The Chemical and Petrochemical Industries [and Discussion]

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The chemical and petrochemical industries

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The manufacturing technology of the 1980s in the chemical and petrochemical industry is not likely to show any radical change. There will, however, be significant advances in some general areas. Part I of the paper is concerned with developments arising from exploitation of fundamental research in the molecular sciences and in biochemistry and microbiology. These are expected to lead, respectively, to methods for the design of selective catalyst and improvements in separation processes, and to increasing use of biochemical processes. Part II discusses developments in operation and design, aimed at reducing construction and operating costs; particularly to make best use of materials and energy, and to conserve the environment economically.

In all areas the pace of technological development will depend on the ability of industrial teams to exploit the results of fundamental research.

Both research and the development stemming from it will continue to be dependent on increasingly powerful measuring and computing facilities, as also will be the larger and more closely integrated production complexes.

The scientist and the engineer welcome the aid of the computer to extend their own abilities, but others (such as process operators) fear their introduction will take away the interest of their work and ultimately eliminate their jobs. This will pose a serious problem to management, not only on the plant, but in all departments of a company. Careful planning and experiments will be essential to ensure that all personnel have satisfying jobs and can develop their full potential.

This is one aspect of the much wider problem set by the need of all organizations (industrial, political and social) to improve the design of their structure and management, to meet the individual's legitimate aspirations in a changing society. It is suggested that the application of the concepts of system analysis and control engineering will contribute significantly to the solution of this problem: but the major contribution must come from sociology and the human sciences.

Introduction

It will be acceptable, I think, in the interest of brevity to refer simply to the Industry and to assume that it embraces both the petrochemical industry and the chemical industry. After all, since its very first emergence as an Industry in the modern sense, the British Chemical Industry has taken advantage of the economies of integration. The first process, the manufacture of sulphuric acid in the lead chambers operated by Roebuck & Garbett in the late 1740s, was integrated before the end of the century with the second process to be developed, the LeBlanc soda process; this combination was the heart of the Industry throughout the Industrial Revolution. Since then, the Industry has continuously increased the range of its products in order to make most use of its investments and of the raw material and energy consumed in its operations, and at the same time to take advantage of new opportunities to supply the requirements of other industries. It has expanded by the growth of individual plants, factories and firms and by their combination to form larger organizations: the large measure of integration the Industry has achieved as an economic necessity, has been made possible by the interdependence of its component parts.

Economic pressures will lead to more integration in the Industry and more cooperation between firms will lead to conditions more favourable to successful planning of investment in new plant. A good deal more 'vertical', as well as 'horizontal', integration is likely.

The search for new markets that has been such a strong feature of the Industry will continue, but new requirements will tend to be fulfilled by modifying existing processes and products rather than by the development of new ones: the pharmaceuticals, and animal and crop protection and development sectors will of course be the obvious exceptions. Another exception will be protein manufacture, which will soon become a large volume commodity business, providing food for animals in rapidly increasing amounts as production costs fall, and becoming important in the human food market of the 1980s.

Speculation about the potential for exploitation in the Industry during the 1980s of specific and basic advances, such as the laser generation of plasma, is best left to authorities in the respective fields to pursue when discussion can be sufficiently detailed to make it significant. A number of such advances were the subjects of papers read at a recent conference referred to in the following paragraph: but the authors were looking forward to the year 2000 and there does not appear to be evidence for supposing that any radically new processes will appear much before then.

The future of the Industry in the U.K. has been much discussed recently: notably at a recent conference on the 1990s organized by the Society of Chemical Industry, in an address by the Chairman of the Council of the Society (Iliff 1970), and in the Royal Society's Fifth Technology Lecture (Davies 1972). The N.E.D.O.'s Chemical E.D.C. has recently issued reports on investment in the Industry and on the plastics and pharmaceuticals sectors. Very large plants, a prominent feature of the Industry, were the subject of an earlier presidential address by Sir Ronald Holroyd (1967) to the Society of Chemical Industry: it set out all the factors which will determine the developments required for their continued growth and profitability in the 1980s.

These publications cover the whole field between them and leave little unsaid about the future of the Industry during the next two decades that can be said with any confidence. They support the generally held opinion that the Industry will continue to expand at something like twice the growth rate for the g.n.p. for the next decade and that some sectors, particularly plastics and pharmaceuticals, will have a considerably higher growth rate than this, although perhaps lower than in the last decade. They also share the view that few new products will appear during the period and that there is too little time left to make probable the application of any radically new technology in the 1980s unless it is already the subject of a substantial research and development programme.

Areas of advance

The purpose of this paper will therefore be to discuss developments in some general areas in which economic pressures will ensure significant advances. These developments fall into two categories: those concerned with design and operation, which are in large part of common interest to all industries; and those of peculiar interest to the Industry itself, arising from recent progress in molecular science or from special requirements of its various sectors.

A feature common to developments in both categories is their dependence on increasingly powerful computing facilities, which have been essential in laying the foundations for future advances.

We shall consider first three areas of technology in the latter category, in which the Industry is particularly well placed to make progress during the next decade: namely, catalysis and separation, and biochemical processing.

The extremely rapid progress made by the Universities in recent years in fundamental research in molecular science has yielded information about the structure and behaviour of molecules that surpasses the most optimistic expectations of only ten years ago. In particular, understanding of surface properties and of the mechanisms of reactions on surfaces now exceeds by far what could possibly have been hoped for by those who were engaged at that time in catalyst development. We can now look forward to very much more understanding and quantitative guidance.

Similarly, the foundations have been laid for an understanding of the behaviour of molecules in solution. This will lead to a more complete knowledge of separation processes, such as those using crystallization or permeable membranes, and in due course will provide a fundamental basis for the design of improved separation equipment.

Catalysis and separation have been singled out because of their direct importance to process economics and because it can be foreseen that continuing advances in molecular science can be exploited in the immediate future in these areas. It must be obvious, however, that the greatest benefits will come from application of basic theoretical knowledge to the design of the process reaction. Calculations of molecular structure and dynamics have already been carried out successfully on the basis of wave mechanics with an accuracy comparable to that obtained by experimental measurement for simple molecules. And it is probable that such calculations will be extended in the comparatively near future to handle much more complicated systems, such as polymers, amino acid chains and so on. Meanwhile, progress in quantum scattering theory and the application of symmetry principles, together with a more detailed knowledge of molecular potentials must in due course lead to an understanding of the mechanism of chemical reactions and consequently to predicting their course.

This objective seems to be a very ambitious one and long removed into the future; but when the rate of progress in molecular science over the last few years is considered, one must allow that it might be possible to describe chemical reactions in sufficient detail for design purposes from basic knowledge of the reactant molecules within the next decade. In any event the designer can expect present inadequacies in information about process reactions to decrease continuously during the next twenty years.

University/Industry research exploitation

To take advantage of these possibilities quickly, it will be evident that the Industry must encourage young scientists of the requisite calibre to envisage the implications of the new knowledge and to bridge the gap between fundamental research and application. It is also clear that the focus for fundamental scientific work, in theoretical chemistry for example, will remain in the universities but it is equally true that their engineering departments will become the focus for basic research in, for example, control engineering; and that the engineers in industrial research departments will have the same function relative to university engineering research as the scientists have to university work in their own fields.

PART I. DEVELOPMENTS SPECIFIC TO THE INDUSTRY

1. CATALYSIS AND SEPARATION

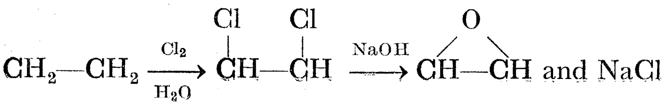
Economic importance of catalysts

To people in other industries, the importance of catalysis to chemical manufacture may not be self-evident. A few examples will show how a catalyst can reduce manufacturing costs by making an alternative process available, or by allowing the original process to be operated in more favourable conditions.

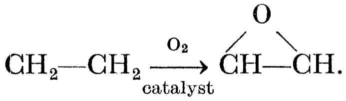
As an example of the former, we can take the catalyst which made possible steam reforming of naphtha under pressure to produce a hydrogen-rich gas; in this case for ammonia production. The original coke oven and water gas process had become quite uncompetitive with the U.S.A. process based on natural gas which was not available at the time in the U.K. The catalyst restored the situation by making the use of naphtha competitive. Later the naphtha process was licensed extensively and used for producing town gas.

A good example of a new catalyst's permitting a process to be operated in more favourable conditions is offered by I.C.I.'s l.p. methanol process; which is governed by essentially the same chemistry as the original h.p. process, but gives the same yield per pass at lower temperature and lower pressure with important savings in compression costs.

Catalysts can also permit the use of an alternative and more economic process route, perhaps replacing a multistage by a single-stage process, as when the two stage route from ethylene to ethylene oxide via ethylene dichloride



was replaced by the single stage direct oxidation



It will be noted that there is a waste of energy in the first process, the chlorine and caustic soda are made by electrolysis of brine and appear again as sodium chloride as a product.

An example of the value of a catalyst in permitting the use of less expensive starting material is given by the swing away from acetylene for making many bulk chemicals, owing to the high-energy requirements of its production: it has largely been replaced by ethylene and propylene for products such as vinyl chloride and acrylonitrile, respectively. As Dowden has pointed out, 'the last decade was the acetylene age, and the present decade is the olefines age: developments in catalysis will make sure that the next decade is the paraffin age' (1970). This implies overcoming the difficulty experienced with paraffins which arises from the energy difference between hydrogen and carbon bonds along the chain being insufficient to allow specific attack easily to take place at any one point, so that random attack and a mixture of chemicals generally result.

Examples abound of new catalysts permitting alternative processes with dramatic decreases in production costs: particularly in large complexes, when the designers must look for processes giving high yield, low activation energy, moderate operating conditions, few stages and lowest separation costs; while constrained to use specific starting materials and to make products balanced to give best overall utilization of material and energy. Naturally, in every instance a compromise must be made.

In fact, such a compromise was made in the acrylonitrile process taken as an example above. Although the new process uses propylene instead of the more expensive acetylene and has the desirable merit of being single stage, it has some undesirable side reactions. Further cost advantages are being achieved by the development of more selective catalysts, which increase yield and decrease separation and purification costs. An important function of catalysts in future will be converting noxious materials in effluents to harmless ones.

The importance of catalysts is reflected in the large sums devoted to their development. Ability to design specific catalysts would bring two advantages: greater selectivity and quicker availability; decreased expenditure on increasingly expensive research and development.

Catalyst design

Experienced specialists now look forward confidently to the development of quantitative methods for designing highly selective catalysts, based on understanding of the chemical physics of surfaces and of the mechanism of heterogeneous processes. They also expect to obtain an understanding of the other equally important properties which determine a catalyst's success in operation: long life, immunity to 'poisons', good adhesion to a substrate and robustness.

The degree of success achieved will depend on the completeness of available knowledge of the entire mechanism of catalysis in given circumstances. To obtain this and to develop the model of the system the combined knowledge and skills of the solid state physicist, the quantum theoretical chemist, the reaction kineticist and the technologist have to be brought to bear on the problem. A great deal of information about the nature of a catalyst surface and the species adsorbed on it (chemically or otherwise) is already available from experimental observations using such techniques as low energy electron diffraction, field emission microscopy, spectroscopy (laser, infrared, electron spin), and photoelectron spectroscopy (e.s.c.a.).

Such data have shown, for a considerable number of catalytic systems, which species are adsorbed on the surface and, in the case of oxidation, in which direction the electron transfer occurs during chemisorption. This allows the role of the catalyst to be incorporated in the kinetic model. Furthermore, using well-established assumptions about the symmetry of the system, it is possible to decide which orbitals of reactants and catalysts are involved in the chemisorption and which molecular transformations have been caused by the presence of the catalyst. The energy changes involved in the separate processes can also be determined experimentally, and this has already allowed the development of a model on the basis of which predictions of the performance of a catalyst, with regard to conversion and selectivity, have been made and tested (W. C. Mackrodt & K. Waugh, personal communication 1972).

It must be expected that, in the natural course of development, it will become possible to define the orbitals of the molecules that are involved in reaction and what electronic perturbation is required of them to bring about 'catalytic action'. In this way, one would anticipate the development of catalysts specific for the oxidation of butenes to maleic anhydride, for the oxidation of propane to acrolein, for ammoxidation of hydrocarbons to nitriles without side reactions.

Catalysts for the low-pressure polymerization of olefines are currently being developed along these lines. Ultimately, it will be natural to ask the biochemist to find among his collection of enzymes one with suitable orbital symmetries and occupancy to act as a catalyst with the specified performance. If such an enzyme were available, it might not be viable in the envisaged conditions: even if it were, the cost of isolating it might be prohibitive.

An alternative would be to ask the biochemist to synthesize an 'enzyme' with the required catalytic action. In fact, the synthetic 'enzyme' could well be designed for use in much more rigorous conditions than the one of natural origin. The natural enzyme may so limit the process conditions as to make plant size uneconomic: but by 1990 it should be possible, judging by recent progress, to synthesize 'enzymes' with selective catalytic properties and able to operate at higher temperatures and perhaps in a wider range of pH. Already such synthetic 'enzymes' have shown a wider tolerance of variation in their environment, than is characteristic of natural enzymes.

Separation

The cost of separation equipment can be a very large proportion, up to half or even more, of the total investment in a plant and its running cost is high when changes of phase are involved, as in distillation. There is therefore a strong financial incentive to develop less costly separation processes.

Advances in the design of catalyst to obtain greater selectivity will lead to the production of less unwanted material and this will certainly decrease the cost of separation: it will not however remove the need to separate required products in many processes operating in the 1980s. It is therefore important that presently available and continuously accumulating knowledge of molecular chemistry should be exploited as rapidly as possible in new or improved equipment for separation processes that have been known, and in some instances used, for a very long time.

Crystallization

The oldest of these is crystallization, which has been used from time immemorial, but which is still carried out in equipment designed primarily on the basis of experience. Fortunately fundamental knowledge is building up as a basis for the development of design methods for crystallizers.

Of all the unit operations, crystallizers may well show the most progress between now and the 1980s. Simply because so little of the available knowledge about crystallization has been applied, development should be able to make a flying start. There are, however, still some considerable gaps in the basic knowledge itself.

Advances will come from an understanding of the principles governing the three interacting factors on which crystallization depends: namely, the two-phase flow of growing crystal in mother liquor; the rate of generation of nuclei, and thirdly the rate of crystal growth. By 1980 it should be possible to design crystallizers that can be operated to give a desired compromise between product purity and crystal size distribution.

Separation processes based on the properties of membranes have also been used successfully for many years on a large scale for some rather special applications, mainly in water and effluent purification; their potential has been recognized for at least fifty years.

Membrane technology

Membrane technology has already proved very suitable for separating low concentration inorganic and organic materials from water. The technology has been studied for a long time, but its application to process operations has been necessarily held up until suitable large surface membranes were available in sufficiently robust and well-engineered equipment; they are now available in several forms. They have been used extensively for purification of brackish water, in desalination and brine concentration plant, and in effluent purification. A number of techniques based on membranes are available: e.g. membrane filtration, ultrafiltration, reverse osmosis, electrodialysis. These cover a wide range of particle and molecule size. The development of plant equipment based on these techniques has been very much encouraged by the successful application of reverse osmosis to large-scale desalination.

Pervaporation is another separation process, based on membranes, which may well become important for separating water from organic materials. It is also likely to be used for applications where fractional distillation is either impossible or very expensive (e.g. separation of azeotropes and close boiling components respectively) for extraction processes (e.g. for the separation of classes of components) and as a competitor to crystallization and adsorptive techniques (e.g. for C_8 aromatics) as well as for separation of aqueous/organic streams.

At present it seems likely that the elucidation of the mechanism of membrane separation may take longer than that of catalysis and a sound methodology for designing membrane separation equipment may therefore not be developed before 1980. However, this prediction may well be unduly influenced by the thought that much less effort may be put into the exploitation of fundamental knowledge in this field, because of the overriding importance of catalysts.

2. Biochemical processes

Biochemistry is another field in which rapid progress has been made during recent years. The nature of enzymes is being explored and proteins of increasing complexity are being synthesized.

Protein is being manufactured in the U.K. on a small but rapidly increasing scale by harvesting micro-organisms grown on hydrocarbon substrates. These processes are of interest in considering the 1980s for three reasons: first, they are the forerunners of a whole new generation of processes depending on natural micro-organisms, and later their modified (or even synthetic) counterparts; secondly, they show the kind of design problems to be expected; thirdly, the history of their development indicates the help designers can expect from research in biochemistry and microbiology.

Meanwhile the pharmaceutical companies are synthesizing large molecule substances found in nature, in multistage batch processes that are bound to present difficult operational problems in obtaining the consistency essential to success.

Protein manufacture

Protein for human consumption extracted from soya beans is now being processed in the U.K. Protein for animal food is being produced by processes depending on the growth of micro-organisms on hydrocarbon substrates.

A yeast-paraffin process is producing 4000 tonnes/annum (t/a) in a plant at Grangemouth commissioned in 1970. Another plant using yeast and gas oil (instead of pure paraffin) at Lavera, France, has 16000 t/a capacity. The bacteria–methanol process reached the pilot plant scale at Billingham in 1972. The fungi-carbohydrate process has completed pilot plant batch production trials and a continuous 100 t/a pilot plant will soon be in operation.

Design problems are set by the micro-organisms, which flourish in dilute aqueous solutions at low temperature: oxygen must be supplied and carbon dioxide removed from the large volumes of liquid, which must therefore be aerated and stirred; the heat of metabolism has to be extracted from the liquid at a temperature (say 30 to 40 °C) little above ambient temperature; the temperature of the large volume of liquid is critical and must be controlled close to the optimal; new strains must be avoided, so that all gases entering the plant must be sterilized or process conditions must favour the strain required to be dominant.

Product separation also poses problems: equipment for 'harvesting' the product streams, such as centrifuges, evaporators and driers, requires considerable development.

Large rewards await economic solutions of the inherent problems of biochemical processes; presenting a challenge to biochemist and engineer. As an illustration of collaboration between different disciplines to produce novel solutions, some remarks about the bacteria–methanol process may be of interest.

The designers aimed at avoiding what they saw as intractable structural problems in providing mechanically stirred vessels for the very large volume of liquid envisaged, without using an uneconomic multiplicity of small stirred tanks. The obvious alternative, the use of aeration for stirring as well as for supplying oxygen, gave low efficiency of either stirring (with consequent intolerably high-power costs) or of oxygen absorption. The problem was solved when it was realized that very large fermenters offered a degree of freedom not available on the smaller scale. The large differences in hydrostatic pressure, only available in large vessels, offered the possibility of differentiating regions of rapid oxygen absorption and rapid carbon dioxide evolution. Large linear dimensions permitted the generation of large driving forces between regions with high-bubble concentrations and regions with low-bubble concentrations. Fundamental studies of the mechanisms of bubble formation and of the hydrodynamics of three-phase flow finally led to a choice of geometry applicable to any scale of manufacture.

An interesting feature of the bacteria–methanol process is that originally the substrate was methane. But work at Sheffield University showed that the bacteria concerned always first converted methane to methanol before utilizing it to build sugars (Quayle 1965). The high activation energy of methane suggested that bacterial oxidization to methanol might be the rate limiting step and this was confirmed by growing selected pseudonomads in very dilute solutions of methanol. The improvement in growth rate, productivity and general robustness was dramatic.

This example shows not only the need for close collaboration between engineer, biochemist and microbiologist, but also the fruitfulness of Industry's taking advantage quickly of university research. Mutual awareness of the importance of this will have an increasing effect on the Industry's technology as 1980 approaches: it is, of course, especially important in the initial stages of development of a new field of manufacture.

In this field, success in utilizing knowledge of the micro-organisms will determine where advances will be made. It is believed that one of the outstanding technological advances to be made in the Industry during the next 20 years will be the use of natural organisms for building large molecules. Concurrently, we shall become more and more successful in synthesizing and manufacturing such molecules on a large scale; as the pharmaceutical industry is already beginning to do so successfully on the small scale.

The full exploitation of the growing body of biochemical and microbiological knowledge in the 1980s depends on the rapid development of this new branch of process engineering in the meantime.

3. Developments expected in some sectors

In the following remarks about some important sectors of the Industry it is indicated that there will be requirements for advances in each sector's technology to meet new objectives, but where these concern products it is not to be expected that the nature of the advances will be divulged.

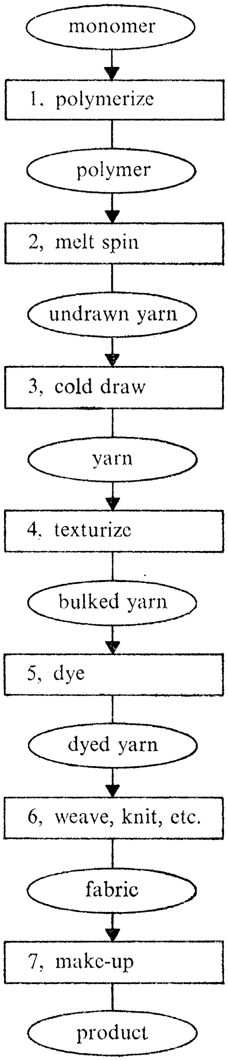
Fibres

In the fibres sector there will be a really basic change in its special technology as a consequence of rationalization of the whole multi-stage manufacturing process from raw material to final product (figure 1). The chemical part of the process is now continuous up to and including the polymerization stage, and in some cases embracing the filament-forming process too. The filaments formed at the spinnerets by extrusion of the polymer are subjected to a great number of mechanical operations to produce fibre for a multiplicity of uses in the textile and other industries. Subsequently, a number of operations have to be performed on the fibre to impart to it various properties, such as 'bulk and handle'. Until recently, these operations have been carried out by separate trades; but now the fibre properties can be modified during the early stages of the process. In the case of dyeing, a serious source of effluent pollution will be avoided by introducing the colour at the chemical stage.

The integration of the manufacturing stages from monomer to textile is being extended further by developing methods for making non-woven fabrics; for example, by the fibre-laying methods invented during the last decade. This new technology and other approaches to eliminating the mechanical processes, such as weaving, must be in common use in the 1980s.

Plastics

The plastics sector has grown very rapidly and is expected to continue to produce existing plastics in increasing quantities but will require a considerable flexibility of operation to provide



1950s

all seven processes were operating in sequence. Research work on continuous polymerization and other rationalizations was proceeding

1960s

integrations of stages 1–2, 2–3, 3–4, 2–3–4–5, 1–2–3–4, and 2–6 were developed to various degrees of commercial viability

1970s

continued development and exploitation of the rationalizations effected in the 1960s: research proceeding on stages 2–6, 1–6 and 6–7

1980s

it is expected to exploit the rationalization already achieved in stages 1–6 on a large scale: the start will be seen of commercial viability of 6–7 and 1–7.

FIGURE 1. Progress in rationalizing the production of synthetic textiles.

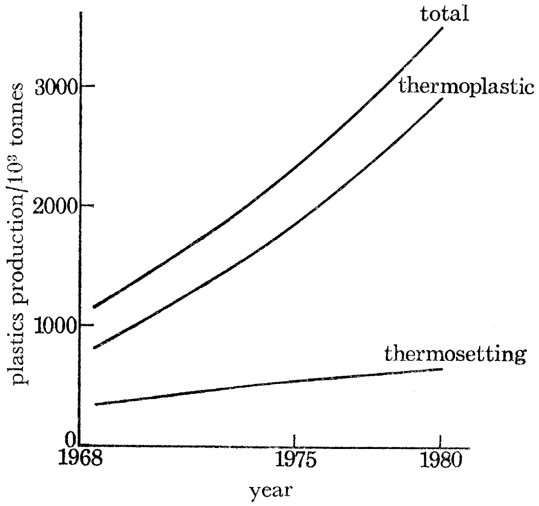


FIGURE 2. Predicted U.K. plastics production

modifications of the polymer characteristics to meet the requirements of various industries and end uses. The tentative and qualified forecasts made by the Chemical E.D.C. for total production are shown in figure 2 (Caress 1972).

The properties of the bulk polymer are changed by variation of the molecular chain length, branching and cross-linking; combined with largely empirically derived physical processing techniques, such as melting, annealing, cooling and so on in various conditions. The likely demand for more precision in polymer specification over a wider range of properties is certain to lead to advances in production technology.

As in the fibres sector, the polymer producers will take a greater part in fabrication; for which the Chemicals E.D.C. expect the capital investment over the next 10 years to be £800M, twice as great as that in bulk polymer manufacture. Problems in producing new or cheaper semi-fabricated or fabricated articles are bound to bring advances in the technology.

Heavy inorganics

In the heavy inorganic chemicals sector it is generally agreed that the technology will continue to evolve gradually. Larger plants will increase the cost of failure, and tend to discourage innovation: but well-tried advances towards plant reliability will be adopted; for example, by using materials more resistant to corrosion, hitherto ruled out by their cost. High integrity alarm and shut-down systems will be improved to protect the plant personnel and the neighbourhood. Production costs are closely linked to the cost of energy, particularly for chlorine and chlorine compounds; forecasts of the costs of nuclear power in the late 1980s are therefore of great interest. Bainbridge (1972) has given the forecasts shown in figure 3, but is careful to emphasize their sensitivity to the assumption made.

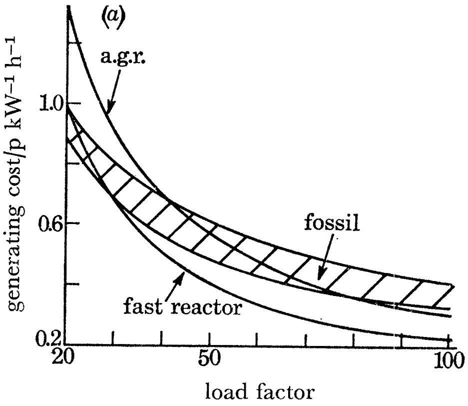


FIGURE 3*a*. Fossil and nuclear electricity generating costs.

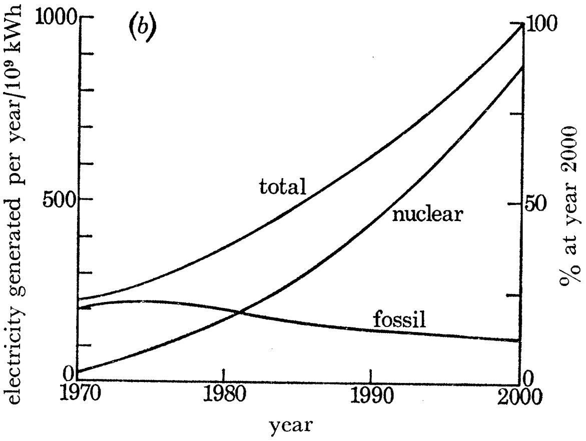


FIGURE 3*b*. Electricity demand trends.

Pharmaceuticals

The pharmaceuticals sector is expected to develop new products, new manufacturing technology, and new and less costly methods to speed up evaluation and toxicological testing. It is very difficult to envisage what such methods could be: but they must come from obtaining a more complete knowledge of the human system and its response to disturbances.

There is opportunity for the development of special technology in the chemical manufacturing stage, where extreme flexibility and provision for complete purity will be necessary in the multi-stage preparation of a variety of more and more complex molecules; such as the prostaglandins, derivatives of prostanoic acid, which perform many vital functions in the body and will be of great importance in pharmacology, as a recent paper shows (Horton 1972); or the polypeptides which have already been synthesized to 40 stages on a tiny scale and may well be taken to 50 stages at least on a commercial scale during the 1980s.

Great emphasis is being placed by the Industry at the moment on the market necessity for producing entirely new methods for administering drugs; including the need to be able to use, for example, plastic-coated inserts and permeable membranes to place the drug at a particular point or in a particular internal organ, or hypodermics to transfer drugs through the skin without penetrating it. These new methods must lead to new demands on other sectors of the Industry for: (i) small quantities of materials with unusual but very accurately defined properties; such as special polymers, which will also be used in prosthetic devices; (ii) monitoring equipment; and (iii) ingenious disposable light mechanical devices. As in the polymer field, suppliers of pharmaceuticals will take an increasing part in such developments to give added value to their products.

Petrochemicals

The high growth rate in the plastics and fibres sectors has been largely responsible for the rapid growth in petrochemicals and the expected slowing up of expansion in those sectors, particularly in fibres, is bound to be reflected in this sector.

Forecasts of markets in this sector must take account of the probability of petrochemical manufacture being established in developing countries with local sources of energy. In addition to these limiting factors and the general rise in construction and operating costs in all sectors, the petrochemicals sector will have to face considerable increases in feedstock prices. The prices in the 1980s will depend on the extent to which the main demands for oil and the naphtha fraction, i.e. for power generation and motor spirit, have been decreased in the meantime. Increase in price is however inevitable and it will be far too large to be offset by foreseeable technological improvements so that, unless some unexpected radical development emerges, product cost is bound to rise correspondingly and the sector will work with this handicap in the 1980s.

Meanwhile everything possible will be done to minimize production costs by such operational and design improvements as are discussed in part III below; particularly to maximize profitable utilization of energy and materials, and to retain flexibility in large, closely integrated complexes to allow advantage to be taken of feedstock market changes and of alternative process routes.

Advances in product separation techniques will also be exploited; particularly improvement in column control and in solvent extraction methods. The greatest economies will however come from the development of new catalysts for the operation of more efficient processes and the utilization of cheaper starting materials. This emphasizes the importance, that has already been noted above, of work leading to methods for designing selective catalysts.

Forecasting

The 1971 report of the Chemical E.D.C. Working Party on investment in the industry stresses the need for improving forecasting, especially of the demand in individual sectors.

Radical improvements can only come from better understanding of the whole system in which the Industry operates, within constraints imposed by political, social and commercial influences; for example, home and foreign governments' policies (as reflected in tax incentives, tariffs, etc.), the growth rate of g.n.p. in the U.K. and in other countries; changes in social habits and tastes; competitors investment plans and the emergence of new processes; war and rumours of wars. These have been so unpredictable that doubts have been raised about the value of devoting effort to trying to improve long-term forecasting.

There are, however, good reasons for supposing that the situation will be improved. International trade agreements and the entrance of the U.K. to the E.E.C. will stabilize the political factors in overseas trading: uncertainty about competitors' plans, which has contributed so substantially to the cyclic swings between 'over-capacity' and 'under-capacity' in some commodity products should be reduced by common agreement to reveal investment plans in critical areas. A good lead has been given to the U.K. by the 1968 amendment to the Restrictive Trade Practices Act; so that similar constructive legislation may follow in the E.E.C.

The forecaster can therefore expect to have much more reliable information for developing the structure and parameters of statistically based models as 1990 approaches. Mechanistic models, based on knowledge of causal relationships in the social/economic system will not be available, I believe, until well into the next millenium.

PART II. GENERAL OPERATIONAL AND DESIGN DEVELOPMENTS

1. Operational developments

We should begin by considering the implications of the increase in plant size, which is a feature common to all the commodity processes.

The very large plant

To achieve satisfactory operation of the largest plants, existing technology has been stretched to its limits. Growth in capacity has been rapid: dramatically so for large tonnage products such as ethylene (figure 4*a*, *b*), but the tendency has been to take advantage of the economy of larger scale production at all levels, in batch as well as in continuous processes, e.g. in dyestuffs manufacture the vat volume has increased from hundreds of gallons to thousands, and in paints manufacture a new plant produces 20000 litre batches (figure 5).

Experience has shown how difficult it can be to bring the very large plants up to designed throughput quickly after commissioning and to maintain full rate subsequently. It is not surprising that some of those most closely connected with the planning and operation of such large plants have come to the conclusion that for the time being the point of diminishing returns from increased size has arrived, because under-utilization of plant due to breakdowns and to swings in demand can be so costly; just how costly has been shown by the examples quoted by Sir Ronald Holroyd (1967), and by recent results. On the other hand, there is confidence that advances in technology will reduce the risk of going off-line for technical reasons and that in the coming years much better planning between companies, at least among those operating in Europe, will reduce the even more serious hazard presented by large, cyclic fluctuations in the market. The general view does appear to be that the economic limit of plant size has not yet been reached for some processes, such as ammonia and ethylene; for which increases of two or even three times are not impossible: other processes such as vinyl chloride may well remain about their present size. Pipe lines, like the ethylene grid in West Germany, will aid economic distribution and sharing of capacity: pipe line technology will be improved to reduce operating costs.

Meanwhile it has been pointed out many times that a better return on capital will have to be shown if the Industry is to find the capital for future growth on this scale: rising costs, especially of raw materials, by leading to more expensive products, will make higher profitability even more difficult to achieve. Improved design and operation must contribute by optimizing material and energy utilization and by minimizing interruptions to production.

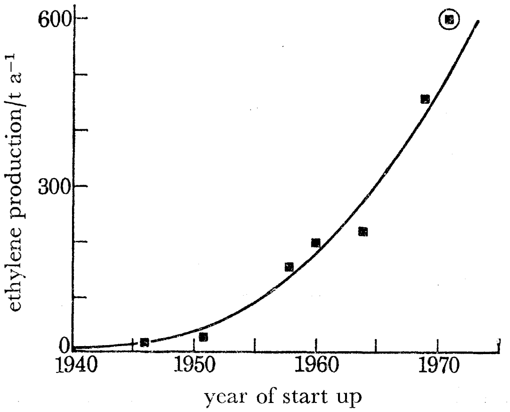


FIGURE 4*a*. Growth in size of ethylene plants. ■, naphtha feed stock; ◉, oil-gas feed stock.

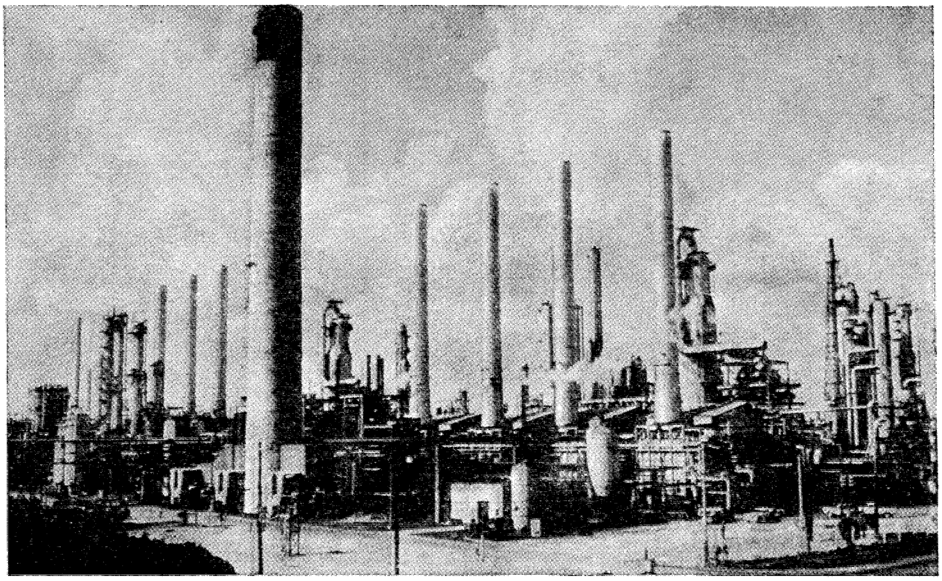


FIGURE 4*b*. Largest ethylene plant to date: 600000 t/a.
Started up 1971 in Texas for Shell Chemical Co.

This will highlight equipment reliability, optimization of process conditions at the design stage and subsequently during operation, maintenance, high performance protective systems. Meanwhile more will be spent on safety and conservation of the environment.

There can be little doubt that the demands of the large plant will be responsible for the most significant advances in the Industry's general technology between now and 1990.

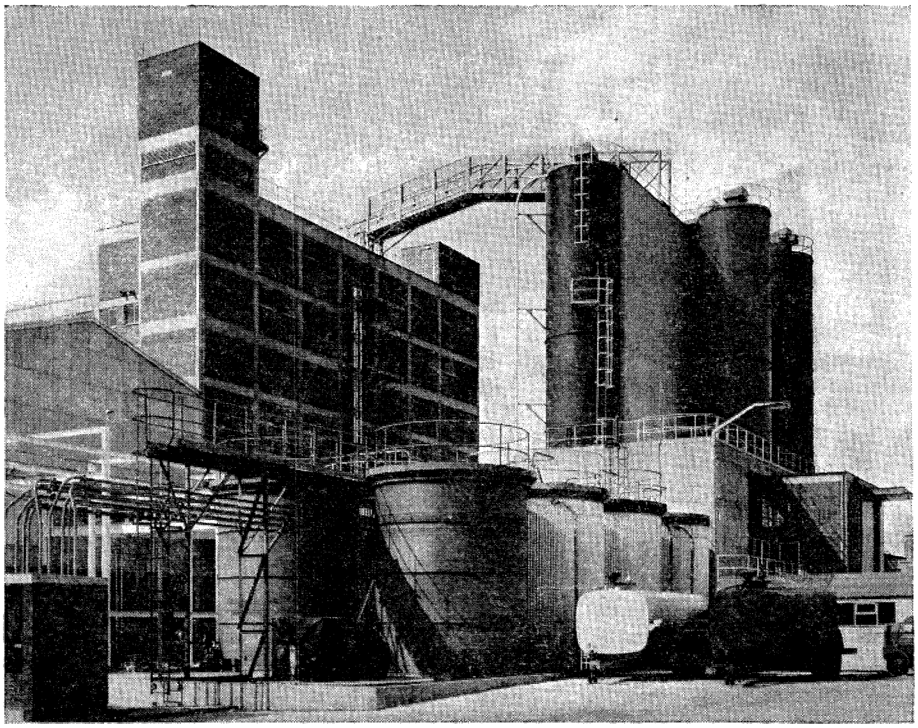


FIGURE 5. Large paint plant for 20000-litre batches. Started up in 1972 at Stowmarket for I.C.I.

Maintenance and materials

Maintenance

In the 1980s designers will achieve a better balance between cost of equipment and cost of down time and maintenance when it fails, using comprehensive information on reliability (stored in data banks), and computer programs for dealing with unreliability and uncertainties. New means of testing and more rigorous specifications will have decreased failures due to faulty fabrication or materials. Designers will help to speed up maintenance, by providing better plant layout and access to equipment: they will specify materials more resistant to operating conditions.

For planning maintenance, computing facilities will be available; with data banks for information on process records, costs and stocks of new materials, intermediates and products; as a guide to relative priorities. Maintenance teams will be better trained and will have better equipment; there will be better diagnostic maintenance manuals based on, for example, the F.I.M.S. system developed for use by the Services (Langham-Brown 1972).

Equipment will be monitored continuously, for signs of wear and incipient failure, by the control system; which will warn operators and maintenance engineers of the source of trouble in foreseeable instances, and the degree of urgency (Anyakora & Lees 1972): the equipment and materials necessary for repairs or replacements will be requisitioned automatically; as is already being done on a limited scale in some refineries.

Rotary machines will continue to replace reciprocating machines: moving parts exposed to process fluids will be eliminated wherever possible. The technology of fluidics now being developed for industrial use, notably by Royle at Sheffield and by the British Hydrodynamics Research Association, will be in use.

Economics will favour replacement instead of repair, where feasible; and more repair *in situ*.

Machines, such as the compressors now operating in very large plants, will be thoroughly developed and reliable, at capacities appropriate to the even larger throughputs of the 1980s. Process economics will have forced developments to eliminate the kind of chronic troubles, for example leakage of seals, which have plagued plant managers in the past but which have not until recently become so critically important.

As a consequence of all these improvements, maintenance (scheduled and unscheduled) will be far less frequent and much more rapid; the maintenance man's responsibility will be greater and his job will be upgraded.

New materials

The use of new materials of construction has been delayed by unsolved application problems, the fear of unexpected trouble and by their cost. Edeleanu (1972) has pointed out that they could have an important effect on process economics, particularly by allowing processes to be considered which are now excluded by corrosion problems, and that events are moving in their favour. Costs will be decreased by standardizing on a few specifications and by increasing usage: design experience will be incorporated in International Codes of Practice for all to use. Problems in using materials with different moduli of elasticity, widely different thermal properties and non-isotropic characteristics will in due course be resolved. Quite new materials might have to await development until they are required by some major national project, such as power generation by nuclear fusion.

The operator

Sir Ronald Holroyd (1967) has emphasized that to ensure successful operation every person concerned must be highly trained, have a full understanding of the relationship of his job with that of others and have a feeling of personal responsibility that makes him his own best watch dog. We have noted the maintenance man's requirements: those of the operator are even more pressing.

Automation is inevitably decreasing the number of operators, while making more demands on their ability. For example, the batch (paint) plant in figure 5 has one central console manned by only two operators. Similarly, on well-instrumented continuous plant the number of operators has been reduced to the minimum needed for start up, shut down and upsets. Now that computers are being used in the control systems of both batch and continuous processes, the operators are beginning to feel that the computer is taking over and their jobs are being downdgraded.

However their responsibilities are in reality increasing as the computer control system extends from individual plants to whole closely integrated complexes: damage to instruments or plant may leave the control system helpless and present the operator with an extremely difficult situation; especially when there is a danger of his having lost familiarity with process requirements and responses. The operator's job is thus in fact being upgraded and he must be given special training and all the aids necessary: such as highly developed presentation of data, simulators to retain his feel for the processes, and computing facilities to provide information and to predict the likely consequences of any action considered.

But also his whole time must be profitably employed between such emergencies, and made more interesting and responsible; by involving him, for example, in process improvement and enabling him to play a more important part in the works management team. To make this happen, it must become a matter of policy and this policy must be seen to be put into practice.

If this is done, the 1980s will see the plant being controlled by a very efficient combination of men and computers. It would be rash to predict the distribution of responsibilities; except to say that they should evolve during the next decade with the complete involvement of the operators, and to hazard a guess that neither men nor computers will be concentrated in control rooms. Some men will no doubt be working as part of the works management team 'at base' while others will be distributed round the works, but in continuous contact with the team at the base; rather in the relationship of the ground staff at Houston to the astronauts. The operator 'out in the factory' must be constantly in communication with the system at base and any local control centres in the system. He must have the equivalent of the designer's light pen to make rapid and direct communication with any part of the control system. While it is not possible to foresee the future pattern, it is very important to study the possible operator/computer systems with the operators, and to test them on the plant.

One thing is quite certain: the operators will have been continually upgraded in status and earnings in accordance with their greater responsibilities and their correspondingly higher standards of general and technical education and of training.

Safety: high integrity protective systems

Every works manager knows that frequent but spurious alarm signals in the control room are not only distracting to the operator but lead to valid alarms being neglected: and that unnecessary automatic shut-downs are responsible for a great deal of lost production time, especially when considerable time is required to bring the plant back to full production. In the interests of both safety and economy, high integrity protective systems are being developed: these can be guaranteed to give alarms and take emergency action when necessary, but can be relied upon not to operate outside a narrow preset range of conditions. Such systems have been highly developed by U.K.A.E.A. for conditions in their plants, and, for example, in the aeronautical field so that the appropriate statistical treatment is well developed (Green & Bourne 1965); but it is also necessary to have quantitative information about the reliability of equipment in the Industry's own range of process conditions (Stewart 1971). As this accumulates, confidence and economy in design will improve.

This quantitative, logical and meticulous attention to alarm and shutdown systems is bound to give good protection to the site and the environment as far as foresight and planning can take account of all the sources of hazard. Unfortunately it is inevitable, as Lord Robens (1972) points out in his report on Safety and Health at Work, that accidents will occur in spite of every care and they can put life at risk in the environment of the factory, the warehouse or transport. It is therefore the responsibility of industry in general to make sure that the potential danger of a new project to the environment is deliberately considered and guarded against, before the project is authorized.

The best early warning system is in many situations a man and it may well be that a new job will appear in the factory; of noticing and giving warning of anything unusual; such as a different noise, a new vibration in a stanchion, an odd smell or anything that could mean trouble. A special kind of man is required, with qualities including absolute conscientiousness and discipline, alertness and good observation, and enjoyment of the job.

Many such men will be without rewarding work in the 1980s: they could be very usefully employed as the eyes and ears and noses of the few operators in the factory, acting perhaps as security men at the same time.

Pollution

People in the Industry are very anxious to decrease pollution and table 1 (Ashby 1972) illustrates the success they have had in the modern plants quoted.

TABLE 1. EFFECT OF THE INSTALLATION OF NEW PLANT ON THE POLLUTION INDEX†

	size	pollution		pollution index (ratio of columns (1) and (3))	
process	output (tons/day) (1)	type (2)	quantity (tons/day) (3)	lb per ton	kg per tonne
nitric acid					
old	490	acid gases	10	45	20
new	260	acid gases	3	25	12
latest	500	acid gases	3.5	15	7.0
sulphuric acid					
old	750	acid gases	5	15	6.7
new	1000	acid gases	2.5	5.5	2.5
ammonia					
old	400	ammonia gas	1.5	8.4	3.8
new	3000	ammonia gas	1.5	0.93	0.42
terephthalic acid					
old	160	acetic acid gases	0.5‡	6.8	3.1
new	330		1	6.6	3.0
terephthalic acid					
old	160	liquids giving a b.o.d.§	2 } as b.o.d.	28	13 } as b.o.d.
new	330		0.5	3.3	1.5
methanol					
old	600	liquids giving a b.o.d.	8 } as b.o.d.	29	13 } as b.o.d.
new	1100		1.5	3.1	1.4
propathene					
old	55	liquids giving a b.o.d.	0.3 } as b.o.d.	13.2	6 } as b.o.d.
new	80		0.1	2.75	1.25
ethylene					
old	200	liquids giving a b.o.d.	0.25 } as b.o.d.	2.8	1.3 } as b.o.d.
new	450		0.1	0.49	0.22
nitrogen fertilizer					
old	800	liquids with nitrogenous chemical	3 } as N	8.3	3.8 } as N
new	1100		2.5	5.0	2.3
ammonia					
old	400	liquids giving a b.o.d.	1.5 } as b.o.d.	8.3	3.8 } as b.o.d.
new	3000		1	0.73	0.33

† Reproduced from Third Report of Royal Commission on Environmental Pollution (Sept. 1972); with permission of The Chairman, Sir Eric Ashby.

‡ The pollution index for this plant is expected to be brought into line with that for the other modern plants by steps now being taken.

§ Biological oxygen deficiency is defined on p. 73 of the Report.

It is often difficult and expensive to decrease noxious components in gaseous effluent, but it is always technically possible. The problem therefore is one of economics and decisions about permissible concentrations should be taken with this in mind. Control of pollution in steady operating conditions is not so difficult: to guard against all accidents, such as spillages and emissions during plant upsets, will be very difficult. More severe problems are often presented by liquid effluents; dilute aqueous solutions containing either metal ions such as Cu, Hg or Va from catalysts or Cr from water treatment systems, or organic materials which may be poisonous or lead to oxygen depletion in the river. There are problems in separating these materials from the effluent before it leaves the treatment plant, but again the problem is essentially an economic one. The membrane separation techniques are playing an increasingly important part in decreasing costs and improving the purity of liquid effluents.

Improvements in plant design and control quality, recycling of gaseous effluents and, on large plants, special recovery units will help to maintain the rate of improvement indicated in table 1.

New types of instrumentation will be developed to monitor effluent before it leaves the factory and pollution of air and water. Satellite, airborne and surface based sensors will record the composition of individual factory stack gases and general atmospheric pollution in the environment and over wide areas, as well as contamination of water surfaces. Instruments will be used that would be considered prohibitively expensive at present: probably depending on spectrometric analysis of reflected daylight or back-scattered laser beams. They will become less costly as production and design techniques develop and components such as tuned semi-conductor light sources and detectors are manufactured cheaply in the large numbers required. Liquid effluent will be monitored by such sensors as ion selective electrodes or liquid chromatographs.

2. Design developments

Once the decision to invest in a new plant to manufacture a given product has been taken, and its capacity has been determined with the help of the best forecasts available, profitability will depend on success in optimizing the process and plant design. Improvements in design technology will therefore be encouraged.

Some considerations governing selection of the process have been noted. Alternatives can be evaluated rapidly with the aid of computers, provided design data are adequate.

Reaction data

Knowledge of the chemistry of important reactions is often not adequate at present, but the rewards for establishing reaction mechanisms and kinetics will ensure that designers will have much more complete information in the 1980s; even though progress in molecular science has not by then made possible prediction of molecular behaviour *ab initio.*

Engineering and cost data

A start has been made in organizing the collection of engineering and cost data for building up data banks, containing updated information that the designer will use in the 1980s; in combination with standard programs for flowsheeting and plant design, in place of the 'data book and design manuals of the 1950s'.

Computer aided design

The progress made during less than 20 years in providing automatic aids for the process designer is remarkable, as was shown at a recent conference on 'Decision, design and computer' organized by the Institution of Chemical Engineers. It is already possible *in principle* to program a computer system to select a process route and appropriate unit operations; calculate the energy and material balances for the optimal operating conditions; carry out the engineering design calculations for the plant, derive physical layouts for the plant (including pipework); and generate 3-dimensional drawings of the final plant from any desired view-point.

Clearly these design stages cannot be undertaken in the simple sequence outlined. It is not possible to select a route or a sequence of separation stages until the most economic way of constructing the plant and operating a process based on the route has been calculated. Thus a practical computer program will initially generate a large number of process alternatives but will carry forward to each successive, more detailed, step of the design procedure only viable alternatives (i.e. those which cannot already be dismissed as less than optimal). A range of successively more accurate costing procedures, each requiring a greater degree of design detail, will be developed in the near future to aid this selection procedure.

Programs of this sort clearly cannot operate without human intervention. The engineer cannot specify rules to ensure that the program will generate all viable process alternatives, nor to recognize, for example, all possible hazards: so that human intervention is still necessary and is most frequently achieved by running a sequence of programs with inspection at each stage. Before the 1980s man/computer communication will be facilitated by refined interactive computing facilities.

Design data are certainly never free from error and no item of equipment is completely reliable. Techniques must be developed to assist the designer to assess and allow for these uncertainties economically. Monte Carlo techniques prove to be prohibitively expensive in computer time. The next stage in development will therefore be to develop techniques for dealing with uncertainty, which do not involve prohibitively large computing costs.

Uncertainties in design data

Computer flowsheeting techniques aid in planning research on new processes and in allocating design margins. At each stage of process development the flowsheeting program should constitute a condensation of all current knowledge of the process. It is therefore possible, in principle, to employ the program to determine whether it is necessary to increase the certainty of the design data by doing more experimental work. In practice the designer is frequently faced with the option of requesting additional experimental work or allowing increased design margins. At present an economic choice is made by using such techniques as sensitivity analysis, but routine methods for computing the consequences of uncertainties are being developed: for example, a method has been described that requires a number of calculations of order $2n$ to compute the consequences of n uncertain variables as compared with a 2^n for a Monte Carlo simulation (W. R. Johns, personal communication 1972). Developed forms of this method will be employed in the 1980s, as a routine in allocating design margins to allow for the effect of uncertainties on overall plant performance.

Such quantitative techniques will be used increasingly by management to compare, for example, investments with different sets of risks: this is symptomatic of an increasing tendency for technical and commercial techniques to merge in one methodology of complete system analysis.

Economics of equipment reliability

Design margins are applied not only because design data are uncertain but also because equipment and services fail from time to time: for example, the capacities of storage vessels to minimize the effect of such failures have to be calculated on the basis of probability. Again Monte Carlo methods are widely used and are found reasonably satisfactory for studies of *existing* plant. However, computing time again becomes prohibitive for *design* studies involving a large number of parameters. Since frequency of failure and average repair time are normally both uncertain at the design stage, a combined availability and uncertainty analysis will normally be required. Such analysis is clearly outside the scope of existing Mone Carlo techniques but it is certain that more elegant and economic methods will come into use within the next 5 to 10 years.

The integrated process/plant/control system

Flowsheeting and plant design will be carried out simultaneously by the computer programs of the 1980s, so that the process and plant will at last be designed as one optimal integrated system; and, well before then, it will have become increasingly necessary to optimize for changing conditions as well as for steady-state performance. One of the control engineer's original objectives will then have been reached; because, to achieve this, the control system and control equipment will have to be designed as an integral part of the process and plant; a significant advance on previous design technology.

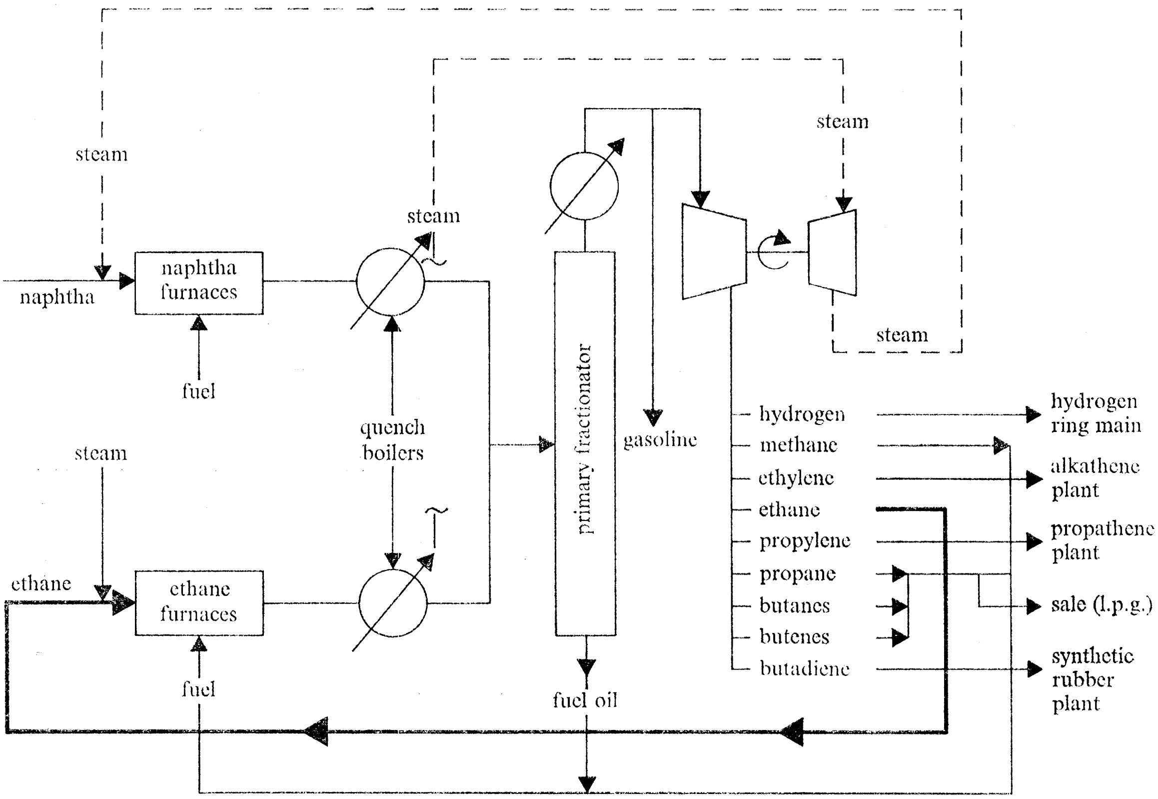


FIGURE 6. A simple example of recycling of material and energy.

The integrated complex of plants

The object of achieving the closest workable integration of the plants on a given factory site is to avoid waste of materials and energy; including release of materials in effluent. A simple example of recycling materials and of utilizing energy of reaction is shown in figure 6.

Similar arrangements in large complexes such as those shown in figures 7 *a* and *b* become very complicated. It will be apparent that any significant change in the energy or materials balance in one plant will affect the whole system: indeed it may render the whole system unworkable. As far as actual day-to-day manufacturing processes are concerned, the central research and development objective in control engineering during the next decade will be to provide a fundamental approach to the design of systems for stabilizing and optimizing the performance of such factory systems of increasing complexity. As we shall see, however, this is only one aspect of a much wider problem in system analysis and control.

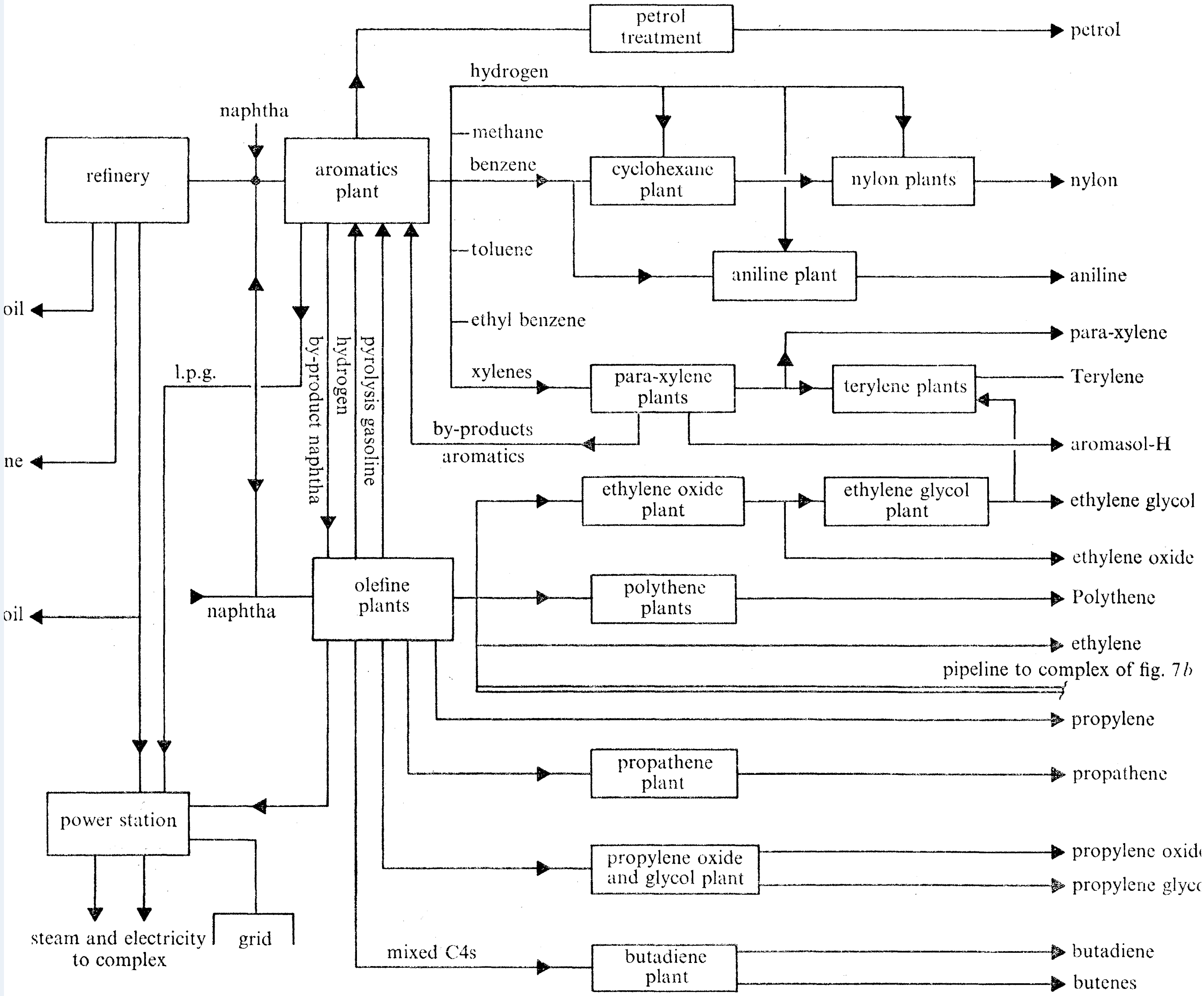


FIGURE 7 *a*. Refinery/aromatics/olefines complex. (See notes on facing page.)

The control system

Research and development in control engineering during the next decade will be aimed at providing a methodology for designing systems to stabilize and optimize processes and complexes with highly interactive loops during changing as well as steady-state conditions.

It is expected that the major part of this research will proceed in those Universities selected for special support in the control engineering field by the Science Research Council; namely, Cambridge, London and Manchester, with Bangor, Sussex and Warwick pooling resources.

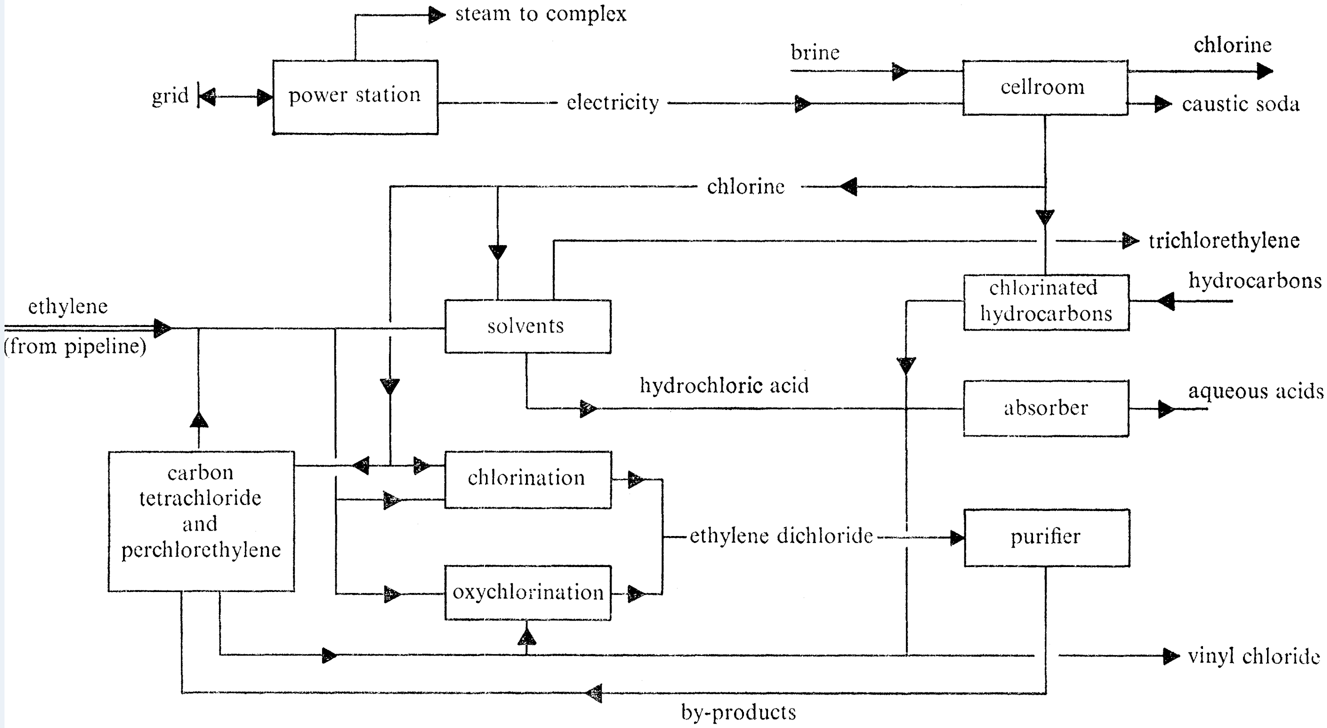


FIGURE 7 *b*. Chlorinated hydrocarbons complex. (See notes below.)

Notes on figures 7a and 7b

These figures are intended to indicate how two tightly integrated complexes located in the NE of England (figure 7*a*) and in the NW (figure 7*b*) are interdependent and can be considered as a single large complex.

The refinery of (*a*) produces the hydrocarbon feed shown in (*b*) and the ethylene feed in (*b*) is supplied from the olefine plant of (*a*) by the 'trans-Pennine' pipe line. The energy and materials balance in both complexes is critical. Storage of ethylene and links with the national electricity grid and power stations provide a measure of flexibility in operating the total system. Steam usage is closely integrated with other works on each site.

Chlorine is produced in the cell rooms which use electricity produced by the power station. Chlorine and caustic are sold and chlorine is fed into the complex for use in the carbon tetrachloride and perchlorethane plants, in the solvents plants, in the chlorinated hydrocarbons plants and in vinyl (direct chlorinators) plants.

Hydrogen chloride is produced in many plants within the complex of (*b*) and is consumed in the vinyl chloride plant oxychlorinators. The hydrogen chloride/chlorine balance is critical; particularly at times of high demand for caustic, which is proportional to chlorine production by electrolysis. The complex must be flexible in order to operate under fluctuating demands for the products (in particular chlorine and caustic) and when part of the complex is off-line.

Steam. In addition to maintaining a hydrocarbon, chlorine and hydrogen chloride balance in the hydrocarbon/chlorine complex, it is necessary to balance the steam flows. The main producers (*b*) are the power station and the oxychlorinators; the main consumers are the perchlorethane plant and the dichloride purification and cracking.

Mathematical models can be used to optimize both the steady-state behaviour and the operation of the complexes in the face of disturbances of a discrete type.

As soon as sound principles are established they will be developed by application to individual processes and complexes: it is hoped that no attempt will be made in the first place to produce a completely generalized all-embracing design method.

In view of the increasing complexity of process systems, such as those in figure 7, the search must continue for methods of simplifying the models used to simulate them. This cannot be done without real insight into the mechanisms.

It is important that there should be some small teams of suitable calibre in industry to provide the universities with specific exercises in system analysis and design, on manufacturing complexes in a number of industries, and to assist in these projects; supplying process experience and, in particular, insight into the mechanisms of the systems studied.

Hardware and software

There are many hardware and software problems to be solved before further advances in system design can be exploited; but they are nearly all, if not all, the subject of current research and development in universities, polytechnics, research associations, or industry; significant advances can be expected by the 1980s. For example, the combination of computers and electro-optic technology will lead to very powerful on-line analysers for determining the composition of polymers, slurries, gases and liquids. Raman spectrometers will be used for analysis, without sampling, of liquids and gases in pipe and reactors, slurries, extruded polymers etc. High-resolution spectrometry with tunable lasers will be possible from 100 to 0.1 μm. Mechanical moving parts will be replaced by solid state tuners and modulators, and spectral scanning in milliseconds rather than minutes will come from these techniques, and from faster detectors and more powerful sources. Data will go direct to computers for subsequent analysis and model-fitting. Better sensitivity and consistency of measurement will lead to accuracies of a higher order in absolute terms, facilitating cost accounting metering and making material and energy balances, interpreting process records and operating optimizing control systems.

In areas where measuring and control equipment have been recognized as being inadequate (in some instances for a very long time), promising developments are now taking place; for example, in fluid flow measurement (Beck *et al.* 1971), in control valves for rapid action and for corrosive fluids, and in fluidics (Boucher & Royle 1972), and in modular/digital systems for data transmission, control and interfacing plant instrumentation with computers (Halsall & Kirby 1972).

It can therefore be assumed that instrumentation will no longer be the Achilles heel of the control system in the 1980s.

Computer controlled systems

It would be a very great mistake to think in terms of general types of system, when once the basic methods of approach have been worked out. Ultimately each control system must be designed to be the best for its particular situation and requirements. In particular no one should waste time discussing the merits for general purposes of specific configurations.

As far as the hardware is concerned there is now complete flexibility so that in any given circumstances the hardware should be chosen to give the most economic performance. This, of course, will depend entirely on the manner in which it is decided to control the system and the cost of developing the necessary software. A compromise will have to be made between hardware and software costs and this is why it is so very important that the most suitable real-time language shall be developed for general use. One language, Coral, has been developed for the Services (1970); I.C.I. has developed another, RTL, for process use but it is in fact suitable for any comparable real-time applications (Barnes, Gray, *et al.* 1972).

3. The large organization

Immensely complex problems confront any attempt to design the structure and management of a large organization, such as a chemical company. The concepts of system analysis and control are in principle applicable but there are two basic difficulties to overcome. The first arises from the great complexity of the large organization: this difficulty will be continuously reduced as methods are developed for dealing with large manufacturing systems, such as that shown in figure 7. Control engineering research programmes, at Cambridge, for example, are aimed at providing design methods for both process complexes and large organizations (Coales 1973).

The second difficulty is of similar nature to that which process designers faced 25 years ago: that before any system can be designed it is necessary to discover the behaviour of the components and units it contains. This had to precede development of process control to maximize each component's contribution to the overall return on investment. In the case of a company, or any other social organization, the chief investment is in people and a great deal of patient research and large scale experiment remains to be done before their behaviour as a part of an organization, either as individuals or as groups, can be understood with anything approaching even our present understanding of process components. Thus we are a very long way from being able to design even small organizations on any basis except experience and qualitative application of the general principles of system analysis and control engineering.

Experience shows that some objectives should be given a special priority: among these is provision for every individual to have the best possible information for doing his job, which must include feed-back and exchange of current and long-term experience; a natural development of judgement; development of individual responsibility; continuous monitoring of individuals' performance (as components are monitored in process operation), to show who can take more responsibility and who needs remedial attention.

Each of these provisions depends on good communication between groups and between individuals: furthermore, design for good management, or at least that part known to engineers as 'controllability', depends essentially on the response of the group and individual to the information communicated; on the time taken for instructions (for example) to be transmitted, judgements made, decisions taken and action carried out: i.e. on the 'time lags' in the system.

Even without quantitative knowledge of these time lags, the control engineer's understanding of their general effect on the response and stability of the whole complex system will enable him to rearrange their incidence to improve performance and to highlight those of special importance: the system can be simulated by a variable parameter dynamic model. Similarly, 'attenuation' and 'noise' in communications can be reduced so that 'they come over loud and clear'. The system analyst can remove many of those obstacles to action which frustrate even the best intentions; thereby decreasing the friction and inertia which dissipate so much time and energy in all organizations.

By such means the structure and management of an organization can be greatly improved with respect to its general efficiency and speed of operation. However, when the system analyst and control engineer have done their best, the greatest problem remains: to ensure that the will of every individual is singly concentrated by his own self-interest to do what is best for the organization. What this self-interest is must be discovered by the organizational sociologist, and more than one decade will pass before the knowledge will be available for system designers to provide for it with confidence.

Meanwhile there is a danger that, in our efforts to improve structure and management, we may pursue speed at the expense of considered decision and quality of work; and encourage compliance at the expense of integrity of judgement. Ultimately our efforts must be self-defeating unless research supplies knowledge of individual and group behaviour in an organization.

These considerations go far beyond any one industry: they affect all relations and organizations whether they are industrial or social, national or international; which is perhaps sufficient excuse for discussing them in the context of the Industry in the 1980s; when already their importance has been emphasized so authoritatively by the Chairman of I.C.I. at an earlier discussion of the Industry's future (Callard 1969).

4. Conservation of resources

Conservation of world resources has been discussed exhaustively (see, for example, Hartley 1968). Nevertheless, with Sir Harold Hartley's memory so fresh in our minds, the Industry's future cannot possibly be considered without emphasizing our responsibilities in this matter, to which Sir Harold devoted so much effort until his very last days.

It only remains to remind ourselves that man cannot live by bread alone; his continuing development, possibly his survival, depends not only on his physical requirements being assured. He is dependent on human relationships and on being able to adapt himself to changes in these and to an environment that some writers consider to be an increasing threat to his very existence. Whatever weight we may give to their views, the nature of the threat must be understood before we can either dismiss it or seek to overcome it. At first sight this seems to mean extending the study of man's behaviour far beyond what might be considered necessary for understanding his behaviour in organizations, so as to be able to design them to release his full potential; as discussed in the previous section. Or do we in fact need to understand the whole man and his interaction with his whole environment before we can understand one aspect of his behaviour in one part of his environment?

Whether we are interested in designing better organizations in industry or elsewhere in the 1980s or whether we are more interested in man's being able to adapt himself to his environment in the far more distant future, one can surely only agree with Tinbergen (1972) when he urges 'all sciences concerned with the biology of Man to work for an integration of their many and diverse approaches, and to step up the pace of the building of a coherent, comprehensive science of Man'.

5. Conclusions

It is obvious that we can expect the advances made in molecular sciences during the last decade to be exploited during the next decade: particularly in methods for designing catalysts, and later for improving separation processes.

It is also evident that the manufacture of large molecule materials using enzymes will be on a large scale, while synthesis of complex molecules will be extremely important to pharmacology.

Designers will have computer programs for dealing with uncertainty and with unreliability of equipment, and adequate information on process reactions; although in 1980 this will still probably be obtained by experimentally based techniques of the kind used now.

Control systems will optimize the profitability of plant complexes during changing conditions; such as start-up. Process instrumentation will have been greatly improved, particularly for the analysis of plant streams; signal transmission will be digital: computing equipment will be flexible.

Increasing attention will be paid to safety and preservation of the environment and to conservation of natural resources.

Personnel responsible for the construction, commissioning and operation of plant will have been given additional responsibility and improved education, training and facilities.

Teams of scientists and engineers in the Industry will be required increasingly to support and exploit basic research.

Application of system analysis and control engineering concepts will make a significant contribution to improvement in the structure and management of large organizations during the 1980s.

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Discussion

Dr J. W. Menter, Treas. R.S. said that he had great reservations about very large industrial plants especially if they only produced a single commodity such as the ethylene plant that Dr Young had mentioned. He asked whether the causal relationships, established in relation to markets and the behaviour of people, such as Dr Young had forecast, would ensure that large plants were economically worthwhile.

Dr Young replied that the establishment of such causal relations (hardly to be expected until well into the 2000s), would certainly improve market forecasting and to that extent would help to ensure that the sizing of new plants and the timing of their commissioning would be more likely to lead to their commercial success. But in the long run this must depend on keeping total production capacity for bulk chemicals in step with demand in world markets. This can hardly be achieved unless governments encourage a measure of coordination of major manufacturer's investment programmes; the enlarged European Economic Community could facilitate this in due course.

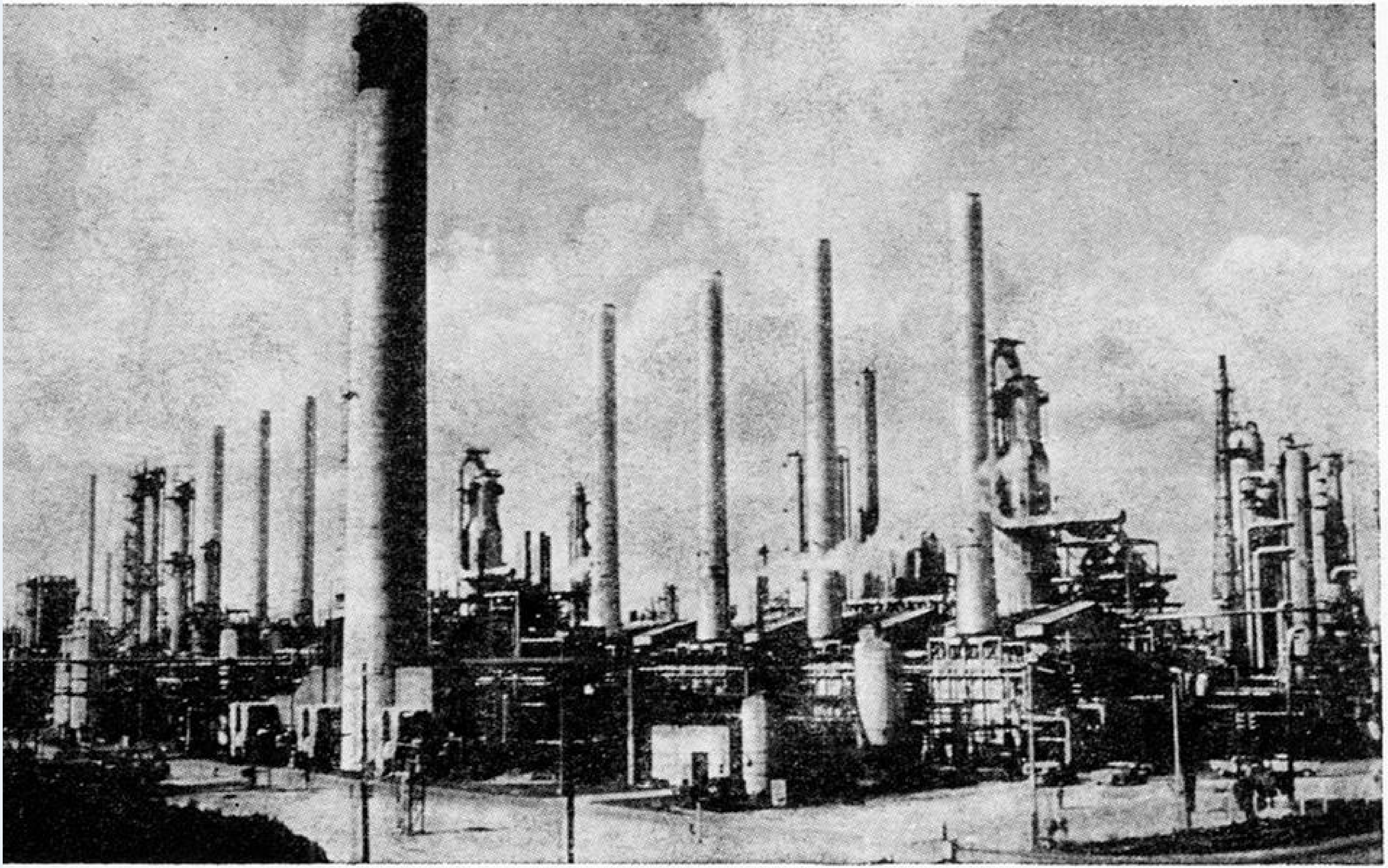

FIGURE 4*b*. Largest ethylene plant to date: 600000 t/a. Started up 1971 in Texas for Shell Chemical Co.

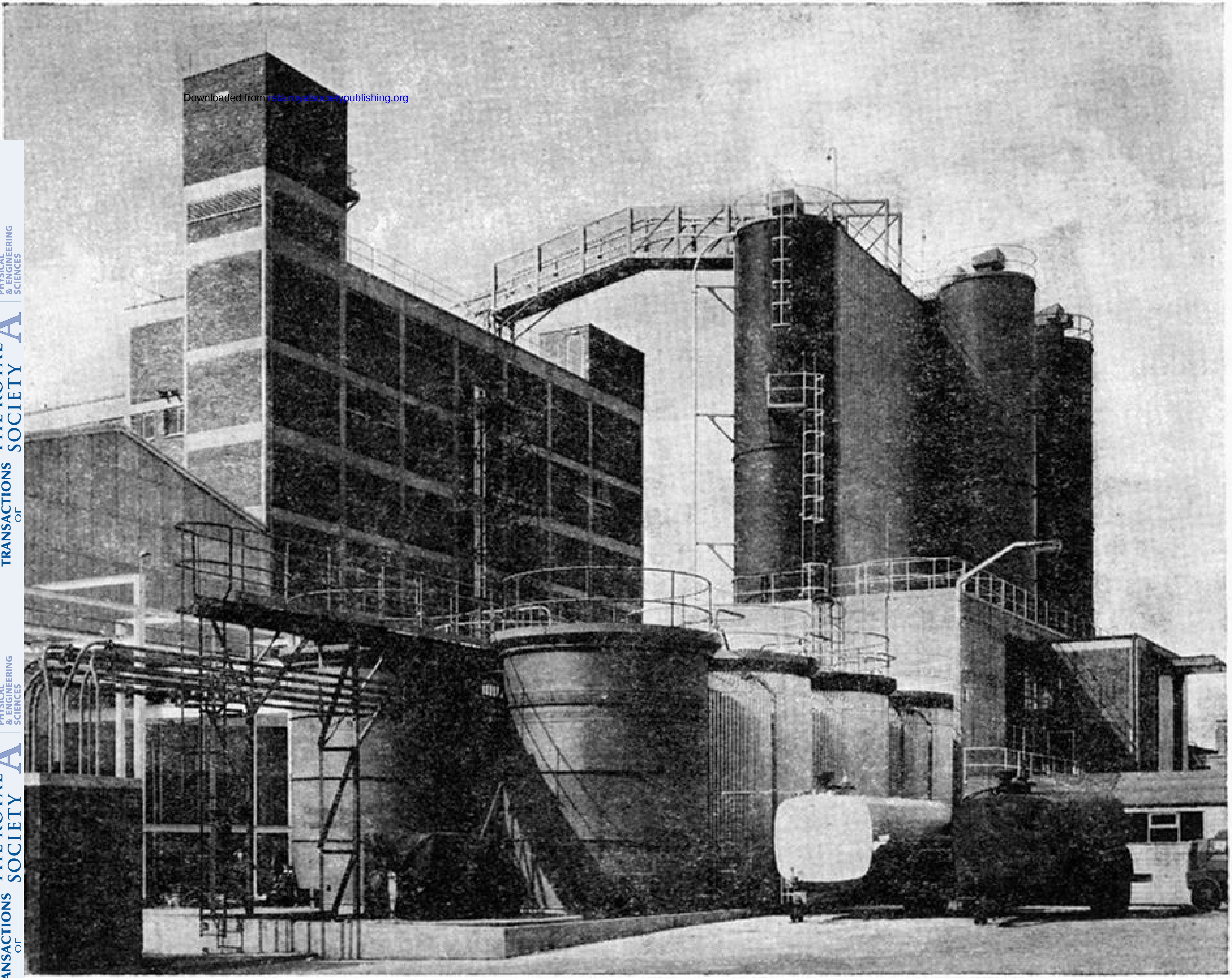

Figure 5. Large paint plant for 20000-litre batches. Started up in 1972 at Stowmarket for I.C.I.