the profession and in communication with the wider public.
- *In the practice of the profession:*
A commitment to the London Communiqué in order to retain a licence to operate and an understanding that proactive community interaction comes with the territory.

Fig. 7. Interacting with society — features of a framework.

the essence of chemical engineering — mass and energy balances, rate processes, HAZOP analysis. Other important factors include

- a focus on risk analysis,
- indicators for effects on the community, and
- guidelines for informing and educating stakeholders.

Such a framework would be acceptable to both the profession and the community — acceptable to the profession because it is “do-able”, that is to say that it is possible to practise the profession within the framework, and acceptable to the community because the framework sits on a common ground of mutual interest in sustainability and, as such, enables a common language for dialogue.

How might such a framework be implemented? At one level, implementation should include the following steps

- Adopted into the chemical engineering curriculum.
- Included in further education and training programs.
- Guidelines stipulated by the societies and linked to certification.

This is all well and good, but at a fundamental level it is the individual chemical engineer who is most important in the process of implementation. This is because it is the totality of the actions of the individual within the profession that is the most significant part of community interaction. Therefore, encouraging proactive interaction of professional chemical engineers is necessary. In a support role, our societies and institutions have a role in education and advice to government, as spelled out above and earlier in this chapter.

In considering development and implementation of a framework, it is important also to be aware of potential road blocks to success, namely “Is the profession ready?”. Is there other work that needs to be done first? Has enough of the background work been done to start implementing something that will be useful or successful over the next 3–5 years? With such a rapid pace of change, will anything conceived today have relevance tomorrow?

The fact remains that we have to do something. There is no indication that the community will lose interest in sustainability. In fact, we are more likely to see the focus intensify. It may be that a necessary factor is the need to ensure the approach we take is flexible, and not limited to today's perception of sustainability but what innovation may provide for tomorrow.

The implication of not adopting a strategic framework for sustainability, as discussed throughout this chapter, leaves the profession vulnerable. There is a need to be proactive in a structured way. A possible framework would encompass the features shown in Fig. 7. For any framework for community interaction to be successful, it must also incorporate the three key elements of trust:

- stick to the facts,
- state your intentions clearly,
- be consistent.

And, in stating the facts and your intended course of action, remain open and honest about the consequences.

5. Conclusion

We end with a proposal. In addressing the topic of chemical engineering and the community, we strongly advise the need for the profession to be more proactive in its interaction with the community. Sustainability is proposed as a strategic framework for such interaction and, indeed, as an overall framework for the profession as it moves into the 21st Century.

There is a need to be more proactive on sustainability because technology and society are changing. Without action, we run the risk of becoming less effective. It can be concluded from the success of others — e.g. Research!America — that being proactive works well, but requires a framework.

We note the likelihood of a World Council of Chemical Engineering being formed. This presents an excellent opportunity to consider potential frameworks and adopt or develop a suitable one for the profession.

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Chapter 5

Chemical Engineering: The Practice of the Profession “Pace, Price, Perplexities”

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1. Chemical engineering commitment

In 1997, the Institution of Chemical Engineers issued the London Communiqué, signed by 18 chemical engineering societies from around the world. The Communiqué designed this broader perspective for the chemical engineering profession

“The key challenge for our profession in the 21st century is to use our skills to improve the quality of life; foster employment, advance economic and social development, and protect the environment.”

While these higher order objectives should be held with conviction, the chemical engineering profession is also challenged to improve the recognition of its value so that it may continue to grow and realize great achievements, as it did in the 20th century. This chapter will address today’s chemical engineering profession, the trends and dynamics affecting it, and look forward to the priorities of the profession to ensure its viability and value in the future.

2. The new era of possibilities

Even in normal times, the future is unpredictable, and now in an era of unprecedented change and rapid knowledge accumulation, it is absolutely impossible. Not long ago, The Czech President Vaclav Havel said it best

“We live in an age where everything is possible, and nothing is certain.”

This clearly is the best definition of where society is at the onset of a new century, and in fact, a new age. At the current rate of knowledge acquisition, virtually everything may be possible soon.

2.1. *The pace of change of technology*

Ever since the microprocessor was invented in the late 1950s, the pace of knowledge acquisition and change has increased exponentially. The ability to access, store and calculate — what once took thousands of researchers years to accomplish — is now executed in nanoseconds. This has radically accelerated the learning curve. Additionally, knowledge accumulation and instant search and retrieval characteristics of ever-advancing cyber technologies are literally putting a world of knowledge at every professional's fingertips.

Today, society stands in the eye of a technological whirlwind of its own creation. Knowledge is building on itself at exponential rates. The experts predict that all human knowledge will double in the next seven to 10 years. But that's only the beginning. Knowledge will double again in less time with each successive iteration. Knowledge builds on knowledge. So the cycle of discovery continues to accelerate and tighten at an exponential pace.

With the Internet, and whatever lies beyond it, the nature of knowledge has changed from solid to liquid. Knowledge once was a commodity that was hoarded and traded like gold. Now it is more like water, only of value when it is flowing and freely available to all.

Because of this tidal wave of knowledge accumulation, acceleration is unchecked. World-class new product development times were once measured in decades, then years, now they are measured in months, and tomorrow in weeks. Society is witnessing enabling technologies arriving so fast that by the time a leading-edge technology is ordered and installed, it is no longer state-of-the-art. The full implications of the hyper-pace of the knowledge age are not truly understood.

One hundred years ago was the birth of the Industrial Age in the U.S. That year, 1901, the number of industrial workers exceeded the number of farm workers in the U.S. for the first time. Twenty-five years ago, this year, was the beginning of the Information Age. That is the year, 1976, that more than half of the U.S. labor pool directly, or indirectly, worked in information processing.

Everyone agrees that in the next few years a new era will begin — some call it a post-industrial, post-information age. From a hundred-year era, to 25 years, to less than 15 years, the whirlwind tightens with each turn.

2.2. *Knowledge breeds competition*

For businesses, it is not the pace of knowledge accumulation, but the pressure to rapidly apply that knowledge in a highly competitive global market, that is acting as an overwhelming agent of radical change. The very technologies that have fostered this rapid pace of change also break down many of the barriers to entry for new competitors wanting to begin new businesses. Unprecedented competition, yoked with

ever-increasing knowledge, is creating a frenetic competitive situation. The traditional essentials for competition, like resources and accumulated wealth, have only limited advantages in the emerging knowledge culture. The global community is caught up in a breathless race for new products, biotech breakthroughs and labor-saving innovations to contribute to the quality, productivity and longevity of life. The pressure to out-learn, and out-earn, competitors is astronomical. That is ultimately good for customers, yet it is changing the nature of global industry.

There are now companies, in fact, entire countries, which are world powers because they have prospered on their ability to take up an idea after its initial development and bring it to market faster and more efficiently than even the original inventors. Japan, South Korea, Switzerland, Singapore, Taiwan — all are crowded nations with highly limited resources that have placed a significant emphasis on rapid application of emerging technologies. Countries with virtually no natural resources now can, through sheer resourcefulness, become global players.

This is ultimately good, for it raises the standard of living and quality of material well being globally. Globalization also removes barriers that separate cultures. No wall, made of iron or ideology, can resist this free flow of information and material awareness. The global village, in fact, has done what all of the ambassadors of history failed to do, truly link people everywhere together economically and reduce the prospects of global confrontation.

3. The new chemical engineering profession

In many ways, conditions that promote the innovative use of knowledge should be ideal for chemical engineers. They have created many new technologies, but they also are truly adept at improving existing ideas in ongoing processes. As bio-chemist and novelist Isaac Asimov said, “Science can amuse and fascinate us all, but it is engineering that changes the world.”

Chemical engineers, whether in owner, contractor or supplier companies, design and build the world’s largest industrial plants and complexes. They take a tremendously complex set of skills, orchestrate them in every remote part of the world and create facilities that make it a better place — an endeavor that makes people proud to be called a chemical engineer.

In a sense, chemical engineers are the proud parents of today and the escorts to a better future. They invent, but more importantly, they nurture and incrementally improve petroleum processing, environmental, biomedical and chemical technologies, to name a few. In the process, they make them safer and more durable, dependable, environmentally benign, cost-effective and accessible to greater numbers of people. To say a chemical engineer’s skills are important to the world’s economic well-being is a gross understatement. They are all-important to a thriving global economy. Even

economists, who have predicted 13 of the last four recessions, are in full agreement that technological innovation is the primary source of growth.

However, as knowledge builds and competition increases, chemical engineers must recognize five outcomes of the changes that are already apparent and affecting the profession.

3.1. *More and fewer specialists*

First, there are seemingly contradictory movements both to, and away from, greater specialization.

The trend toward specialization is logical. As the pie of knowledge grows, one simply has to take a thinner slice to digest the same amount. Up until now, chemical engineers may have performed as generalists, but in the not-too-distant future, they may have to focus their expertise as specialists, for example, on elasticity properties of fiber-reinforced polymers in some highly specific application. In this respect, chemical engineering is going the same route as the medical profession. General practitioners, where they exist at all, are there more as traffic cops to refer patients to the appropriate specialist.

Yet there is an equally significant trend away from on-staff specialists, especially in major corporations. Executive teams may feel that as accessible as knowledge is, a good generalist engineer on staff can monitor the work of supplier experts. Some contend here that the total number of experts may, in fact, decrease as expertise is more readily accessed over various information Internets and joint-venture brain trusts. Actually, this really is not a rejection of specialization, but rather a trend toward seeing knowledge-pools not as integral but rather as resources.

3.2. *Extended reach*

Second, the trend toward deeper levels of specialization makes each chemical engineer more dependent on knowledge in the global community rather than in his or her own company. Today, many companies have only one specialist in a narrowly defined area of expertise. That means the individual must reach out as never before, establishing a knowledge-centric peer culture that crosses all organizational and political boundaries. There is a consequential blurring of the distinctions between organizations that are knowledge suppliers. Chemical engineers, more than ever before, are expected to establish their own distinct lines of communications, and to be masters of their own priorities and time.

3.3. *Matrix mindsets*

Third, entirely different kinds of corporations are being created. The trend is toward streamlined leadership, empowering the people who actually know the technology and do the work to make the decisions.

Traditional corporations, with their top-down decision making structures, are proving to be too cumbersome to provide the necessary agility. In the new organization, individual specialists are given the authority and responsibility to make key decisions on elements within their purview. This is essential to create a robust environment where thoughts are transformed into action in real time to achieve, and sustain, unprecedented agility. It really does place a great deal of demand on individual chemical engineers to manage themselves, not just their technologies and projects.

3.4. *Cross-functional team players*

Fourth, chemical engineers have to expand their traditional role as team players. Today most organizations fill their knowledge gaps by utilizing cross-functional decision-making teams. To be an engineer means being involved in customer satisfaction, research, product development, process and manufacturing controls, and marketing.

For example, a chemical engineer may be a member of the original new concept team and stay with a product throughout the entire development cycle, throughout its service life and right through to material recycling.

3.5. *Core business focus*

The fifth, and perhaps most dramatic change, is that virtually no company has enough knowledge or resources to go it entirely alone. The pressure of pace — to accomplish so much in so little time — has placed inordinate demands on organizations for capital investment and talent. This has mandated a retreat back to concentrating on core competencies. It is, in a real sense, a return to chemical engineering's historical origins. Chemical engineering companies were originally small, innovative specialty factories. Then, beginning in the 1920s, the trend was consolidation into large, integrated chemical companies, which could take advantage of strong resources for development and advanced research facilities. The conglomerates continued to grow right up into the 1980s. These super chemical companies crossed fields and borders with impunity, creating a wide range of products.

In the past decade the pendulum has swung back. The trend is away from all-things-to-all-people mega managements, and back to specialization and concentration on a few core competencies. Yet, many large companies today have gone full circle by segmenting their service or product lines and spinning them off to better balance the parent companies' focus and resources. Today, there are far more companies focusing their investments into their core business and divesting all segments of their businesses that are peripheral. And whether large or small, companies are using technology, knowledge management, partnerships and alliances to strengthen and leverage their own knowledge and expertise.

4. The universal engineer challenged

By all logic, these changes in our technical and business environment should work to the chemical engineering profession's benefit. The chemical engineers' multi-discipline education and training have made them far more team oriented and cross-functional. Chemical engineers can be called "universal engineers" for a good reason. The strong scientific, mathematical and technical background found in chemical engineering education has allowed the chemical engineering professional to enter new fields that often lie in the white space between disciplines.

Currently, chemical engineers are pursuing career opportunities in a variety of fields. Oil and gas, petrochemicals, biotechnology, microelectronics, food processing, pharmaceuticals, environmental clean-up and biomedical implants all offer possibilities for chemical engineers. Attracting, retaining and investing in the talent of chemical engineers is crucial for companies that are pursuing business in these fields.

Yet, despite the opportunities that these five outcomes would appear to create for chemical engineers, the profession must also recognize the challenges that must be faced if it is to excel in the future.

Chemical engineers' skills have never been more in demand by a wider set of industries. The possibilities for chemical engineers, and the engineering profession in general, should be unlimited, but to take advantage of this opportunity, the profession must take control and define its own future. Yet there are challenges to the profession. Incomes for chemical engineers in the largest industrial countries are not going up as rapidly as demand should indicate. And worse, fewer young people are drawn to careers in chemical engineering, and engineering in general. As the war for people heats up, the value of chemical engineers' knowledge and services needs to be addressed and recognized.

4.1. *More than tools, talent*

Chemical engineers can achieve what once were thought to be miraculous incremental improvements in productivity and cost reduction through the effective use of technology. To stay abreast of the latest state-of-the-art tools requires ever increasing reinvestment. Leading-edge computer-based analytical, design and process tools are exceedingly expensive, and many companies try to "get by just a little longer" using outdated tools.

While investing in technology is one hurdle, it must be realized that the tools themselves are not enough. Buying a Stradivarius does not guarantee an Isaac Stern performance. Talent and training to use the most sophisticated tools are essential. Each practitioner must fully understand the calculations being made by each tool and be able to measure and manipulate the results.

With the current manic pace of knowledge acquisition, investing in talent and training can, and should, be significantly greater than outlays for tools. Short-term price

obsession undercuts this critical technology reinvestment cycle, ironically negating the advantages that would have resulted in significant cost reductions.

4.2. Penny wise, pound foolish

Chemical engineering employs a systemic approach that guarantees each step in the long process, from concept to commercialization, is creative and taken with care. However, the rapid pace and competitive frenzy is placing the very industry in jeopardy. Products and services are often conceived of as commodities today. Price has become the easiest, and therefore the preeminent, decider.

In response to competitive pressures, engineering services, once kept in house and highly valued, now are part of the supplier service package, where predatory pricing takes a toll. Major companies are farming out not only manufacturing, but also developmental and maintenance services to second- and third-tier suppliers. These suppliers are competitive only by keeping overhead down through a combination of constraining compensation and increasing productivity.

Cost pressure is, or at least can be, a positive motivating force. It urges companies to stay on the leading edge of enabling technologies, and leverage the production, quality and pace improvements possible with the application of ever-advancing electronic tools.

Keeping costs down is part of the total value equation that chemical engineers need to bring to their clients. The challenge to any profession, whether it be doctors, lawyers or engineers, is when price becomes the only determinant of "value." In such an environment, profit margins begin to erode, and with that, a company's long-term viability erodes as it fails to reinvest in its people, systems and innovative practices because of short-term cost demands. Ultimately, this has an impact on the service provider who participates in such a price war, not only in terms of diminished returns to its investors, but also as a negative impact on the pride, quality and, in the worst case, financial viability of a single competitor or the entire industry. At the very time the public has grown to expect a steady stream of innovative new products and services and companies are demanding greater certainty of cost, schedule and function, the process that delivers them is faltering.

Worse yet is that this problem was created, in part, by the engineering professionals themselves. Unique to engineering, industrial suppliers have provided their clients with far more enhanced visibility into their actual costs of doing business than is the case in many other services. Many clients not only require to see the actual costs of items that are procured, but, in addition, look for detailed breakdowns of burdens and benefits, overheads and other items that make up the contractor's costs to provide services. Other professional disciplines, such as lawyers, have resisted this breakdown of costs and competition on margins.

With this visibility by clients into the cost structure of the engineering and construction business, owners have tended to normalize costs and negotiate to the lowest

common denominator on contractor margins. As a result, an engineering provider, which has invested in systems and processes to significantly improve the schedule, reduce total installed costs or enhance performance, is in a compromised position to grow margins, invest in tools and retain chemical engineering talent, even in periods of high demand for services.

Devaluing the profession inevitably results in safety, quality, environmental and durability problems for the customer. That may be acceptable for computer programs where the user is expected to be the final inspector, yet it is a disaster in the making for most products, from gasoline to polymers and pharmaceuticals.

The phenomenon of pricing pressure is not new. Similar periods of predatory pricing develop temporarily during business down cycles and are certainly not unique to engineering. The difference is that the same forces that animate desperate producers during times of recession are now considered the sustaining reality of a hyper economy. As lower pay and prestige continue, the world will suffer the consequences of this narrow mindedness with lower quality, safety and performance outputs.

4.3. *Unbalanced chances*

And there are other disturbing outcomes of predatory pricing. Major companies now are requiring that suppliers and engineering contractors assume greater developmental and liability risks. There is nothing inherently sinister about these general approaches by owners to mitigate their risks. There is a potential advantage in moving project risk to the party that can best mitigate that risk or, regardless of the ability to mitigate, the party that is willing to put a lower-risk premium on the assumption of risk and the cost of risk mitigation.

To the extent owners continue to contract with financially strong suppliers and contractors that properly evaluate the risks they are assuming with the rewards they may achieve, then the system stays in balance. However, when an engineering contractor assumes risks that it cannot effectively mitigate, or when it undervalues the risk premium necessary to address such risk, the delicate balance between risk and reward becomes out of balance.

These risks take on a variety of forms, from lump-sum price risks to schedule and plant performance guarantees. In many cases, engineering contractors are taking on more risks than the rewards they have requested would warrant. Well-executed risk management is a fundamental discipline in the engineering profession today.

One of the first critical steps of risk management, following a comprehensive assessment of the risks, is having the courage to say "no." Ultimately, to be a successful business enterprise, risk management must continue throughout the life of a project, particularly the development of large, fixed-price projects.

4.4. *The social contract*

One of the greater values of the global community, and those who operate in it, today is social responsibility. There is a new expectation that producers have obligations far beyond fiduciary responsibilities. Companies now operate under an implied social contract that says a company's right to exist and do business is determined not only by its ability to create viable products and shareholder profits, but also by serving environmental and societal goals in every community and country where that company does business. As Lester Brown, head of World Watch Institute, put it: "The public today realizes that there is something fundamentally wrong with treating the earth like a business in liquidation."

Chemical engineering has been on the forefront of environmental and work-environment innovations. An outstanding example is ISO-14001, a global management system that allows companies to effectively manage environmental responsibilities, reduce and control costs, document commitment to government and promote concern for the public.

Environmental stewardship, with quality, health and safety, are all definable processes that can yield immense benefits from management systems. Academia, owner and contractor companies and suppliers will be judged not only on the value they deliver but also on their ability to protect and improve the world. No longer are chemical engineers just working on a finite task; they must broaden their view and set the benchmark for global responsibility.

5. Meeting the challenge

Yet there is much that can be done immediately to redefine these challenges and turn them into value-added opportunities. Business leaders and academia alike must address the new realities.

5.1. *Accounting for creativity*

Intellectual capital must be recognized as the only viable property in the Knowledge Age. In this fast-paced era, the only competitive advantage — the only source of profitability and productivity any organization has — comes from robust, incremental innovations from individuals, both inside companies and in their partner organizations.

Business leaders must learn to recognize, respect and employ in broad measure, the value of an enterprise's most intangible assets — intellectual capital. As Albert Einstein put it, "not everything that can be counted counts, and not everything that counts can be counted." More intuitive measures should be employed. Chemical engineers need to accommodate what counts, internally by rewarding talented engineers

with financial rewards and ever more intellectually challenging and stimulating assignments. And it must be done as a profession, to draw the brightest and best into the chemical engineering community.

The most successful companies have already realized the returns on investment of intellectual capital, and the ongoing challenge of inspiring an environment that brings out the individual's best. Fostering a culture that ties productivity to the human spirit, is certain to grow a team that has practically no limits.

Somehow, chemical engineers need to communicate these knowledge-age values into their equation for partnership and supplier services. The accounting ledger must be rewritten to incorporate the most valuable asset — the industry's professional assets. When that is accomplished, the return on investment of chemical engineering will become as apparent as the bottom line.

Yes, business is in the business of beating competitors. However, commodity thinking must be countered, and up front accounting has to be looked on in broader terms.

Hard questions have to be asked. What are the actual costs of doing business? The long-term cost of reduced quality in lost product loyalty and warranty liability? What are the costs in productivity for knowledge workers when wages are low, and personal training and development opportunities non-existent? What are the costs of taking on much more risk than the rewards warrant? How will it affect the organization to set environmental stewardship aside for short-term profits?

5.2. *Better using our heads*

Advanced technologies improve schedules and quality across the entire value chain, and the pace of change in available engineering tools has never been greater. The profession must not just keep abreast of the latest tools but also become sufficiently adept at using them, so that real competitive advantages can be derived. Knowledge management is key to greater productivity and intellectual capital retention. Those companies most successful at capturing internal and external knowledge in an easily retrievable and reusable form can lower the cost of services or facility operations, while at the same time, increase quality.

As an example, Fluor's Global Automation Team develops or customizes high-value, business-driven project automation solutions and, in doing so, creates value for clients. At Fluor, knowledge flows freely between employees located in more than 50 offices worldwide. The company's proprietary program, called Knowledge Online, is an Internet collaboration that allows members continuous access to Fluor experts located around the world and also to more than 22,000 knowledge objects.

In the knowledge age, there is no longer independence, only interdependence.

5.3. *Power in numbers*

Engineering partnerships, joint ventures and alliances have always existed. What is new is that they are now essential components of competitive life. The distinction

between the engineering corporation, its suppliers and contractors is dissipating. Virtually all successful global engineering-based enterprises today are immersed in complex webs of relationships. It is not at all unusual today to see competing companies, universities and government agencies all working together on a common challenge. The firewalls that once kept companies and institutions of all kinds apart have crumpled. The “not-invented-here” mindset should no longer exist in practice. Ideas flow freely in multi-company, and typically multi-national, alliances.

Yet an age of specialization, in which a matrix of relationships is an essential norm, requires an entirely new attitude toward partnership. Each must view the other as internal, an integral component of one’s own company and perceive the partner’s success as tantamount to the parent company’s own. The idea that companies can create dynamic products together, or not at all, is still alien. The new reality of equality, and of genuinely shared fate, is difficult for traditional competitors to fully appreciate.

My own company is a case in point. Fluor was once a self-contained family-owned business, much like the majority of companies were in the last century. At last count, Fluor had no fewer than 47 different major strategic alliances, partnerships and joint ventures to better serve customers in the U.S., Central and South America, Europe and the Asia-Pacific market.

5.4. *Improving the chemistry*

In the media age, chemical engineers need to do a far better job of managing their image. Most professions blow their own horns. Yet when an engineer takes up a horn, he would rather take it apart to see how to improve it than to attract attention by blowing it. Chemical engineering is not a noisy profession.

A chemical engineer’s pride too rarely gets translated into positive visibility for the profession. The challenge for future engineers is to be more visible, more involved in professional organizations, alumni efforts, corporations, communities and organizations that are important to their customers... to take great pride in what is accomplished and communicate that pride at every opportunity... to displace a little of the dispassionate logic with vocal and visible passion. Chemical engineers need to become as adept at interacting with societal and political forces, as they are with chemical and mechanical forces.

5.5. *A company balancing act*

Whether large or small, serving multiple markets or specializing in select areas, companies will need to find the right balance to stay competitive. The cyclicality of growth and contraction will not change in the 21st century; therefore, chemical engineering companies need to effectively manage and continuously move their resources to the markets where the opportunities are greatest. As Jack Welch, the recently retired CEO of GE who holds a doctorate in chemical engineering, likes to put it, “We have to find

a way to combine the power, resources and reach of a big company with the hunger, agility, the spirit, and the fire of a small one.”

5.6. *The new professional*

Chemical engineers have improved the quality and quantities of many products that enhance the quality of all our lives. At the same time, they have continued to serve as leaders in environmental and safety innovations. It is, in fact, the adaptability of a field that can successfully straddle both science and engineering, physics and physical plumbing, that makes chemical engineering so viable in an age where change is the only constant, and constant improvement the only option.

Can all of this be accomplished? No question, chemical engineering faces many challenges in this new century, yet certainly no more fundamentally insurmountable than this unique profession has already overcome.

From its inception, there was tremendous resistance to a new profession that was neither pure chemistry nor engineering but a hybrid of both. Most questioned what, if any, role chemical engineering should play. From day one, chemical engineers had to define their dualistic vision and demonstrate their value.

As the profession struggled to prove itself, particularly in North America, little respect was given to chemical engineers. Even less respect was given on payday, as chemical engineers at the turn of the 19th century received less remuneration than a master plumber or machinist. As late as 1921, one prominent chemical engineering innovator said, “We [chemical engineers] are not even able to convince other engineers that we are engineers.”

Despite opposition, and some might say because of opposition, chemical engineers have made a contribution to the Industrial Age that was far greater than numbers would indicate. Chemical engineers have been the major innovators in industrial age processes, from petrochemical, food additives, fibers, antibiotics, polymers, therapeutic devices, isotopes to splitting atoms. In large accomplishments and incremental innovations, chemical engineers have changed the world for the better. As Linus Pauling said, “The best way to have a good idea is to have a lot of ideas,” and chemical engineers have had a lot more good ideas than virtually any other professional field.

To meet the energy and development demands of the 21st century, process technology in the chemical processing industries must answer the call for new products and new facilities to produce them. Additionally, continued development of chemical processes will be required to meet environmental objectives. These include the recycling, reuse and disposal of waste materials using physical chemical principles, and a host of others to protect future generations.

Further reduction of emissions from combustion processes is a key area requiring chemical technology. Improvements in energy, thermal efficiencies and reductions in emissions will be key areas of future chemical engineering expertise.

Some of the greatest contributions may be in the biomedical field. Just as chemical engineers have advanced chemical processes in manufacturing facilities, there is tremendous potential to bring value to the processing units of the human body.

Reflecting across the many industries that chemical engineering enhances, the designs of today will not meet the requirements of tomorrow. Sustainable development will require new designs, new thinking and the creativity that only the chemical engineers of the third millennium can provide.

Chemical engineers will need research, and the combined cooperation of facility owners, contractors and academia as never before to meet this challenge. Collectively, they will need to invest in their industry — in their future.

6. Conclusion

In this new age of partnership and interdependence, each side in every relationship must be concerned with the long-term viability of the other. How well chemical engineers succeed individually will determine the fate of their organizations cooperatively. How well they succeed as a professional community will determine the fate of their industry.

I am personally optimistic that there will be a continuing and growing need for the unique and varied skills that the chemical engineering profession will bring. The huge number of industrial complexes that will be built as global economies continue to strengthen will require much from this industry. Through automation tools that create faster and more accurate designs, logistics tools that create just-in-time delivery to remote jobsites, and advanced electronic tools that drive efficiencies in every part of the business, engineers have an opportunity to make a step change in what they deliver. Reductions in the capital costs of facilities of 20 or 30 percent and reductions in schedule of the same magnitude can be achieved. The impact of such changes will be fantastic.

If there is any real certainty of today, it is that there is no calming the knowledge whirlwind, and no reversing the integration of companies' and countries' urgent need for collaboration and cooperation.

Ultimately Vaclav Havel was correct. We live in an age where everything is possible, and nothing is certain. Yet if we make the effort to eliminate the uncertainties, then the possibilities for chemical engineers in the new century will be limited only by their ability to work together in mutually beneficial ways.

Chapter 6

Formulation of a Vision: Chemical Engineering in the 21st Century

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1. The framework

It would be presumptuous to say that I have a vision for the future of Chemical Engineering. A vision has value only if it is a shared one, and only if it is reached after focused and thorough discussions with those involved.

What I would like to present, rather, are some personal perspectives on the formulation of a vision of the chemical engineer's role, discussing its components from a personal viewpoint, drawing on the ideas presented in the previous chapters.

I would like to propose a framework which focuses on the chemical engineer as a person and three related aspects of his life: the job, the contribution to the society, and the responsibility to the physical world (Fig. 1). First, however, I shall highlight the important social, technological and economic factors affecting the life of the chemical engineer.

2. A new environment for the 21st century

Science and technology have occupied a central position in the 20th Century and have ushered in the knowledge-based economy. The profound changes in the social-economical environment that science and technology have brought about will be carried further. The characteristics of our present environment are illustrated in Table 1, showing the trends that can be expected to influence the future. Most of the features listed in Table 1 will be familiar to the chemical engineering community.

We live in a world changing at an increasingly rapid pace. To illustrate the pace of technological innovation, consider as a benchmark the number of years for a technology to reach 50 million users worldwide. It took radio 35, personal computers 16,

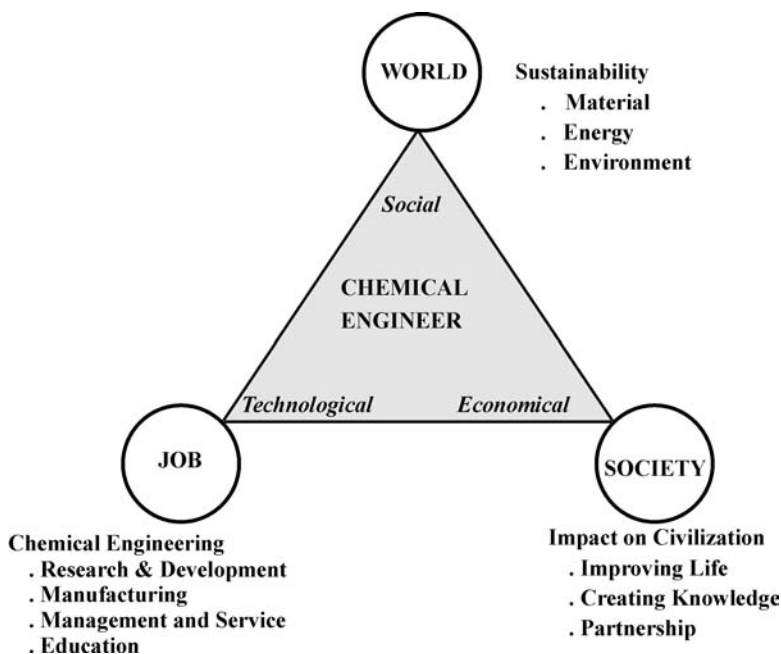


Fig. 1. Formulation of a vision: the chemical engineer in the 21st century.

color television 13 and the world wide web 4 years respectively to reach this mass audience [1].

The structural changes in the chemical industry in the last two decades have been phenomenal and are still occurring. At one time, a chemical engineer would have been proud to pursue a career opportunity with corporate giants like Hoechst, ICI, McDonald Douglas, Rhone Poulenc, Union Carbide, or American Cyanamid. Where are these companies now? The answer is that they have been down-sized, divested, acquired, merged and re-structured, some many times over, as vividly illustrated by Professor Felcht in Chapter 3.

The nature of competition between companies is changing. In the past, a chemical company knew who its competitors in the marketplace were. In the future, competitors will emerge unexpectedly from all directions. Suppliers, customers, partners can all change roles to become competitors. Competition from new technology will be severe in many instances. The only advantage is that in every competition, there will also be an opportunity for cooperation. In the knowledge-based economy, knowledge has more value if shared. This is the essence of this non-zero sum game.

Thus we have witnessed technological and social transformations at multiple levels with far-reaching effects in our home, office and factory, and impacts on the routines of our daily life, our jobs, our modes of operation and our ways of thinking.

Table 1
The characteristics of our world

-
- Compression of time and space
 - the world is a global village; things occurs ever-more rapidly
 - Ubiquity of personal computers
 - the personal computer has become the major tool of mankind
 - Internet connected world
 - information is linked and shared instantly worldwide
 - Disappearance of the business giants
 - whither Monsanto, Rhone Poulenc, Union Carbide...?
 - Re-structuring of the chemical conglomerates
 - re-engineered and re-incarnated
 - Prevalence of WWW, E-commerce and M-commerce
 - the middlemen is an endangered species
 - Manufacturing for mass customization
 - tailor made product at mass production price
 - Overlapping manufacturing and service sectors
 - information technology makes it happen
 - Convergence of basic and applied sciences
 - information technology facilitates this too
 - Reduction in lead time from research to commercialization
 - availability of IT and venture capital
 - Manufacturing with zero environmental impact
 - reduce, re-use, re-cycle
 - Genetically modified world
 - GM becoming significant sources of food and materials
 - Rising opportunities in new technologies
 - information, bio-, micro-, and nano-technologies
 - Global competition and local strength
 - compete globally with local advantage
 - Life-long learning
 - improvement through recharge and renewal
 - Competition from unexpected sources from all directions
 - suppliers, customers, partners, new technology
 - Cooperation for survival and growth
 - more wealth can be created and shared
-

3. The job: chemical engineering

A chemical engineer may perform one or more of the following functions: research and development, manufacturing, management and service, and education.

3.1. *Research and development: product*

Analyzing the disintegration of big conglomerates and the restructuring of the chemical processing industries, especially in Europe, Felcht portrays in Chapter 3 two basic types of chemical companies: the Molecule Suppliers and the Problem Solvers.

Molecule Suppliers include manufacturers of commodities and fine chemicals while the Problems Solvers are manufacturers of specialty chemicals, pharmaceuticals, agricultural and other active ingredients. To compete, Molecule Supplier companies will rely on sophisticated process technology, economies of scale, access to cost-effective raw materials, interlinked energy and material saving processes and excellent logistics systems. Problem Solver companies will compete on unique product property and performance, or high end-use value provided to customers. Thus whilst Molecule Suppliers can easily be substituted on cost and availability criteria, Problem Solver companies are not easily, if at all, substitutable, and thrive on the “magic” performance of their products.

A chemical engineer pursuing product R&D should strive to analyze the nature of his business and the success factors concerned — and then design for an architecture of high end-use values, or for an interlinking of material and energy efficient processes. Additionally, the reduction, re-use and recycling of a product during its full product-life cycle should always be considered during its product development.

Chemical engineers working in product R&D should have an intimate knowledge of nano-science, life science, biotechnology, genetic modification technology, advanced materials technology, computer modeling and computational science.

3.2. *Research and development: process*

It is the job of a chemical engineer to develop and optimize chemical and physical processes in the transformation of raw materials to products. The efficiency and effectiveness of chemical processes will remain the heart of the chemical engineering profession.

There is a new twist in process design though. Chemical engineering processes should be optimized not only for economic but also for environmental performance. This places new constraints and boundary conditions on process modeling and computer simulation. Chemical engineers are required to have in-depth knowledge not only of process efficiency but also of the chemical pathways involving both common and uncommon raw materials.

A product will thus be designed by considering molecular composition and conformation for its end-use value as well as process options for minimal by-products and wastes. This sort of integrated product and process design may require the formulation and analysis of multi-objective nonlinear mixed integer systems of very large scale and complexity.

Nano-technology will play a prominent role in the future synthesis of molecular thin films and devices. Nano-technology is defined as the study and manufacture of structures and devices with dimensions about the size of a molecule. Nano-scale physics and chemistry might lead directly to the smallest and fastest transistors and the strongest and lightest materials ever made [2]. Likewise, bio-catalysts such as proteins will be increasingly used to facilitate relevant chemical reactions at ambient conditions. Natural macromolecules will be explored to provide selectivity similar to inorganic chemicals such as zeolites.

Micro-fabrication technology and micro-reaction engineering will be explored extensively so that reaction processes can be conducted on much smaller physical scales and with high precision controls. Micro-scale unit operations are likely to gain acceptance for the manufacturing of fine and specialty chemicals.

End-of-pipe treatment will be the last resort for minimizing pollution. Government regulations will mandate high prices to be paid for discharging volatile organics, aerosols, air borne particulates and various waste streams to the environment.

To assure product quality and process safety, modern instrumentation and automation technologies including multimedia interfaces, artificial intelligence and virtual reality will be increasingly adopted.

3.3. *Manufacturing*

Manufacturing of basic chemicals and their downstream products will remain a major pillar of the world economy. Many of the strategic consideration and success factors discussed for product and process R&D will apply equally in manufacturing.

A manufacturing facility will continue to strive to optimize cost and delivery time. It will require sophisticated instrumentation, automation and data dissemination. To the greatest extent possible it will streamline the design and control of the flow of people, materials, and data. It will include zero loss, zero hazard and zero pollution as targets of operation. All this will require innovations at all operational levels.

A manufacturing plant will not simply be producing physical products. Instead it will be viewed as providing to its clients solutions which may require software, consultation and services as well as hardware. Thus a manufacturing company will behave like a “service” company for which customer satisfaction is a key element of business.

Agility will be a new paradigm of manufacturing. Increasingly, products will not be made on the basis of forecast demand, but made to order. Personalized or customized products will be available at the right time and at a mass production price.

Micro-processing will be another paradigm. Micro-reactors, micro-heaters, micro-exchangers and the lab-on-a-chip will be developed to provide industrial scale production, especially for liquid and gaseous phase reactions. Process intensification will also offer new opportunities for industrial safety and pollution control [3].

The future chemical plant will have a very intensive information technology component on the inside and will have a total face-lift on the outside.

3.4. *Management and Services*

Managing a plant, and running a business in general and a chemical business in particular, will in the future be quite different, due to the advent of electronic commerce and global supply chain technologies. Electronic commerce deals largely with the front-end, the customers-to-business relationship, while the supply chain deals with the back-end, the business-to-suppliers relationship. By combining these, a chemical factory or business can be managed with minimum amount of inventory, and reduced marketing, warehousing, technical service and sales forces. This minimization will revolutionize the business model of the chemical processing industries.

Ventures such as OMNEXUS, ELEMICA and ENVERA, that offer a platform for business transactions through the internet, demonstrate the paradigm change in the chemical business. Logistics support is an important element of any successful chemical business operation [3].

Globalization will be a key element of the knowledge-based economy. Capital, market and human resources will travel around the world transcending national boundaries. Thus when one engineer sleeps, his customers, suppliers and competitors will be busily working on the other side of the globe. A global business culture with 24-hour service readiness will become the norm.

While the factors of production will be global, the core strength that gives rise to the competitive advantage of a company is basically local. Thus for companies to globalize successfully, they will need to enhance their local strength. It is also noteworthy that only with globalization can a company fully utilize its advantage in technology, and in natural and human resources around the world. Like technology and democracy, globalization can be deferred but not deterred.

The key question in all management or service functions is: what is the value that can be provided to the clients? The answer to this will determine the mode of operation of the business.

3.5. *Education*

After a century's development in Europe and the USA, chemical engineering has matured to become a well-rounded discipline. It has made remarkable contributions to the economy especially in fostering the growth of the petrochemical and downstream industries as reviewed by Professor Perkins in Chapter 2. However, the need to re-examine and improve chemical engineering education is now commonly accepted.

Problems in chemical engineering education have become apparent in several ways. First, the rapidly changing economic environment has required practising professionals to master skill-sets different from what they gained through the traditional curriculum. Second, it has become increasingly difficult to attract and retain the best students in the profession. Third, the rise of microelectronics, bio-engineering, nanotechnology and other new technologies, while broadening the outreach of chemical

engineering, has also significantly stretched the cohesiveness of the traditional chemical engineering curriculum. These phenomena have been observed not only in Europe and the USA but also in the Asia-Pacific region.

The sources of this unsettling situation are many. They include:

- the dwindling prominence of the chemical industry in the new economy,
- the restructuring of the chemical processing industries with diverse business models and strategic foci,
- the association of chemical engineering with environmental pollution and industrial hazards,
- a profession increasingly being marginalized, and
- a lackluster appearance compared to many more glamorous technologies.

Within the field of chemical engineering, there is a constant pressure to strike a balance between specialization and generalization, between analysis and synthesis, and between chemical engineering science and process system engineering.

The principles and methodology of chemical engineering have been instrumental in the development and application of many new technologies like bio-engineering, genetic engineering, microelectronic processing, micro-fabrication and nano-technology. The 1988 Amundson Report has related the salient features of chemical engineering to the frontiers of science and technology [4]. However, an adequate appreciation of these relationships is often beyond the interest or capability of a normal chemical engineering graduate student. A new curriculum should cultivate a greater interest and more familiarity with current scientific advances.

There is also a great need for communication between chemical engineers and society to foster an active partnership in bringing the fruits of technology to the benefit of mankind. A new education program will have to bolster the communication skills, professional culture and leadership qualities of future chemical engineers in this era of globalization. Chemical engineers have been recognized as leaders in the society of the past century and should continue to play that role in the future.

Whereas many key issues facing the universities are common, each university must develop its own program in line with the mission and vision of the institution. Whether, for example, it is appropriate for a university to foster bio-engineering as a separate discipline, as MIT has done, is something that can only be decided locally.

We conclude that, though the problems in chemical engineering education are abundantly clear, the availability of solutions is not. It is widely known that universities frequently originate radical ideas, but seldom in curriculum matters. Thus the chemical engineering education program is expected to change in an evolutionary rather than a revolutionary fashion, but change it must.

4. Society: impacts

Chemical engineers, as a group, have made significant contributions to society in the last decade, as recorded earlier in this volume. These contributions have improved the quality of life — providing food, clothes, shelter, transport, health-care, and the like. Much of the comfort and enjoyment that the Industrial Revolution has brought to mankind can be attributed to the work of chemical engineers.

Chemical engineering has also contributed to the formation and development of other disciplines such as information technology, telecommunication, bio-engineering and the life sciences. An examination of national critical technology lists of the USA or OCED countries will show that chemical engineering is a major enabler [5].

Many of chemical engineering's contributions to other fields may not be obvious to society at large. It hurts when young students making a career choice do not recognize this, but consider chemical engineering as simply a dreary, mature discipline. It also hurts when society views chemical engineering in a bad light due to misunderstanding and inaccurate publicity on accidents, explosions and pollution. When the public sees a fire in a chemical plant, the chemical engineer usually gets the first blame, even if a defective electric motor may have caused the fire. This is not to absolve the chemical engineer of his responsibility for plant safety, of course!

Thus the contribution of chemical engineering to society has been obscured since it generally remains in the background, sharing the limelight generally only on unpleasant occasions.

Hence there is an urgent need for chemical engineers to properly inform and engage society so as to foster an active partnership. This is a priority for chemical engineers, for their licence to practise, continuously and productively, as has been pointed out in previous chapters.

5. The world: sustainability

The world is focusing now on sustainability (see Chapter 4). Chemical engineers are vitally concerned with processing and producing materials, so we have a special responsibility to make sure that all the materials involved are deployed efficiently, that scarce resources are conserved, and that energy is used effectively. Most of all, what we produce, by-product or intended product, should not harm people, or the environment with its natural diversity of plant and animal species. Indeed, the day may come when a chemical plant can release to the environment only water and carbon dioxide, both in controlled quantities. A recent survey of leaders in the chemical and chemical engineering community revealed a consensus on the attainment of environmental sustainability as a top priority for the industry [6]. If chemical engineers do not take the initiative responsibly and voluntarily, they will be forced to take action

by the government. The balance between voluntary and involuntary actions defines the license to operate for chemical engineers.

In the 20th century, certain national or multinational companies were apt to set up relatively inefficient manufacturing operations in regions or countries requiring less stringent safety or pollution standards. This type of practice has resulted in the deterioration of the overall environment quality. In the future, chemical companies will be expected to establish industrial practice and standards beyond the minimum environmental requirements, regardless of location. Legislative actions and the availability of knowledge to the citizenry will enforce this practice.

The movement of Responsible Care, started in Canada in 1987, has been adopted by a majority of chemical producers in the developed and developing economies. If it extends to small and medium size enterprises, this will provide a good framework for sustainability ([7], and see also Chapter 4). The more recent development of the Global Reporting Initiative (GRI) defines a further process of environmental reporting and has increasingly gained acceptance world-wide.

6. A chemical engineer's view of the future

The chemical company of the future will be lean and agile. Today products are made to forecast and for groups or sets of customers. In the future, many products will be made to order and for individual customers, to satisfy the specific effect they require. Further, this level of customization will be available to the individual clients at a mass production price and supplied with a short time for delivery through a mastering of logistics and global supply chain management. A chemical business will require very little inventory and warehousing.

The traditional roles played by various middlemen providing financial, insurance, brokerage, distributions, and trading services are gradually being squeezed out or significantly transformed by e-commerce and wireless technologies. The distance between producers and consumers is shortening, and the segmentation of manufacturing and service sectors is becoming diffused.

The boundaries between basic and applied sciences will increasingly overlap in many fields. The lead-time from research through development to commercialization will be much shortened. The traditional way of allowing years of laboratory work and pilot production before introducing a product to the market, such as in many chemical engineering fields, will be untenable. Increasingly, chemical engineers will find it necessary to integrate computational science, nano-technology, process simulation and market research to synthesize product with the desired performance and shortens the time-to-market by orders of magnitude. This will be a new dimension of the paradigm of manufacturing.

Our air space, bodies of water, urban and rural landscape will tolerate no more pollution. Consequently, a product will be allowed to circulate only if its manufacture,

use, and final disposal leave little or no environmental footprint. Few communities will allow a plant to be built that takes up hundreds of hectares of land, as seen in traditional chemical processing industries, which will require extra attention to the containment of processing hazards and pollution.

Major advancement in minimizing processing risks will be accomplished by using arrays of micro-reactors, in series or in parallel, in conjunction with robotics and sophisticated control schemes. The use of mini-factories will also enhance product flexibility and production agility. Most chemical plants, except those for petroleum cracking and well-established bulk materials, will be miniaturized to the extent possible. This will be another paradigm of manufacturing.

The advent of genomics and genetic engineering will enable the creation of many genetically modified plants, animals and micro-organisms. In the years ahead, many uncertainties involving the use of genetic modification will be resolved and thus its application broadened. Many new materials such as catalysts, additives, specialty chemicals as well as components or devices may be prepared by incorporating biotechnology or genetic modification technology to increase its efficiency and reduce hazards. At the same time, chemical engineering will demonstrate its multi-faceted contributions to the developments of these fields and other emerging technologies.

7. Conclusion: the role of chemical engineer

In concluding, let us summarize the three roles that emerge for the chemical engineer in the 21st century.

First, chemical engineers will develop, operate and optimize chemical and physical processes to transform raw materials into products for the enrichment of the quality of life. This is our traditional role, which will continue to be played with professionalism and distinction.

Second, chemical engineers will promote and exploit the applications of new scientific advances to benefit mankind. This, arguably, represents an expanded role for the profession, and through it chemical engineers will come to be recognized by society for their versatility, high potential and multi-faceted contributions. This will place chemical engineers in the forefront of the changes of the time.

Third, chemical engineers will apply related knowledge to achieve sustainability and harmony for the world environment. This role is one that can be played best by chemical engineers among all professionals. I believe this is a role in which chemical engineers can offer the greatest value to mankind and is also a responsibility that they cannot refuse.

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Chapter 7

Commentary on the Visions

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1. The first hundred years and tomorrow's world

During the twentieth century the chemical and process industry was one of the greatest contributors to improving mankind's quality of life. This contribution arose from the application of chemical engineering to manufacturing products on a wholly new scale. It involved both academic and industrial practitioners in the development of the discipline, which acquired a coherence suited to this period, based initially on the "unit operations" approach pioneered at MIT. The major achievement of the discipline was in the development of economic and safe processing of materials in bulk, often based on petroleum feedstocks.

The perspectives of Chapters 1 and 2, show how the profession addressed the challenges of growth and change in the past. This survey reminds us that many of the issues debated were never "solved", but remain with us. The tension between science and technology, between analysis and synthesis, the question whether Bird, Stewart and Lightfoot's book was really dangerous in its consequences¹; all these are issues with real current relevance to the profession.

¹It was argued by Sherwood that the book was so well written that its emphasis on an analytical approach would tend to relegate the aspects of design and synthesis to a lesser role. The debate is recounted in Chapter 2.

2. Future shape of the process industries

Chapter 3 shows how the commercial world is responding to changes in science and technology supply, and consumer demand. The case is built on the chemical industries, but similar pressures are driving changes throughout the process sector — in oil, minerals and utilities. Driven by the competitive pressures of a truly global market, companies demerge and reform so as to focus firmly on a narrower core business. These changes will continue in the twenty-first century as companies concentrate on their core strengths and make better use of supply chain partnerships.

The new chemical industry will have two main types of companies. The “molecule providers” will focus on delivering commodity and fine chemicals at the lowest cost. These will require all the traditional skills associated with chemical engineering with a particular emphasis on supply chain and logistics optimisation, plant efficiency and reliability. The “problem solvers” will provide customised effects. Whether these are speciality additives or personalised drug systems, the customer is more concerned with the efficacy of the product than with specification of the composition of the product.

The new companies will be focused on innovative products and consistency. Their manufacturing processes will still need to be cost-effective but they must also be agile and flexible. The traditional skills of chemical engineering will need to be enhanced by a greater focus on sciences such as informatics, biotechnology and nanotechnology (materials) as well as traditional chemistry. Molecular engineering will allow new products to be designed on a molecular basis and foster new industrial and academic relationships.

3. The chemical engineer and the community

Chapter 4 sets out a view on proactive engagement with the community. Interaction with society is a key theme of the visions, and it is helpful to note the different ways in which they perceive this interaction. Two paradigms for the role of the engineer are summarised in Table 1². The Business Model corresponds to what has become the conventional role of the engineer, whereas the Social Contract Model corresponds to the view of the Engineer as not just a technical expert but also a “social agent”³. The vision of Chapter 5 follows the Business Model, whereas Chapters 1 and 4 are grounded in the Social Contract Model. Engagement with the community is seen as a two-way process — mutual learning, not one-way instruction. The key phrase “practising our profession in direct partnership with the community” means taking an inclusive participatory approach to decisions.

²Dr Cynthia Mitchell of the Institute for Sustainable Futures and Anna Carew of the University of Sydney communicated this approach.

³See R. Clift, *Trans. IChemE* 76B (1998) 151 for a discussion of the role of an engineer in society.

Table 1
Characteristics of Business and Social contract models of engineering practice^a

	Business model	Social contract model
Accountability	Our colleagues, our clients and our organisations	Our community and ourselves
Objective	Primary focus on wealth generation for business	Primary focus on pursuit of public good
Operating paradigms	Legislative compliance; economic primacy	Transparency; inclusion; participation in decision making

^aBased on E.A. Taylor, Australasian Journal of Engineering Education 6 (2) (1995) 145.

The Social Contract Model for engineering practice has a long pedigree. The first Australian Professor of Engineering, William Charles Kernot of the University of Melbourne, clearly envisaged engineering practice this way. Kernot commented on the poor professional standards of engineers in the 1890s: “They are quite unable to place themselves in the position of an intelligent person ignorant of the special matter in hand. They commonly assume that it is discreditable for another not to know what they know, but do not realise that they are subject to criticism for not knowing what others know.”

The London Communiqué, issued in 1997 and endorsed by 18 chemical engineering societies worldwide, explicitly adopted the Social Contract paradigm, for example (see Fig. 4, Chapter 4):

Chemical Engineers will... engage in honest and open dialogue with the public on the challenges presented by manufacture of the products which the public requires.

The Melbourne Communiqué, announced during the 6th World Congress and supported by 20 societies, equally clearly follows a Social Contract Model, for example:

We will use our talents, knowledge and organisational skills for the continued betterment of humanity to protect the public welfare.

Chapter 4 poses the challenge of building and maintaining the trust of the community in which and for which chemical engineers work. It refers to the need to learn from past mistakes, and to focus on knowledge-based products. Engineers are justly proud of their knowledge-based products, but ignorance-based products also occur, and do indeed illustrate our past mistakes. Here are a few examples of ignorance-based products:

- *Thalidomide*: a drug whose unforeseen side-effects were calamitous;
- *CFCs*: compounds with the right physical properties, but globally damaging chemical effects;

- *DDT*: good for killing insect pests, but with the unfortunate property of accumulating right up the food chain;
- *Viagra*: a counter example — intended as a heart drug; ineffective for that purpose but with an unforeseen side-effect which has made it popular and profitable.⁴

These examples remind us that there are good reasons why the lay public does not always trust the assurances of experts. DDT is a particularly instructive example. The effects of DDT and related agrochemicals were documented in Rachel Carson's book, *The Silent Spring* (and Chapter 1 reminds us of the continuing risk of silent springs). The agrochemical industry tried to suppress the work and thereby worsened the long-term effect on the reputation of the industry. The lesson from this is contained in the idea of "proactive engagement with the community", but we continue to see examples of industries which have *not* absorbed the lessons of past mistakes, and still think that "engagement with the community" means "educating the public to understand the expert assurances".

The nuclear industry remains an egregious example; it was even said⁵ that the public would be more accepting if only "nuclear" power were called something different! This attitude denies the fact that there are at least two sound reasons for public mistrust of the industry. One is the risk of operating accidents. The other, probably more serious, is nuclear waste — for practical purposes, a permanent risk with no accepted technology for making it safe. The key principle of sustainable development lies in not stealing from future generations. This includes not creating and bequeathing a long-term environmental problem for which we have no solution. Until the nuclear industry works out how to manage its waste, it cannot claim to be a sustainable technology.⁶ The same conclusion follows from the principles of *The Natural Step*, discussed in Chapter 4. Denial of the reasons for public opposition only lowers the standing of the industry even more.

Other examples abound. A principal cause of Shell's embarrassment over the Brent Spar rig was that they believed they were winning the media campaign, in denial of what was obvious to those outside the company management. Chapter 4 reminds us of the lessons from the accident at Longford, on the outskirts of Melbourne.

The Silent Spring was a seminal book in the development of the environmental consciousness which is one of the threads leading to the concept of sustainable development espoused by the London and Melbourne communiqués. Another seminal work, referred to by several speakers at the 6th World Congress, was *The Limits to Growth* — the first report of the Club of Rome. If we concentrate on the accuracy (or inaccuracy) of the predictions in the book we miss its principal message: that exponential growth in use of resources and environmental emissions is unsustainable.

⁴Professor G.B. Lawson communicated this example.

⁵Stated in plenary discussion at the 6th World Congress.

⁶The route to achieving a low-carbon economy without nuclear power is discussed in "Energy — the changing climate" the 22nd Report of the (UK) Royal Commission on Environmental Pollution (RCEP, 2000), The Stationery Office, London.

Yet the visions of Chapters 3 and 4 refer to sustained growth as part of sustainable development, an equation which is impossible unless it is accompanied by much greater improvements in resource efficiency than are at present foreseeable. Recognition that there are constraints on resource availability and the “carrying capacity” of the biosphere is an essential part of the concept of sustainable development, underlying the concern for equitable distribution of access to resources and services. *The Limits to Growth* differentiated between growth as increase in quantity, and development as improvement in quality. Sustainable development includes recognising that quality of life is not to be equated with quantity of material consumption.

The particular areas which mark out the discipline of chemical engineering include systems analysis and thermodynamics (see Chapter 2). So the underlying message of *The Limits to Growth* should be clear: in chemical engineering terms, it amounts to pointing out that the earth is a closed thermodynamic system. Our professional responsibility to engage in public dialogue includes the responsibility to ensure that our particular perspectives and understanding are represented. In the short term, it may be tempting to acquiesce in denying thermodynamic reality by equating sustainable development with sustained growth, but our grandchildren will not thank us if we fail to articulate this essential chemical engineering insight.

4. Practice of the profession

Chapter 5 presents a vision from the perspective of a global business employing technologists and competing aggressively for market share. Operating in an extremely dynamic business environment means introducing new technology and new business methods ever more rapidly, to satisfy customers and out-compete rivals in the market. This is the Business Model of engineering practice, as remarked above. The social contract (referred to in Chapter 4 as a licence to operate) in this model follows from compliance with environmental and social goals, in the setting of which chemical engineers and their global employers will be able to play a key role.

Technological innovation, rather than societal development, is seen as the primary source of growth.

This model of the present and vision of the future suggests some interesting consequences for chemical engineering practitioners. For example, the need for engineering specialists able to cope with the high pace of technical change and to generate and handle the advanced technology remains high. Yet commercial (cost-cutting) pressure reduces the ability of companies adequately to remunerate these skills. The predicted result is lower pay, lower prestige, and in the long term a shortage of those professionals who could and should be able to drive this model of growth. It is suggested that this result, and others that follow from severe pricing pressure, will not just be a feature of downturn periods in the economic cycle, but are inherent in the super-competitiveness of the “hyper economy”.

Chapter 5 explores this world of very rapid technical change and hyper economy. A variety of measures suggests that human knowledge is growing very fast — at least measured in quantity, if not necessarily quality. This in turn is leading to increased specialisation, as any single individual is unable to understand all the dimensions of an issue. One consequence is the growing importance of knowledge management, where the challenge is to develop both formal and informal networks both within institutions and with outside stakeholders, including society. An institution which succeeds in this difficult task will have a clear competitive advantage, and an ability to renew itself in response to changing exterior forces.

Of equal importance in this world is the need for individuals to embrace lifelong learning, an area where professional bodies can be powerful factors. Only the most progressive employers, faced with the short-term pressures of the hyper economy, readily give enough attention to training which has a long-term pay-back. Yet constant investment in skilled people is needed to make this business model work.

In this business-oriented worldview, the role of the engineering professional in interacting with society is as adviser and guide, using marketing skills to communicate a rational message. The challenge for professionals then is in not merely *telling* society, but equally in *listening* to society's view, and being ready to respond positively to that view — however scientifically correct the professionals may feel their own position to be. A number of delegates at the 6th World Congress raised the issue of the need to “educate” the public. While this is important, it is equally important to recognise that it is often the engineering professional who most needs “education” when he or she fails to recognise the legitimacy of society's concerns.

Tackling this two-way communication positively will require new partnerships between industry and society, between the profession of engineering and that of public health, between a chemical plant and its immediate neighbours, and many more such combinations. A key challenge for the process industries and chemical engineers as they strive to create new wealth will be to gain the approval of the public. We must learn to understand and respect public perceptions and opinion and use gentle persuasion rather than stating “facts”.

5. Teaching and training

Education received considerable attention at the 6th World Congress, from the discussion of its historical role in the development of the profession presented in Chapter 2, to consideration of the new curricula required to equip us for various visions of the future. The tone was set by Lord May (Chapter 1) in offering this as part of his future vision: “I believe the widening sweep of the Biotechnological Revolution has implications for Chemical Engineering practice beyond the dreams of its wildest chauvinists”, and he goes on to suggest some elements of an appropriate curriculum.

5.1. *The expanding scope of the discipline*

The various strands which have come to make up chemical engineering have been identified in Chapter 2 — unit operations, the chemical engineering science movement, transport phenomena, the formalisation of the systems approach in the ideas of process synthesis, and the development of biochemical engineering. The discipline is now facing several new challenges, summarised also in Chapter 6.

First there is the very rapid development of the science base. In informatics, new materials, synthetic chemistry, and particularly the new biological sciences, those who hope to make an engineering contribution are faced with the need to master, or at least understand, new fields of significant scope. This is being tackled in some Universities by the establishment, for example, of separate Departments of biological or biochemical engineering. Another option, popular in Australia is the introduction of double or joint degrees, in which a student studies, in depth, a second subject in addition to chemical engineering. Often, extra years of study are required. Whether these moves are a demonstration of flexibility of the discipline, or the beginning of disintegration, only time will tell. They are however an obvious response to the opportunities offered by these new sciences, and are a consequence of the view that biological sciences, at any rate, are now too large and complex to be simply added on to a conventional chemical engineering course.

This introduces the second challenge, which is that whilst there is pressure on the education system, particularly from research funders, to gallop into these new areas, there remains a substantial demand for “conventionally” trained chemical engineers, able to service and develop the manufacturing industry that has been providing the developed world (at least) with essential goods and services. The core of the subject cannot be neglected, but curricula obviously have to be developed to accommodate both old and new subjects. One delegate quoted Woodrow Wilson’s wry comment “Changing curricula is like moving graveyards”. (Wilson had been a professor of Political Science and president of Princeton before becoming President of the USA.)

It is clear that we need to develop a student’s ability to apply science and chemical engineering fundamentals. But the “core” must be continually re-examined and refined, and just how should the science component, particularly biology, sensibly be incorporated? Rather than facing a big slab of sciences at the beginning of the course, would it not be better to introduce them as needed?

On top of the challenge of the new sciences is the requirement that our graduates be more conscious of their ethical responsibilities and able to deal with the agenda of Sustainable Development. This priority has been strongly underlined in the vision of Chapter 4 but features, not surprisingly, in all the visions. The understanding of what Sustainable Development means for us, and for our business or other professional activity, is expanding rapidly. It is surely a topic that all engineering courses now have to treat seriously, as we train engineers who will, let us hope, still be practising in 50 years’ time. The hard fact is that although academic staff tend to look

towards a technical definition of the profession (in terms of thermodynamics, transport processes etc), many practising engineers in industry spend a large part of their time actually dealing with economic, environmental and community aspects of the job. A definition of chemical engineering, and thus the composition of the University course, should take account of these aspects.

Whether it is in the new science (nanomaterials, protein chemistry and structure. . .) or in Sustainable Development (global warming, stakeholder analysis. . .), graduates are moving into fields remote from the traditional chemical engineering core.

5.2. *Recruitment to the profession*

The attractiveness (or otherwise) of the University course is a vital factor in recruitment to the profession, which, as pointed out in Chapter 2, is one largely staffed by graduates. This attractiveness is enhanced by an exciting and modern course of study, but also by the perception that interesting and rewarding careers will follow. In many countries the chemical industries are held in low public esteem, associated with “smokestack, old economy” manufacturing, and with pollution or explosion/toxicity hazards, and this poor image is a hindrance to recruitment. There seems here to be a good case for action by academia/industry partnerships that were once such an important part of chemical engineering education, but which in recent times have fallen away in many parts of the world.

It is significant that all the visions, from their different perspectives, offer a bright future for chemical engineers, with exciting and significant contributions to be made by those now entering the profession.

5.3. *Resources and methods*

How can teaching institutions do even more with ever-reducing funding? One way is through clever utilization of new information technologies in teaching and learning. A drawback is the reduced face-to-face contact that students have with their professors, but there are many benefits, for example in individual students working at their own pace. The “Open CourseWare” initiative at MIT, whereby the University aims to make all its teaching material freely available through the World Wide Web, is another concept that may be usefully taken up by others. The importation of material from other teachers has always happened (for example through the use of text-books), so that the availability of web-based material is not a break-through in principle, though its ease-of-use may help to disseminate new ideas and material more quickly. This will depend on the rigorous maintenance of a quality-control system — something that has not always been a feature of “free” material. Education involves far more than just content, though, and teaching material, whether from the web, from video/CD or

other electronic source, has to be integrated into a coherent course of study by the University using it. There is no easy alternative to planning and delivering a good course of study.

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