ISBN 0 86076 090 1

PAUL PREECE

CHEMICAL ENGINEERING - A PROCESS OF CHANGE

University College of Swansea

CHEMICAL ENGINEERING - A PROCESS OF CHANGE

Inaugural Lecture

**Delivered at the College
on 1 March 1993**

by

**PAUL E PREECE
Professor and Head of Department of
Chemical Engineering**

* * * * *

UNIVERSITY COLLEGE OF SWANSEA
1993

First Published 1993 by **University College of Swansea**

Obtainable from Registrar's Office, University College of Swansea,
Singleton Park, Swansea SA2 8PP

ISBN 0 86076 090 1

Paul Preece, Department of Chemical Engineering, Swansea University

Inaugural Lecture - March 1st 1993

"Chemical Engineering - a process of change"

The journey

In 1972 Robert Persig wrote in his book, 'Zen and the Art of Motorcycle Maintenance', about a journey on an old motorcycle across the Arizona desert with his son Chris. In parallel with his description of the motorcycle trip and the difficulties which he encounters with the performance and reliability of the motorcycle, he also tells of a journey of a different kind; the discovery of the relationship between himself and his son. I was influenced by Persig's book not only because of my own interest in motorcycle maintenance, but also by its underlying, simple analogy that, for each of us, our experience of life is also a journey of discovery on which we encounter challenges that may temporarily halt us and which need to be overcome before the journey can be continued.

Persig describes a 'breakdown', actually of the motorcycle, in the middle of the desert. During the course of the repair a single bolt, deep in the body of the broken gearbox, becomes the focus of attention. The gearbox is a complex unit of interlocking gears and shafts; the bolt must be unscrewed before the gears and shafts can be taken apart to determine where the problem lies. None of the spanners Persig carries in the tool-box on the bike will fit the bolt. Using his experience and talent for motor cycle maintenance Persig eventually fashions a suitable instrument from the bits and pieces he finds in the tool-box. The bolt is then removed and the complex internals of the gearbox come easily apart for repair and reconstruction. Continuing the journey, Persig relates for us the philosophical parallel between fixing old motor-bikes and his need to analyse the complexities of his relationship with his son, and how this too can be made to work better.

This metaphor of a journey on an old motorcycle, and its necessary maintenance, with a parallel journey of self discovery is a very powerful way of telling a story. It led me to an idea about how I might approach this Inaugural Lecture. In one sense, like Persig on the first page of his book, I am at the beginning of a journey; one definition of to inaugurate is to commence officially or formally. In another sense I am at the end of another journey, having come here recently to Swansea.

For this lecture I have chosen a title intended to imply how my personal journey of discovery as a teacher of chemical engineering has changed me and my career, and also how the historical journey of discovery and development in chemical engineering has changed the design of process plant.

"Chemical Engineering - a process of change"

During my own journey here to Swansea I have had an opportunity given to members of few professions other than to those of us in academic life; this is to travel the world as an itinerant teacher with a camera. The history of Chemical Engineering is also a journey; of discovery, of invention, of people and of places, and there is certainly a great deal of improvisation and maintenance involved as we shall also see. With the help of the photographic slides accompanying this lecture I will reflect on several adventures I have had as a teacher and also on a journey through time in Chemical Engineering.

The lecture

I have attended many Inaugural lectures and it seems to me that the speakers adopt one of the following two approaches:

- to assume everybody in the lecture theatre has a PhD in exactly the same subject as the speaker, and then to launch into a discussion of the intricacies of the solution of a system's second order differential equations or the structure of its molecular chemistry

- to assume most people in the lecture theatre are, for one reason or another, under an obligation to attend a talk about a subject of which they have only a marginal knowledge

In the latter approach, the lecturer displays the talents of my colleague Professor Morgan who, with the exception of one equation, treated his audience to an insight, in an informed and logical way, into how a branch of engineering can contribute to our understanding of every day events that we often take for granted. I will also try to take the second approach. So no equations and no formulae.

My own area of interest is in computer aided process engineering. In other words, the application of computers to the solution of a range of problems associated with the design of chemical plant or processes in the field of chemical engineering, in particular the way in which engineers interact with design programs, about which I will talk later.

What is a Chemical Engineer?

Firstly, it is important to establish what is meant by the term Chemical Engineer. Most people can identify with Civil Engineers, they design and build bridges and roads; Mechanical Engineers design and build motor cars; Electrical Engineers design and build power stations and computers (with apologies to electronic engineers), but what of chemical engineers? We don't get any real answers from looking around us for the equivalent of bridges, roads, cars and overhead pylons. It is easy to show some of the products arising from the activities of chemical engineers but not what they actually do.

We cannot get away from the fact that chemical engineering involves chemistry. But what distinguishes the chemical engineer from the chemist? Some people would say the scale of the operation is important - if it involves equipment bigger than test-tubes or buckets then it must be chemical engineering. But surely there must be something else

rather than just the scale of the operation. The clue lies in the issues of *Design* and *Operation* of chemical plant, or what has come to be called *Process Engineering*. This is the arrangement of a number of operations involving chemical and physical change so that they produce a product having some value which is other than simply intrinsic. Or, more precisely, how a series of such processing operations can be designed on a large scale in a safe, environmentally friendly, and economic way to produce items which consumers perceive as being useful.

A theme of my lecture will be the historical identification of chemical engineering as a profession in its own right by reference to design activities, distinct not only from other forms of engineering but particularly from all forms of chemistry including applied chemistry and industrial chemistry.

A brief history of time - in Chemical Engineering

How far back in history is it necessary to travel to find the first influences of chemical engineering? One approach we could adopt is to look for the time when chemical engineers first called themselves chemical engineers; this actually happened in 1880, of which more will be said later.

An interesting historical aside, which is relevant even now when my students choose jobs in a wide range of industries, is that the first - the very first - person entitled to call himself a chemical engineer by virtue of a named degree, emerged from MIT in the USA in 1891 and promptly entered the insurance business.

For an early definition of Chemical Engineering we can turn to J T Davies (Furter (1)), not to be confused with G E Davis (2), of whom we shall hear more later, says rather romantically:

Chemical Engineering evolved from a mixture of craft, mysticism, wrong theories and empirical guesses

Furter (1) in the 'History of Chemical Engineering' makes reference to the fact that a lack of a generally agreed date for marking the emergence of Chemical Engineering as a distinct profession is that it has not one but two main roots. In Europe, on which I shall concentrate initially, chemical engineering was based on 'chemistry' i.e. the manufacturing on a large scale of fairly complex molecules, involving the understanding of complex chemical reactions. Furter was referring here mainly to developments in the production of synthetic dyes in Germany. In the USA on the other hand, chemical engineering was based on 'processing' or the physical treatment and processing of one major 'chemical', that is to say oil, resulting in its separation into useful parts such as engine fuels and lubricants. This dichotomy of direction continued for several decades, and only after the beginning of the second World War did the two roots converge again.

In general, the authors of the books I consulted in preparation for this lecture focused on 'processes', 'inventions' or pieces of 'equipment', to determine an historical 'starting point' for chemical engineering. Only Tailby (3), comes close to what I believe is the single most important factor in the establishment of chemical engineering as a profession, and it has very little to do with chemistry or processes in themselves.

Let us turn our attention briefly to a period which for those of us studying history on the 'O' level syllabus in the 1960's was crammed commonly into a two year study. This period, 1756 -1914, embraces the Industrial Revolution and the changes that arose from a great increase in population, and the movement of people from agricultural activities in the countryside to the mass production factories in the towns.

We see here the first shift in the standard of living of the majority of the population away from subsistence or self-sufficiency towards consumerism on a relatively large scale. It became an economic proposition, for some already rich people, to invest in technological processes (and later in chemical processes) on a relatively large scale with an expectation of a good return on investment. The motivation came from meeting the needs of the consumer and the creation of markets, together with the ability to construct relatively large scale equipment, rather than the more esoteric motivation of experimentation in pure science.

The first phase of the Industrial Revolution was essentially mechanical - the invention of the steam engine and of the machinery to permit the rapid growth and expansion of the textile industry had the most important impact. Until the rise of the textile industry there was little demand for chemical products on a large scale.

The base (inorganic) chemicals

Before the Industrial Revolution most consumer products were derived from naturally occurring materials, and manufactured in primitive single stage processes. In the case of soap for example, one of the natural materials was sea-weed which was burned in a simple earthen-ware pot (hence the name potash) to produce the alkali (caustic soda) needed for mixing with tallow to make the soap. The soap was not required primarily for domestic use but much more importantly in the preparation of the raw materials (wool and cotton) of textile making and for washing the finished cloth. With the growth of the textile industry, the previously adequate supply of sea-weed quickly lagged behind the demand for alkali to make soap. However, in 1789 Le Blanc, apparently with great luck by all accounts, discovered a process for making alkali from common salt, which was much more widely available than sea-weed. It is interesting to note that one of the critical stages of Le Blanc's alkali process was the use of a kiln in which limestone and coal were burnt. The existence of such kilns, at least on a large scale can be traced back to the very beginning of the Industrial Revolution where coal was roasted before being used, as coke, to smelt iron ore. The by-products (at the time by-products were thought of as waste materials) of coal coking were coal gas, ammonia and coal tar.

It was nearly another 100 years before the Belgian Solvay in 1863 approached the problem of producing alkali from an engineering standpoint and a more direct route to alkali from common salt became available. The process found its way to the UK with Mond and Brunner (who's names we shall come across again later).

The other important chemical for making soap, apart from tallow, was sulphuric acid - so important that, in 1790, a country's consumption of the acid was said to be a measure of its commercial prosperity. Like alkali it was initially manufactured only on a small scale, in primitive apparatus made of glass. (sulphuric acid is extremely corrosive). In 1746 Roebuck and Grabett, in Birmingham, moved the process out of the laboratory into a field where they constructed a large chambered vessel made not out of glass but lead; one of the materials other than glass which was known to be resistant to sulphuric acid. It thus became possible to produce sulphuric acid in commercial quantities.

In 1789 Charles Tennant began commercial production of his new bleaching liquor. The bleaching properties of chlorine had been discovered in 1784 but, used alone, it severely damage cloth. Tennant passed chlorine through alkali to make his new bleach.

It was found later, in 1841, that animal bones dissolved rapidly in sulphuric acid to make fertiliser production more efficient. Hand in hand, it was found that the ammonia by-product from coal burning when treated with sulphuric acid was found to make a nitrogen fertiliser. This led in turn to even greater agricultural efficiency and a further move of the population away from farming to the towns.

The early chemical engineers having contributed, together with the mill owners and the great 'machine' inventors such as Arkwright and Hargreaves, to clothing the population through the improved textile production, and to feeding the population through increased agricultural production, now set about improving its health and the colour of the clothes that it would wear. While it was not evident at the time, the clothes of the population provide one of the most important historical links binding the two branches of chemical engineering together; those of organic and inorganic chemistry. The treatment processes utilised in textile production were based essentially on inorganic chemistry, while the colour of the clothes was soon to benefit from advances in organic chemistry. We cannot be certain that Le Blanc stumbled inorganically into an improved method of producing alkali for soap from his work with coke ovens, but there is written evidence that the first man-made dye for fabrics was derived directly from organic coal.

This coal (or more significantly the by-product coal-tar), which keeps cropping up in our brief history, is going to play a very important part in our story much later, but by 1746 we now have in place all the players for the beginning of one branch of Chemical Engineering - the part which does not involve carbon - called inorganic chemical engineering. Vast quantities of the acids, alkalis and base chemicals were consumed in the textile production industries and their auxiliary processes of woollen and cotton washing, softening and preparation.

The carbon (organic) chemicals

The cloth manufacturers realised that there was an overwhelming competitive advantage to be had by being able to produce cloths in colours other than those such as madder and indigo which are derived from naturally occurring dyes. They could mass produce textiles with the help of the base chemicals but had to rely on increasingly scarce supplies of natural products for colourant dyes. They needed either additional sources of dyes or alternatively new dyes.

As luck would have it the solution lay in their own hands. It was soon found that if drops of the coal-tar derived from the burning of coal were dissolved in alcohol a blue/green colour was apparent in bright light. In 1856 a young Englishman, William Perkins, was attempting under the supervision of his German professors to synthesise the drug quinine from coal-tar and inadvertently found that the product of his experiments could dye silk a mauve colour. He had discovered the first synthetic dye, called aniline, and effectively established the start of the second branch of our profession - organic chemical engineering.

Why is it called organic chemistry? - Berzelius described it as being the chemistry of the substances found in living matter- coal is not living but it is certainly derived from once living things. It was soon realised that all the organic substances seemed to contain the element carbon and more importantly almost all the organic chemicals were much more complex than the inorganic or base chemicals. It is interesting to muse on how the word *organic* has been used (absurdly to my way of thinking) in very recent times to describe food grown without synthetic fertilisers. All potatoes (and come to think of it all foods) are organic; there is no getting away from it!

Almost at the same time as Perkins discovered dyes, some workers in the coal-tar plant noticed the beneficial effects that the tar had on some skin ailments. This was to lead later to the development of another important sector of chemical engineering; the pharmaceutical industry, notably in Germany, Switzerland and the UK. Unfortunately, these early workers were not aware that the short term medicinal benefits of coal-tar treatment was fraught with long term dangers. Coal-tar is now known to contain over 100 differing compounds, some of which are the most carcinogenic materials known to man. It is still possible to buy coal-tar soap in Sainsbury's but it no longer contains coke and therefore is not the 'real thing'. Many of our modern synthetic medicines, including most antibiotics are directly or indirectly derived from this single source of raw material.

This then is the beginning of the chemical engineering industry from a European perspective. We see two independent but related strands developing, both based on an understanding of chemistry rather than physics or mathematics. On the one hand the basic acids and alkalis and, on the other, complex chemicals derived from coal. But the profession of chemical engineering in the UK got off to an inauspicious start. In a famous meeting in 1880 the first Society of Chemical Engineers was established. It failed almost in the same year due to lack of support!

Early Chemical Engineering in the UK

No account of the development of Chemical Engineering in the UK would be complete without mention of John Brunner and Ludwig Mond (Dick (4)) who, after meetings with Ernest Solvay and a Mr Gamble of St Helens, established the ammonia-soda process for the conversion of salt into carbonate of soda (soda ash) and alkali at Winnington just after Easter 1873 with the words "I have arranged with the builder to begin next Monday". Thus began an industry which was to become eventually the giant

ICI of today (formed in 1926). However, the start of this enterprise was not without problems; in the spring of 1874 Brunner wrote of his process "Everything that could break down did break down, and everything that could burst did burst". In 1881 they were selling most of their soda ash to Joseph Crossfield & Sons and Lever Brothers (later Unilever), the largest soap making firms in the world. The environmental devastation caused to the surrounding landscape by emissions of the by-products ammonium chloride, hydrogen sulphide, and hydrochloric acid caused such concern that the Government of the day set up the Alkali Inspectorate, the pre-cursor of today's Health and Safety Executive. During the First World, War Brunner and Mond turned their attention to manufacturing ammonium nitrate, TNT and, with the end of war, to large scale ammonia production (by the Haber process which they cribbed from BASF in the 1919 aftermath of war) and eventually to fertilisers. In 1933 the Alkali Division of ICI, founded by Brunner and Mond, announced the discovery of polythene (originally called alkathene! with the obvious emphasis on its inorganic roots). There is little explanation of why ICI's inorganic chemists were attempting to polymerise ethylene. Eventually the discovery led to a vast man-made plastics industry.

Meanwhile in the USA the impetus for chemical engineering had come from the discovery in the 1859 of oil in California, and took off in the direction of distillation columns and heat exchangers, which led to the study of equipment (unit operations) rather than the processes (reaction based) of the UK.

Some important milestones

We'll move quickly through the decades before moving back to the central issue at the heart of my talk. We need to look at the design of chemical plant and how it has progressed from 1756, but firstly we should note some of the milestones of chemical engineering in addition to those already mentioned.

- 1840 Towns Gas from coal
- 1869 Mendeleev's Period Table
- 1876 Patent Act !!
- 1900 Saccharin, artificial silk (rayon) (viscose), explosives (from coal tar), Bakelite
- 1910 Ammonia, nitro-cellulose fabrics (false leather - Rexine), synthetic indigo, hydrocarbon cracking
- 1920 Continuous processes, synthetic rubbers, rayon, cellophane, photographic films, insecticides
- 1930 Freon, Perspex, Polythene, Polystyrene, Neoprene, Nylon, DDT, Sulphonamides
- 1940 Polyethylene, Penicillin, Teflon, Polyester, Herbicides, Silicones, Atomic power, Quinine (remember Perkins' dye!)
- 1943 Computers, Plutonium
- 1950 Computers, Lycra, Virus (Poliomyelitis vaccine), linear polyolefins
- 1960 Insulin, process simulators
- 1970 Synthetic vitamins, Beta-blockers, data-bases
- 1980 3D design, dynamic simulators

Perhaps the most important thing to notice about the list above is that many of the chemical routes leading to products which we now take for granted were 'discovered' many years ago, but that it often took many years of development before mass scale production became possible. This demonstrates the essential difference between Chemistry and Chemical Engineering; the ability to design, construct and operate the equipment required to produce, on a large scale, the raw materials that can be turned in to products needed by consumers.

A brief note about Chemical Engineering education

In the lecture for which this paper has been prepared there will not be sufficient time to cover all aspects of the development of chemical engineering. However, in the interests of completeness it is appropriate to make some historical reference to the establishment of university courses in chemical engineering teaching in the UK and to the contribution of some the individual characters involved. The following shows the important dates.

- 1880 - The first 'Society' of Chemical Engineers was established, but it failed because of lack of numbers
- 1885 - Department of Chemical Engineering - Imperial College - later closed
- 1887 - GE Davis Manchester Technical School
- 1901 - 'A Handbook of Chemical Engineering' - GE Davis (2)
- 1909 - Course at Battersea Tech - Hinchley
- 1918 - Chemical Engineering Group of the Society of Chemical Industry
- 1922 - Institution of Chemical Engineers formed
- 1923 - First Chairs in Chemical Engineering - University College - Williams, Imperial College - Griffiths
- 1928 - Kings College London - one course of lectures
- 1939 - Manchester College of Technology
- 1946 - Birmingham University
- 1952 - Newcastle University - Coulson
- 1953 - Leeds University
- 1955 - Edinburgh/Herriot Watt - Denbigh
- 1955 - Swansea - Sellars (later Richardson)

Starting out on my own road

My main research interest in chemical engineering centres on way computers can be used to expedite the design process. It arose, in 1969, from a postgraduate research project which involved a study of fluid flow in pipe networks. Natural Gas had been discovered in the North Sea in the early 1960s and for the first time the distribution network reaching out to consumers was spreading across the entire country. My project focused on methods of predicting the flowrates and pressures at points in the network, with a view to specifying where to locate the pumps needed to push the gas through the system and also where to install new pipes in order to ensure continuity of supply should one part of the network fail (for example, in the case where one of the producing platforms might be taken off-line).

From a chemical engineering point of view the mathematics of simulating the flow of gas in the pipes are relatively simple. The real problem I faced was a need to do many simulations of different network configurations for different supply and demand situations. The computers of the time were relatively slow and our jobs needed to be run overnight, batch-mode; but this in itself was also not a problem. The main problem was that for each computer simulation I needed to prepare a data file specifying, amongst other things, the network topology (the connections between each of the pipes in the network). This had to be done each time by transcribing the data from a map or plan of the network firstly on to eighty (80) column paper, then on to eighty column cards. This was not only tedious but also error prone. Often, a whole night's work could be lost because of a slip of the pencil or a finger, at any of three stages of data preparation.

It became obvious that it would be a great advantage if a method could be found for by-passing the limitations of the existing data preparation procedure. At the time, in the Department where I worked, there was just one computer terminal with a screen on which it was possible to draw very primitive pictures. This was a Tektronics 4006 (a cathode ray tube) which we hard-wired to the computer. Soon, I could not only draw a picture of the network to be simulated on the screen, but also could construct automatically from the picture the data file needed for the simulation. This enabled me to do many more simulations than would have been possible with the then conventional methods of data preparation. However, another problem arose because I now had masses of results to analyse, on reams and reams of computer print-out.

It seemed a good idea at the time to look at ways of displaying the results from the network simulations on the same computer screen where I prepared the drawing of the networks. Eventually, it was possible to display the flowrate and pressures for all the pipe and pumps in the network. This approach of using pictures of processes or networks as the input medium and as the output, or analysis, stage for simulation programs has now become the standard way of working for chemical engineers involved in the study of complex design problems.

Following PhD work, I realised that there were two areas in which very few other people were interested at the time, and I have concentrated on these for the past twenty or so years. They are:

- the management of data i.e. the inputs and outputs to and from computer programs used for design (including data-bases and knowledge based systems)
- computer graphics, including graphical user interfaces and, more lately, new methods of storing and representing design data - hypermedia

As computers have developed we have been able to tackle more and more interesting problems so that we can now automate almost the entire design processes. Before describing this in more detail and showing some examples of how computers have changed the way we do design, I want to spend some time examining how the way chemical engineers approach the problem of process design has evolved over the past one hundred years.

The origins of process design

The great or classical advances in physical chemistry including the understanding of atomic theory, molecular structure, the gas laws, kinetic theories thermodynamics etc. were in place by the end of the 19th Century. The practical consequences of these developments began to be recognised at a time when the chemical industry was undergoing great changes. It became apparent that the empirical methods of plant design which had served in the past to meet the requirements of the industry growing along conventional lines were ill-adapted to cope with the more complex processes and operations then coming into use. It was felt amongst technologists and the more enlightened industrialists that much of the practical value could be learned by a study of the scientific basis of their industries; that the efficiencies of the physical and chemical processes could be improved by an accurate control of operating conditions and that more rational methods of plant design would result from an understanding of the mechanisms of heat, mass, and momentum transfer. From this philosophy arose chemical engineering in the UK.

Here we see the essential difference in approaches between; (a) the UK where the engineering of the whole process in the manner of Brunner and Mond was important; (b) the USA where they concentrated for a long time on the so called unit operations approach, see Little AD in Cremer (5); and (c) Germany where they concentrated on the chemistry of the process and left the designs to mechanical engineers.

As we have seen, during the period up to 1880 the people responsible for the production and manufacture in the chemical industries were either chemists, who had little understanding of the underlying physical processes of heat, mass and momentum transfer required to design large scale equipment, or mechanical engineers, who were mainly interested in developing specific types of machines such as pumps and transmission systems and knew little or nothing of reactions or separation processes.

As a result, the chemical factories of the time consisted of not much more than appropriate arrangements of pots, open vats, crushers, dyers. That is to say, the factory owners made use of the equipment which was available more or less off-the-shelf from their mechanical engineering suppliers and brought it to bear on the simple chemical reactions and separation which they needed to achieve in order to make certain chemical products. There was no real basis for the design of individual equipment specifically suited to meet the needs of the process.

We call this empirical design. There was no real concern for, or understanding, of the underlying physical processes taking place in the vessels and equipment that were being used at the time. There was little emphasis on the development of new processes to meet the needs of production - reactors, separators, distillation columns, absorbers. What was missing was the ability to describe what was happening in the equipment in such a way as to apply the knowledge in a general way so that the design would become based on facts (as in mathematical equations and fundamental laws) rather than astute guesses.

In the early part of the twentieth century, chemical engineering began to develop as a distinct discipline, in answer to the needs of a chemical industry no longer able to

operate efficiently with manufacturing processes which in many cases were simply larger version of laboratory equipment. Thus, the primary interest in the profession was initially devoted to the general subject of how to use the results of laboratory experiments to design process equipment capable of meeting industrial production rates. This led naturally to the characterisation of design procedures in terms of process operations, those elements common to many processes. The basic operations include fluid flow, heat exchange, distillation, extraction etc. A typical manufacturing process will be made up of a combination of the unit operations.

It was thought that skill in the design of each of the units at a production scale would provide the means of designing the entire process. All over the world, but notably in the USA and later in the UK the attention of the emerging profession of chemical engineering, especially in universities, focused attention on understanding the processes taking place within the specific vessels and equipment of interest, rather than the overall process. This is the era of the *unit operations* approach to design, and led, from the 1920s and 30s to great advances in the design of heat exchangers, separation/extraction columns, absorbers, evaporators, liquid-liquid extractors, crystallisers and, to a lesser extent, reactors. The unit operation concept dominated chemical engineering education and thus practical chemical engineering for many decades, until the middle 1950s.

A definition of chemical engineering reflecting the unit operation philosophy in vogue at the time comes from HW Cremer in 1956 (5) - "In practice the chemical engineer is principally concerned either with physical operation entirely, or with the purely physical effects of chemical reactions such as in the transport of solids, fluids, mixing and agitation, the transfer of heat and the means to deal with reactions and reaction products over a wide range of temperatures and pressures. Thus, commercial success in translating a laboratory method of preparation into a full scale manufacturing process depends as much upon careful study of equipment and plant as upon consideration of the precise reactions to be employed".

Starting in the late 1950s there began a move away from the equipment dominated philosophy, especially in universities in the USA, towards an engineering science approach. The philosophical emphasis shifted towards a concept which assumes that the unifying concept is not specific processing operations, but rather the understanding of mass, energy and momentum transport that are common to all of the unit operations, and it was argued that concentration on unit operations obscures the similarity of many operations at a fundamental level. This approach is most significantly shown in many of the academic texts produced in the early 1960s, typical of which is 'Transport Phenomena' by Bird, Stewart and Lightfoot. This single book probably turned off more chemical engineering undergraduates than any other book in the history of chemical engineering. It is what R Sinnott (6) might have called "*one of the books written by academics that are largely philosophical discussions of the nature and methodology of the design process and which are usually of little practical use*".

Although there is no conflict between the goals of unit operations and the engineering science approaches, the latter has tended to emphasise mathematical skills and to de-emphasise the design aspects of engineering education and practice. More recently, approaches have been directed towards the development of skills that will enable the creative engineering use of fundamentals, or a synthesis of engineering science and unit operations, and as we shall see the impact of computers has been significant.

Process Design

A difficulty with the formal design of chemical processes is that we not only need an understanding of what goes on in the individual equipment (unit operations) but also what happens when they are connected together with pipe-work (the overall system), and how the processes taking place in one vessel affect the processes in another vessel further on in the plant. In a sense this sentence defines the design problem for chemical engineers. This akin to dealing with one jigsaw consisting of the pieces of equipment which must be connected together, but one where what happens inside the individual equipment items is itself a jigsaw of chemistry, physics and mathematics, all of which affect the size and shape of the equipment and the way in which they can be linked with other pieces of equipment. The problem for the designer is knowing where to solve the jigsaw - at the overall process or system level or at the equipment level. Do we use the jigsaw solver's common trick of finding all the edge pieces (look at the overall system) and then try to fill in the middle, or do we look for some essential features in the middle of the picture (look at the unit operations) and then build the rest of the picture around them?

In fact, for modern design methods with computers the jigsaw solver's analogy is very appropriate. Neither the systems nor the unit operation approach is used exclusively. It is now possible to switch the focus back and forth to achieve an optimal balance between the performance of the individual pieces of equipment and the overall process.

The design of almost every chemical plant depends on two factors: bringing two or more raw materials together into intimate contact in order that they may react together (which they may do to a greater or lesser extent); then separating the products of the reaction in order to obtain the desired product and, if necessary to reclaim the unreacted portions of the initial raw materials so that they can be re-cycled back for further reaction. In most chemical plant this combination of reaction and separation may occur several times. Each reaction and separation process is usually carried out in a separate piece of equipment, with the result that a typical chemical plant is made up of a large number of quite different pieces of equipment. All the items of equipment then need to be connected together so that the materials which they hold can be passed safely from one stage of the process to another.

In the initial stages of design, consideration of the chemistry of the process dominates. Attention is focused on the main reaction steps and on the design of the pieces of equipment (reactors) in which the reactions will be carried out. A difficulty is that the design of these reactors cannot be carried out in isolation of consideration of the other equipment necessary for recovery and separation of the reaction products, and of the control of the overall process. Furthermore, the raw materials, the products and any of the intermediate stage chemicals may need to be heated or cooled; and usually everything needs to be pumped through the different stages.

Following on from the initial stages of design, the general structure and layout of the final process begins to emerge. This is both a conceptual and physical representation of the process and is traditionally drawn on paper as the process block diagram (flowsheet). Up to the stage where the flowsheet becomes established, there is often little consideration of how large or small the individual items of equipment will be. This is different form the situation in the early days of chemical engineering where any choice of equipment was more often than not determined by the size and shape of vessels used in other engineering situations, such as ships boilers, rather than by any consideration of fundamental design of the equipment. These days, in general, the size of the plant is not related to chemistry or engineering, nor the availability of equipment, except in the case of very high pressures and temperatures, but rather depends on economic factors such as how much of the product can be sold in a certain period and how big or small the equipment need to be to meet this requirement.

The process plant as a picture

The block diagram tells us nothing about what the eventual process will look like from a physical point of view. We get a picture of the general shape of the process but no clear idea of the size of the items of equipment nor where they will be located in the factory, nor indeed what the purpose and function of some of the equipment items will be (as in the case of separators where there may be several different ways of achieving what is desired). Arriving at the block diagram is equivalent to joining all the edge pieces of the jigsaw, with a few 'strong' features of the process clearly identified. The next stage for the chemical engineer, like the jigsaw solver, is to look to the detailed chemical engineering design of the process (the mechanical engineering design comes later). This means dealing with the design of the individual items of equipment one by one. Today, computer program called simulators are commonly used to perform this detailed design.

From the flowsheet and the detailed design stages, the amount of information (data) to be handled by the design engineer rapidly mushrooms. Eventually, the whole process begins to emerge. The result being millions of items of information concerning calculations for the design of individual items of equipment, specification sheets defining the characteristics of the equipment, drawings for flowsheets, piping and instrumentation, control, layout etc. In the case of one real plant it was estimated that over 70 million items of data were necessary to define the finished plant but that more than ten times this number had been used at some stage in the design process. Today, most of the data are now stored on computers in data-bases, but block diagrams, the process flowsheets, piping and instrumentation diagrams, piping isometrics, mechanical drawings, civils, layouts and specification sheets are still the main form of working documents, preferred by engineers not only for reasons of convenience but also for legal reasons. These drawings and data sheets are *pictures* of the process from different points of view. Considered as a whole they represent a complete definition of the entire process plant.

It is simply not possible to handle the amount of data that needs to be processed in the design of a modern chemical plant without the use of computers. Indeed, the huge amount of data arises directly from the use of computers for design. Which brings me back to my own area on research interest.

Impact of computers on design

Arguably, the first electronic computer was developed at Manchester University in 1948. Next came transistor based computers (although the transistor was actually invented in 1947), with the first integrated circuit being produced in 1958, and the reign of the mainframe. The first microprocessor went on sale in 1971. In 1981 the IBM personal computer was launched, and the rest is history.

A typical and early example of the mathematical penetration of the solution of problems supported by computers was the development and design of a high-pressure polyethylene plant with a capacity of 24,000 tonnes/year in 1958, based on laboratory experiments only, with no pilot plant work being carried out whatsoever.

Computers are, of course, now used in many aspects of chemical engineering other than design of processes, most notably in control. However, it is in their application to design where we can see the most impressive illustration of the difference the computer makes, as demonstrated with the *walk-through* view of a chemical plant. This represents the final stage of the design process; it brings together almost all the data that has been generated over the life of the design. Each frame represents a different drawing, and thousands of frames make up the sequence. Traditionally, each drawing would have taken man-months if done by draughts persons. This walk-through cannot be achieved without a computer. In the latest walk-through computer programs the sequences are not made up of individual drawings, the images are computed 'on the fly' from a single set of three dimensional data representing the entire plant. The advantages of using a walk-through are obvious in, for example, the design of an off-shore oil rig, where the misplacement of a valve or pipe connection would involve remedial work costing about one hundred times more than if it were done on-shore. *Walk-throughs* have also been used to simulate the problem of repair of the internal equipment on the 'active' side of nuclear reactors, where the robots involved must be guaranteed to be able to perform their function, moving around, removing damaged equipment and replacing it, without coming in to contact with any other equipment or internals.

The *walk-through* represents the current *state-of-the-art* in process visualisation but there are many other instances where computer graphics have been shown to improve the speed and reliability with which the design process can be performed.

A particular interest of mine in the past has been to investigate the suitability of conventional commercial data-bases, such as those used in banking and airline booking systems, for storing process design data. Put bluntly, they simply do not work. I do not propose to go into the details here, but the problem lies not only with the type data with which process engineers deal, but also with the way that they need to see it.

A major method of communication between engineers involved in the design process is through drawings in various forms such as; sketches, diagrams, flowsheets, piping diagrams, of parts of equipment, graphs and other forms picture-like images such as specification (data) sheets. Almost all of these drawings contain data which need to be cast into some other some form so that it can be processed by a computer program.

For example, the flowsheet drawing is the starting point for simulating the process on a computer. Similarly, the drawings exhibit design information which has been generated by other computer programs, (of course, the drawing itself has probably been computer generated). If a conventional data-base, by which I mean one not capable of storing data in picture form, is then used to store the design data, this creates yet another interface between the engineer, the computer program which processes the data, and the data itself. Of course, this aspect of process design is not at all different from the research project work I did at university some twenty years ago, where there was a need to transform the information held in the picture of a gas pipeline network into a data file ready for the computer.

Advances in computer graphics in the past ten years and the availability of relatively powerful computers on the desk of every engineer have allowed us to investigate new ways of storing and accessing design data and to improve the interface between engineers and the design programs which they use. We call this area of work the study of graphical users interfaces (GUIs).

We combine this work in GUIs with other work in data management - the result is fast, efficient process design with careful document control. An objective is to devise systems which map natural ways of working, based on physical metaphors such as drawings and data sheets, onto computer programs and data-bases in a way that does not constrain the design engineer to working with pre-determined methods imposed by computer hardware and software, as has been the case until very recently. It is important to note that out work does not involve the development of new computer programs for design calculations; many other people are experts in this field. We do develop computer programs but they are intended to facilitate the design process itself, rather than do detailed design calculations.

Our main concern is to investigate ways in which data can be communicated to engineers, between engineers, and between the calculation and data-base programs which use and generate the data. We are concerned with computer graphics, data modelling, data representation, data management, data storage, and integration of calculation programs. We use pictures of the process plant, in a number of different abstractions, to display data to design engineers. In one sense the pictures we use to display information to engineers are exactly the same as the traditional paper based metaphors seen in all design offices but, unlike fixed inert images on paper, the objects on our pictures are active. They have behaviour. For example, simply by pointing at the objects, engineers can start up a design program, call up a data sheet (itself a picture with its own objects each having their own behaviour), pass the results of a calculation from one object to another, retrieve data from a data-base etc.

A secondary objective is to ensure that the pictures, which the users of our methods see on the screen, conform to the same standards and conventions of display and presentation as are used for paper based metaphors. Thus, in theory, the need for storing data on paper can be completely eliminated. I say *in theory* because at the present time there are probably not in existence the legislative procedures for dealing with authorising signatures (exactly as for personal cheques) on drawings held solely on computers. Accordingly, a third objective is to be able to print pictures of several types to the same or better quality than can be achieved with manual methods.

Drawings and data sheets

The drawings that chemical engineers deal with today are not really any different from those of a hundred years ago. Some of these old drawings are close to being works of art in their own right. It is interesting to look at some of them.

Modern drawings have gradually become formalised, especially with the introduction of international Standards which define how individual equipment items, process streams, and control lines should be represented on drawings. To the experienced eye today's drawings display not only the general impression of the process plant but also intimate detail about its design, operation and construction. It is also now conventional to categorise drawings in to process flowsheets, piping and instrumentation diagrams, piping isometrics etc. But engineers also deal with other, informal drawings such as sketches, graphs and charts. In the past these drawings would have been stored in huge specially made drawers and cabinets or, more recently, on micro-film. In the 1970s data-base systems were widely heralded as best method of storing process design data, including drawings. However, considering the complexity of some of these drawings it is easy to imagine the contradictions which arise in attempting to use conventional data-bases to store the data which the drawings exhibit. Traditional data-bases are excellent for storing numerical data and text but not for pictorial information. They can be used to store drawings but the drawing information first has to be converted to numerical data. This is usually done by a draughts-person having the same level of skills as those who made the working drawings a hundred years ago. Then when the engineer wishes to inspect or work with the stored drawing it must be reconstructed from the numerical data before it can be displayed on the screen of a computer. Normally it would not be possible for the design engineer to make changes to the drawing.

By exploiting new concepts in data management such as hypermedia, it is now possible in the 1990s to not only overcome the limitations of storing drawings in conventional data-bases but also to create design aids which make the drawing *come alive*. We do this by using object oriented programming methods so that simply pointing at a piece of equipment on a drawing will automatically start up a computer program that deals with its design, or another program that brings up the information stored in the equipment's data sheet.

Data sheets are also drawings of the process but from different conceptual point of view compared with flowsheets etc. In practice every piece of equipment on a process plant will have its own data sheet (usually a collection of several separate sheets). The data sheet is a complete description of the equipment; its identifier (name or number), its operating conditions, manufacturer, service and maintenance history, safety conditions, construction details (including drawings), results of design calculations and much else besides. Everything that is known about the piece of equipment in question should be written down on the data sheet. It is a single point of reference. Together with drawings the data sheets represent a complete description of a chemical plant. For a typical plant there would be thousands of such data sheets and several hundred drawings.

In the same way as for drawings, conventional data-bases are not appropriate for storing data sheets. Again, it is possible to use a conventional data-base to store the information which the data sheet contains, but displaying the data in its natural and easily appreciated form (i.e. as a conventional paper based sheet) is difficult to achieve. In the methods we have been investigating data sheets and the data they contain are stored as a graphical images. This obviates the need, arising from the limitations of conventional data-bases, to transform the data from the way it is stored in the data-base to the way it is displayed to the engineer. Further, by again adopting international standards and conventions for the display of data sheets on the screen, we can also print high quality working documents.

The future

So here we are at the end, but only at the end of this lecture. Like Persig in the Arizona desert repairing his gear-box, this Inaugural Lecture has been for me a necessary, if time consuming, diversion. Now its done. I have enjoyed learning a little about the beginnings of the profession I practice. The journey of discovery goes on.

In the same way that Persig reaches an understanding of his relationship with his son, I too am aware of the contribution made to own journey of discovery by my teachers, my students and above all my colleagues, who have made my first three years here at Swansea eventful and interesting, shall we say, and without the support of whom this job I do would be so much more difficult. I thank you all.

Like Mark Twain, chemical engineers are "*concerned with the future since that is where they will spend the rest of their lives*". Conditions demand new ways of doing things and the years ahead will be unusually hospitable to technical innovation - but there will be **a process of change**. Now is the time to get back on the motorcycle.

References

1. Furter WF, 'History of Chemical Engineering' American Chemical Society, ACS/CSJ Chemical Congress, Honolulu, Hawaii, April 1979
2. Davis GE, 'A Handbook of Chemical Engineering', Davis Bros, Manchester 1901
3. Tailby SR, 'Early Chemical Engineering Education in London and Scotland', unknown source
4. Dick WFL, 'A Hundred Years of Alkali in Cheshire', Imperial Chemical Industries Ltd, Mond Division, 1973
5. Cremer HW, Davies T, 'Chemical Engineering Practice', Butterworths, 1956
6. Sinnott RK, 'Chemical Engineering Design', Coulson and Richardson, 'Chemical Engineering Vol 6' Pergammon, 1983