1976 Presidential Address*
Chemistry and the New Industrial Revolution

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My object in this Presidential Address is to supplement the Symposium on the 'Conservation of Resources' organized by the Industrial Division and the Royal Institute of Chemistry, by a consideration of the options available to the U.K. when supplies of North Sea oil begin to be depleted, and the implications for chemistry and the chemical industry of the change from one form of energy to another. It is the rapid expansion of the world's population that is rendering the problem of energy so acute and urgent.

1 Exponential Population Growth

Although the population of the U.K. is at the present time almost static, this is not true of the world as a whole. The world's population is now 4 billions and will be 7 billions by the end of the century. It is increasing exponentially (Figure 1), doubling itself every 33 years, and the doubling time will gradually become smaller unless effective measures are taken to reduce the growth rate. Attention was first called to the implications of exponential population growth by the Club of Rome, which commissioned a group of workers at the Massachusetts Institute of Technology to study the interaction of the technical, social, economic, and political factors involved in what they called the 'world problematique' or the 'Predicament of Mankind'. The group's report, 'The Limits to Growth', was published in 1972, and had a mixed reception – from anger and dismay to scepticism and indifference. However, in some quarters it was taken very seriously and, just as Rachael Carson's 'Silent Spring' stimulated public opinion to react vigorously against the extravagant and unintelligent use of pesticides, so 'The Limits to Growth' helped to stimulate the introduction of anti-pollution measures in many parts of the world, so effectively indeed that it seems most unlikely that the disastrous effects predicted in this book will ever come to pass.

2 Exhaustion of Non-renewable Resources

The warning given in 'The Limits to Growth' about the exhaustion of non-renewable natural resources did not, however, create the same sense of imminent peril, and the so-called 'fuel crisis' of 1973 actually resulted from the quadrupling of crude oil prices by the Arabs and was little more than a nine-days wonder to the average man. It did, however, alert governments and industry to the importance of conserving fuel resources, but in my experience it was the scientists,

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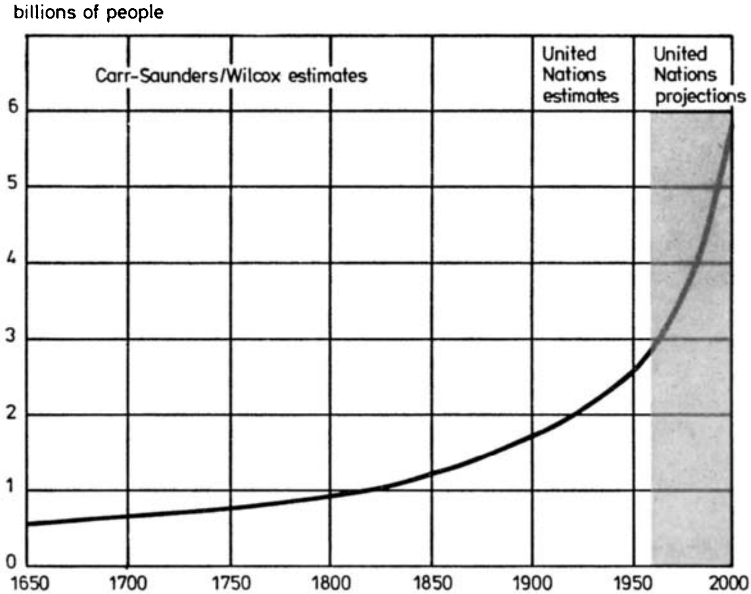

Figure 1 *World population since* 1650 *has been growing exponentially at an increasing rate. Estimated population in* 1970 *was slightly higher than the projection illustrated, which was made in* 1958
(Reproduced by permission from 'Limits to Growth', Pan Books Ltd., London and Sydney, 1972)

technologists, and engineers who gave the most serious attention to the consequences of our rapidly diminishing reserves of fossil fuels. This is because they are probably far more conscious than are politicians, economists, or the public of the difficulty and expense of innovation and the time that is likely to be required to replace fossil fuels by other forms of energy and make all the adjustments consequent upon such a change.

I have given this address the title 'The New Industrial Revolution' because I believe that nothing short of another industrial revolution will enable this highly urbanized, industrialized society of ours to earn a living in the future, and not necessarily a good living at that. Before the discovery of North Sea oil, it was assumed that the U.K. would always be able to import crude oil from overseas. Oil was cheaper than coal, it was cleaner to burn and easier to store and transport, so most of our electricity generating stations were converted to oil-burning or else designed to burn either oil or coal at will – a wise precaution when the price of oil was suddenly increased in 1973 from \$11 to \$50 per tonne.

3 North Sea Oil

With the discovery of North Sea oil, and the steadily mounting estimates of yields, the country became positively euphoric, but by 1974 it was evident that to recover oil from the sea-bed would be a difficult and expensive operation, taking much longer than the original estimates indicated. Now it is recognized that North Sea oil will cost ten to twenty times as much to extract as oil from the Middle East. Even so the reserves are very substantial, being estimated at over 3000m tonnes of oil together with gas equivalent to another 1000m tonnes of oil – of the same order of magnitude as the Alaskan and Siberian oil-fields – and worth together over £100 000m. Figure 2 shows the oil fields in the North Sea and suggests that other fields may be awaiting discovery. However, uncertainties over Government participation, the oil tax, and the future level of oil prices have recently slowed down the exploration in this area, as witness the large number of unfinished platforms around the coast of Scotland. The life of North Sea oil is not easy to estimate with any degree of accuracy, as it will be determined by the size of each field, the technical difficulties of extraction, the rate of new discoveries, and the demand for oil in the future. Certainly if the demand continues at the present rate, the reserves will be exhausted by the year 2000. However, if the demand can be reduced as, for example, by economies or a partial return to coal, North Sea oil will last correspondingly longer. The escalating development costs in the North Sea, and the falling price of oil in the Middle East may help to reduce the rate of exploitation. The estimate made in July 1974 by the Central Policy Review Staff was that 'if no further finds were to be made, production from existing fields would decline by 1990 to a level significantly lower than the demand'. Nothing that has happened since suggests that this cautious statement needs to be revised, and some recent pronouncements support the view that North Sea oil will have passed its peak in about 15 years time unless some restraint is exercised or increased amounts of energy are provided from other sources during that time.

4 Coal

Several other sources are of course available. First, we could buy oil from the Middle East, which will probably be cheaper than British oil for the time being but will require foreign currency and in any event will only last 40 or 50 years; in the meantime it will become progressively more expensive. Secondly, we can use coal, of which Britain has abundant supplies, estimated at 160 000m tonnes, although only 9000m tonnes can be mined by modern machinery. Even so it will be dearer than coal imported from Poland or Canada, and whether further increases can be avoided by closing down uneconomic pits and replacing them by new mines is uncertain. The aspirations of the miners are well known and, if realized, might well make British coal too expensive to use. However, approval has just been given for work to begin on the new Selby coal-field, the costs of which have escalated in the meantime from £80m to £400m, and Sir Derek Ezra has announced a 25-year plan under which £1400m will be spent up to 1985. The National Coal Board is contemplating moving into the chemical industry with coal as feedstock, but no reference has yet been made to the problems of pollution by the large quantities of carbon dioxide and sulphur dioxide that will be emitted.

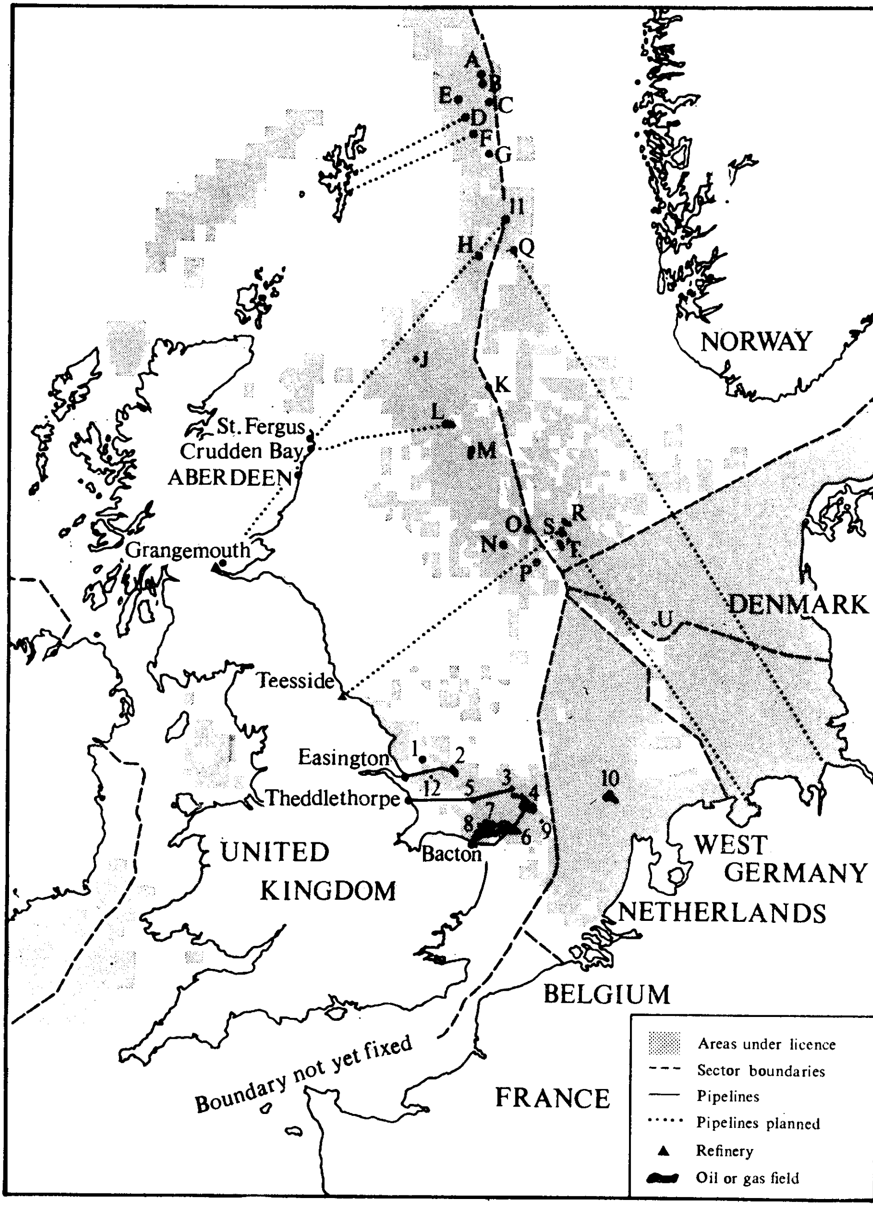

Figure 2 *North Sea oil and gas fields*
(Reproduced by permission from 'UKAEA Annual Report 1974/75', UKAEA, London, 1975)

5 Nuclear Power

The third option for Britain is to increase the number of nuclear power stations, which already supply about 10% of the country's electricity. Delay in expanding nuclear energy has been due to: (1) difficulties in deciding on the best types of reactor to use; (2) escalating development and construction costs; and (3) public apprehension that radiation will escape from the reactors and from the nuclear waste that may be left lying around, possibly for thousands of years.

It has now been decided that the third stage of the building programme will be based on the steam-generating heavy water reactor (SGHWR) at Winfrith and not on either the old Magnox reactor or the advanced gas-cooled reactor (AGR). It is very important that public fears about the alleged hazards of nuclear power stations should be allayed; and anyone who has visited one of these stations is bound to be impressed by the elaborate precautions taken – in shielding the reactor, in removing the spent fuel rods, and in monitoring every operation. The SGHWR is of special interest to members of this Society, since the monitoring is very much the responsibility of chemists. Because all the water used for steam generation passes through the pressure tubes that enclose the fuel elements, any impurities in the water are exposed to neutron bombardment so the amounts present must be kept at very low levels, not exceeding a few parts per billion. Continuous monitoring of critical impurities, including calcium, that might have leaked in from a fractured pipe, is carried out and the results are checked regularly by independent methods. The heavy-water moderator which contains boron is also monitored, and from time to time the lithium-7 into which the boron is converted has to be removed.

The disposal of atomic waste from power stations has received a great deal of attention, and is of course controlled by statute. Some waste is released into the environment at a controlled rate such that the internationally accepted dose limits will not be exceeded. The radioactivity released is monitored by examining, for example, laver bread, oysters, or fish taken from the close vicinity of the stations and is in practice minute compared with the general background radiation (Figure 3). Whereas a change from oil to coal would seriously increase pollution levels, a change from oil to nuclear power would reduce it. Other radioactive waste is concentrated and stored, but the volume of radioactive liquid in store at the present time is only about that of a four-bedroomed house. Most of the activity arises from fission products which will decay within a few hundred years, and the real hazard arises from the formation of small amounts of trans-uranic elements with half lives of tens of thousands of years and it is to ensure that these do not reach the environment that their incorporation into a very durable glass for long-term storage is being investigated.

At some time, possibly during the 1990's, in the operation of the large and increasing numbers of nuclear power stations that are being built both here and in dozens of other countries, supplies of uranium will become inadequate and, long before this stage is reached, fast breeder reactors must be available to replace thermal reactors. The fast breeder uses a mixture of plutonium and uranium and breeds more of this fissile material than it consumes, giving a 50-fold increase in

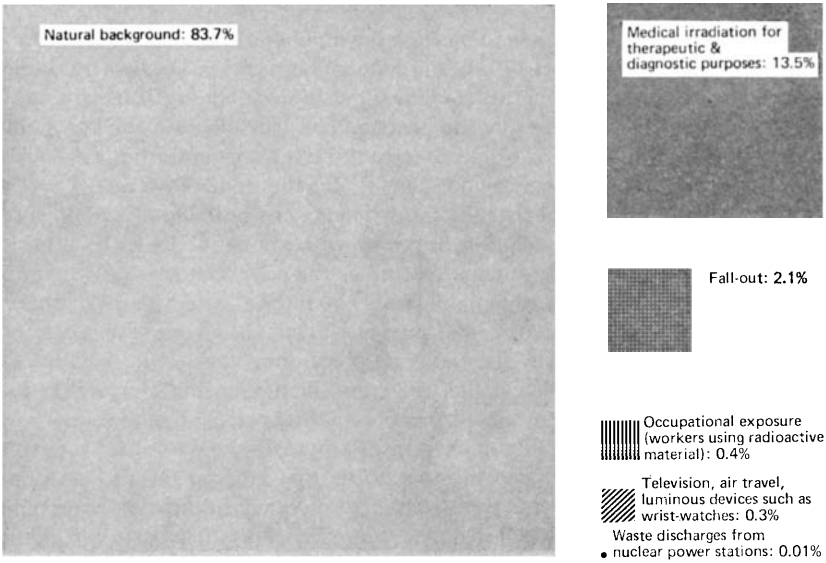

Figure 3 *Sources of radiation exposure of the public*
(Reproduced by permission from 'UKAEA Annual Report 1974/75', UKAEA, London, 1975)

uranium utilization. In this way not only will the reserves of uranium last considerably longer but the stocks of uranium from which the ^{235}U isotope has been depleted by fission or from the enrichment process and now held in drums and tanks in the U.K. would become useful fuel producing as much heat as 50 000m tonnes of coal. One day perhaps (and this is already being investigated in the U.K. and other countries) it may be possible to utilize these very long-lived isotopes by making them into fuel elements and converting them into shorter-lived fission products by irradiation. But this is not yet in sight.

Nor is controlled nuclear fusion yet in sight, a process in which nuclei of light elements are joined together to form heavier ones, thus eliminating the need for radioactive fuel altogether and utilizing cheap and abundant fuel materials instead. The proposed transfer of this work from Culham to Ispra in Italy would in my view be a tragedy for British science, but is obviously a political decision.

6 Other Sources of Energy

There are other options that might provide some of the world's energy requirements as oil becomes less readily available, but few of these could help very much in this country. The possibility of using solar energy is a very attractive idea, for only 0.01% of the solar energy reaching the earth's surface would provide for the needs of the whole world. However, the low sunshine record in this country, especially in the winter months, would only allow solar energy to be used for limited purposes such as domestic water heating and even then the capital cost would be too high for general use at present. In tropical countries sunlight might be concentrated by mirrors on to a boiler to produce steam, as in the solar furnace in the Pyrenees. A novel large-scale use of solar energy comprises the first stage in the production of potash from the Dead Sea by solar evaporation at the southern shallow end, but comparable situations must be very rare. Hydroelectric power is almost fully developed in the U.K. but is capable of expansion in the less developed areas of the world, whilst the conventional type of windmill offers promise for small local purposes only. However, new types of rotor are being developed and, if tests prove to be satisfactory they could make quite a contribution to the electricity supply in Britain.

Tidal energy is also under discussion, and the small but technically successful scheme at La Rance in Brittany is being cited as an example of what should be done in this country. The most attractive site for tidal energy and possibly the only one suitable in Britain is the Severn estuary, but there are many engineering problems to be solved and the environmental costs would be very high, as the estuary is used for the disposal of vast amounts of domestic sewage and industrial effluent. The capital costs have been estimated at between £1000m and £2000m to produce only 1000 MW, perhaps half the output of a large modern power station. Geothermal energy does not appear to show much promise in this country although used for electricity generation in the U.S.A., New Zealand, Italy, and Japan.

7 Wave Power

There is much greater interest in and support for a proposal to generate electricity from wave motion by means of a long rocking boom device suspended somewhere off the coast, probably the Hebrides, to convert wave energy from the Atlantic into electricity or hydrogen. S. H. Salter, of the Department of Mechanical Engineering at Edinburgh University, is working on a grant from the Department of Energy. In his laboratory, a cam-shaped 'nodding duck' facing the waves is coupled to a dynamometer which measures the power absorbed. The full scale equipment will consist of some 40 of these 'ducks' mounted on a cylindrical backbone, each 'duck' with a built in spline-pump feeding a common turbine at the centre of the backbone, generating electricity from which hydrogen will be produced by electrolysis. The machine will be anchored 10—15 metres deep and is estimated to produce 30—50 kW of power per metre. A prototype is expected to be in operation in 5 years time, and would of course be non-polluting.

Summing up the future of energy in this country, therefore, I believe that North Sea oil will meet our requirements for the next 15 years – or longer if we use it prudently – and that during this period we shall be saving considerable amounts of foreign currency that ought to be invested in future energy projects, for by the 1990's we must have available the means of producing energy from other sources. Which of these are likely to be the most practicable? Coal probably, wave energy possibly, but geothermal energy, tidal energy, hydroelectric, solar and wind energy probably not. I believe that nuclear energy is the only source that can solve the problem in the long run, bearing in mind that the population of the world as a whole is still expanding exponentially and that large sections of the population who have always had a low standard of living now have aspirations for a standard of living comparable with that which we enjoyed until a few years ago. This is illustrated by a graph taken from the second of the Club of Rome's publications 'Mankind at the Turning Point' (Figure 4), showing estimates made by the U.S. Atomic Energy Commission of the demands for energy in the U.S.A. from 1975 to 2025. This takes into account the estimated life of oil and gas from various sources, coal, hydroelectric power, and geothermal energy, and leads to the conclusion that only nuclear energy can fill the gap remaining between the energy available from these sources if the increasing

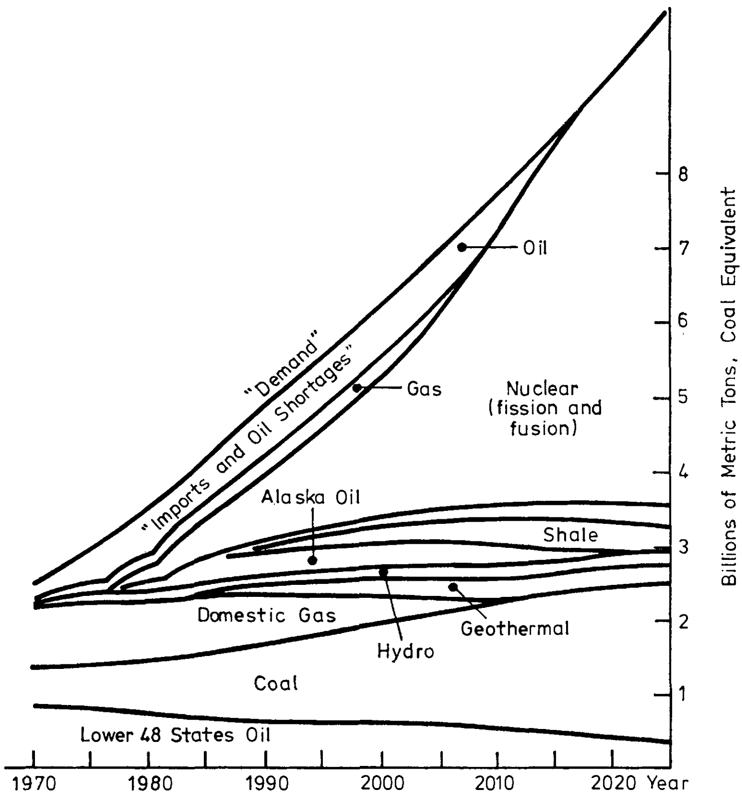

Figure 4 *Projections made by the U.S. Atomic Energy Commission of energy demands in the U.S.A. from* 1975 *to* 2000, *and how this demand could be met if the decision is made in favour of relying on nuclear energy production. The full impact of such a decision can be seen when the projection is extended further. By the year* 2025 *sole reliance on nuclear power would require more than* 50 *major nuclear installations, on the average, in every state of the union*
(Reproduced by permission from 'Mankind at the Turning Point', Hutchinson, London, 1975)

demand is to be satisfied by around the year 2000. Forecasts by the Central Electricity Generating Board (Figure 5) also imply that by that time this country will also be largely dependent on nuclear power.

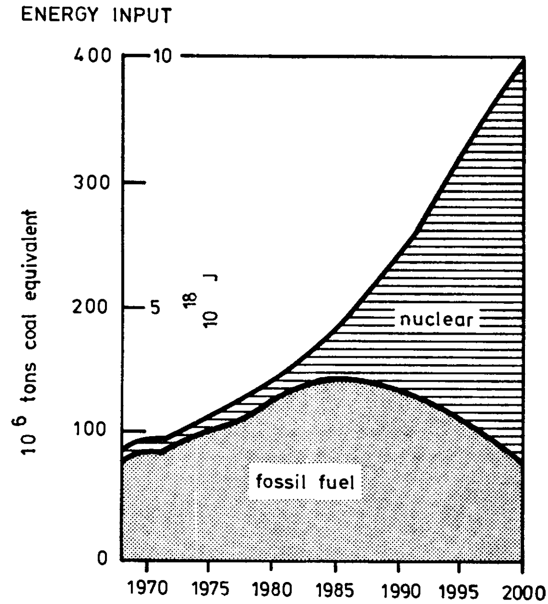

Figure 5 *CEGB energy input forecast*
(Reproduced by permission from *Chem. and Ind.*, 1975, 673)

8 Minerals

Energy, unfortunately, is not the only non-renewable resource which is being used up by an ever-expanding population. Many minerals fall into this category, minerals that yield metals deemed essential for industrial purposes in the West. In the early years of the last century, the U.K. produced 40% of the world's copper and was also a major producer of tin and lead. Now we have to buy from overseas the ores from which these metals are produced, and the countries from which we are now compelled to buy are not always very friendly. But they know that the West will continue to buy in spite of increased prices, and the price of Jamaican bauxite has increased sevenfold, and that of phosphate from the disputed territories of the Sahara fourfold, whilst the Council of Copper Exporting Countries (CIPEC) is working hard to force up the price of copper – so far without much success.

In addition to becoming more expensive, many of these metals are rapidly becoming exhausted (Figure 6) and at the present rate of consumption tin, zinc, lead, mercury, silver, and – I emphasize again – uranium will last between 13 and 26 years only. Copper will last 36, tungsten 40, and molybdenum 80 years.

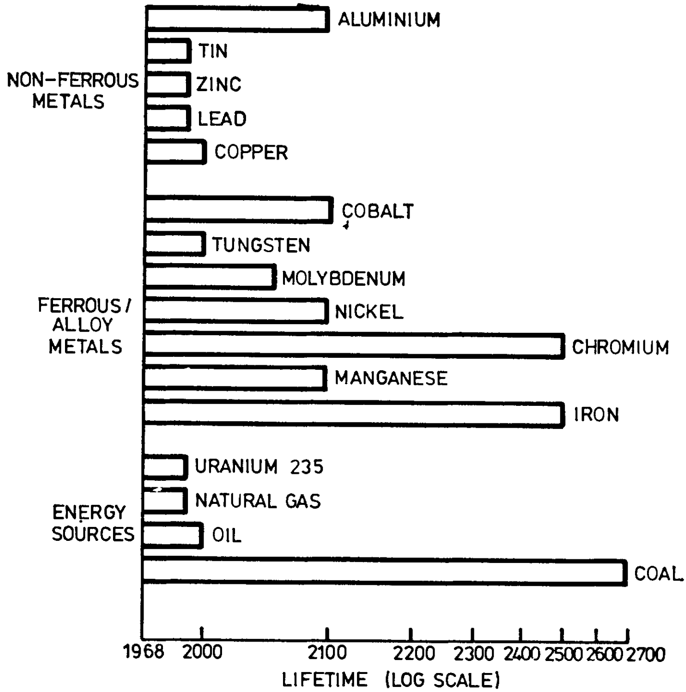

Figure 6 *Mineral reserve lifetimes*
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Aluminium and iron are relatively abundant and will last about 100 and 240 years respectively at the present rate of usage. Metals of course do not disappear in the way that hydrocarbons do when burnt; they become dispersed or diluted in the process of being used. They can in some instances be recycled and this is important in order to reduce contamination of the environment by increasing quantities of metals, many of them toxic. Recovery of metals also helps to prolong their life. Thus supplies of chromium (Figure 7), which would be expected to last 420 years at constant usage will last only 95 years if usage continues to increase exponentially at the present rate of 2.6% per annum. If new reserves of chromium were to be discovered amounting to five times the known reserves, then the life of the metal would only be extended from 95 to 154 years, but if all the chromium were to be perfectly recycled, its life would be extended to 235 years if demand continued to increase exponentially.

As with fuel reserves, so with reserves of metals: it is exponential increase in demand by an increasing world population – a population determined to improve its standards of living – that accounts for the increasing pressure on these non-renewable materials.

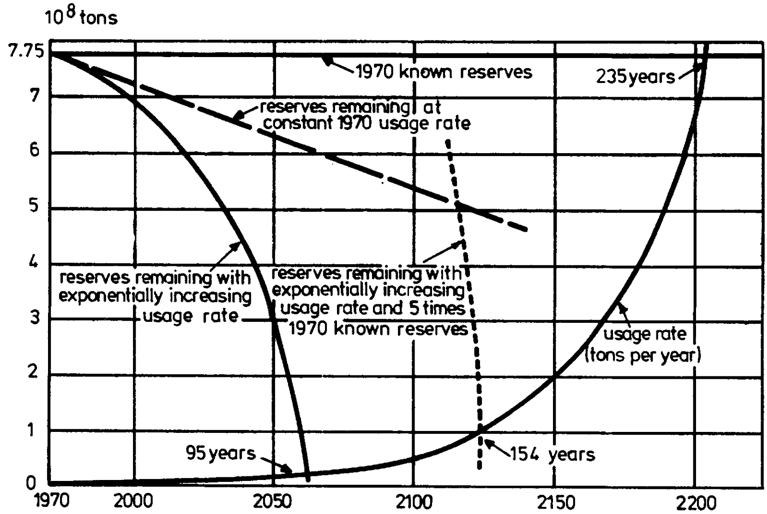

Figure 7 *Chromium reserve lifetimes at various usage rates*
(Reproduced by permission from 'Limits to Growth', Pan Books Ltd., London and Sydney, 1972)

9 Importance of Technology

Technology alone is not the complete answer to the survival of mankind. Technology cannot break down class barriers, it cannot of itself improve standards of living, it cannot resolve the greed of the haves and the envy of the have-nots, it cannot pronounce on the ethics of a situation and it cannot apparently give adequate assurances to those who are afraid of atomic radiation, environmental pollution, and dangerous chemicals. Lord Ashby in his Fawley lecture 'A Second Look at Doom' said:

> 'My own opinion is that we are not just in a crisis: we are approaching a climacteric. Not only up to 1985, or to the year 2000, shall we be anxious about supplies of food and raw materials to sustain consumption, and about the equitable distribution of energy and the disposal of wastes, and about the unbridgeable gap between standards of living in affluent nations and what we now call the Fourth World.' and later:
>
> 'But the conventional economic response to impending shortages is inadequate to deal with the problems of the climacteric, for the impending problems are not technological or economic: they are geopolitical. You only have to glance at the locations where the chief reserves of some minerals essential for western technology are to be found, to see my point.' (Table 1)

I agree about the climacteric, which may I remind you means a change of life, and I agree about the inadequacy of technology and economics to solve the problems of the climacteric, but as members of a scientific Society we have an

Table 1 *Locations of principal mineral resource deposits*

Resource	*Duration** *(years)*	*Sites of reserves*†	*Prime producers*†	*% requirements which U.S.A. imports*
Aluminium	31	Australia (33) Guinea (20) Jamaica (10)	Jamaica (19) Surinan (12)	100
Chromium	95	S. Africa (75)	U.S.S.R. (30) Turkey (10)	100
Cobalt	60	Congo (31) Zambia (16)	Congo (51)	over 90
Manganese	46	S. Africa (38) U.S.S.R. (25)	U.S.S.R. (34) Brazil (13) S. Africa (13)	over 90
Mercury	13	Spain (30) Italy (21)	Spain (22) Italy (21) U.S.S.R. (18)	over 33
Nickel	53	Cuba (25) U.S.S.R. (14) New Cal. (22)	Canada (42) New Cal. (28) U.S.S.R. (16)	over 50
Platinum, *etc.*	47	S. Africa (47) U.S.S.R. (47)	U.S.S.R. (59)	100
Tin	15	Thailand (33) Malaysia (14)	Malaysia (41) Bolivia (16) Thailand (13)	100
Tungsten	28	China (73)	China (25) U.S.S.R. (19) E. Asia	75(?)

*Number of years the known global resources would last at present exponential annual rate of utilization.

†Figures in brackets are percentages of totals.

obligation to examine all possible technological solutions that might help, before we dismiss them and accept the inevitability of a geopolitical solution.

I believe we can give a great deal of help, but without intensive research and development carried out successfully during the next few years the world will become a very unpleasant place to live in and any geopolitical solution will be discovered too late to ensure the survival of mankind. We are very fortunate in this country to be able to buy time with North Sea oil, but the 15 years in which it will be available in quantities sufficient to meet our needs is a very short time indeed in which to carry out all the desirable investigations, such as searching for more oil, probably in deeper waters than the North Sea, processing coal to make it a more suitable and less polluting feedstock for the chemical industry, building new nuclear power stations, and developing the fusion reactor.

10 Finance

The other major problem, and it is a very major problem, is that of financing the projects resulting from successful innovations. It has been estimated that the energy industries of the non-communist world need to invest \$2 000 000m between 1971 and 1985; of this, \$500 000m will be spent in developing new sources of oil, and a further \$75 000m in new oil refineries, many of them in the Middle East, an example of the geopolitical complications of the future. Huge investments are also planned in the production and transportation of liquefied natural gas, in the development of new coal-fields and in the construction (at a cost of $295 000m) of nuclear power plants throughout the world. In addition, the search for new uranium deposits and the mining and milling of the ores when discovered is estimated to cost another $40 000m. Of special interest to chemists are the estimates, published recently by the Chemical Industries Association, of the expenditure by the chemical industry in this country for the next three years. The CIA expects to spend £2800m on plant and will require £2000m of working capital in addition.

11 The Industrial Revolution

The Predicament of Mankind is therefore not simply a problem of how to conserve energy, although conservation will help, or of how to deal with increasing pollution but a problem of finding new sources of energy for an expanding population that will require far greater capital expenditure than anything previously known in the history of mankind. The industrial revolution that started with James Watt's steam engine in 1769 saw a change from the manufacture of goods by hand to the manufacture of goods by machinery. These required capital that was provided by private individuals who often became rich on the proceeds of the enterprises. The new industrial revolution is rather different. The change that is now necessary is from a relatively cheap source of energy, operating fairly sophisticated machinery and plant paid for to a large extent by large numbers of private individuals who lend their money voluntarily, to sources of energy that will require the investment of vast sums of money, so large in fact that they can only be provided by compulsory taxation of all members of the community. This may well leave the individual with relatively small amounts of money to spend as he wishes. I believe therefore that the standard of living must continue to decline until much of the necessary capital has been provided and new technology has been devised and successfully operated.

The new industrial revolution will probably start with the engineers, just as the old one started with James Watt and his steam engine, Arkwright and his spinning jenny, and Crompton and his mule. Already the professional engineers are giving a good deal of thought to improving the machines at present in use, particularly how to increase the efficiency with which steam is converted into electricity, at present around 30%, or utilize the large amounts of waste heat discarded from power stations.

The engineering developments of the late eighteenth century soon stimulated developments in the applications of chemistry. The new textile industry required soap, and soap required alkali; it required chlorine for bleaching and this required sulphuric acid. It is appropriate to recall at this Glasgow meeting that it was near here at St. Rollux that Charles Tennant in 1797 established his plant for making both chlorine and sulphuric acid, whilst his partner, Charles Macintosh, invented bleaching powder and a few years later used naphtha produced by the distillation of coal tar at Leith to dissolve rubber and so produce the garment that bears his name.

In the same way I believe that the engineering developments of the next decade will be accompanied by important chemical developments. Initially, chemical industry will expand using oil from the North Sea as feedstock, and the NEDC report on 'U.K. Chemicals 1975—85' called attention to the tremendous opportunities this will provide, for example, the possibility of producing polyisoprene for conversion into synthetic rubber, and there are plans for tripling ethylene production from naphtha at Grangemouth and in N.E. England, and for producing ethylene from ethane provided by the North Sea Brent field. However, in 1972 the British chemical industry already consumed 6m tonnes of oil equivalent as feedstock and 9m as fuel, and if the current growth rate of 8.5% per annum for world petrochemical production were to continue in Britain the industry would be consuming one-quarter of the fossil hydrocarbons from the North Sea by 1990. Clearly, unless larger amounts of oil are reserved for use as chemical feedstock, this rate of growth cannot continue for long, and the production of chemicals from oil must begin to slow down, even before the 1990's. The situation might have been much better had the delay in expanding nuclear energy not been so prolonged.

The industry is already examining the possibility of using smaller amounts of energy in the production of chemicals. For example, the Agriculture Division of ICI has developed a low-temperature, low-pressure process for the synthesis of methanol using a copper–zinc–aluminium catalyst. By continuous and simultaneous precipitation of the catalyst under precisely controlled conditions the process has been greatly improved, and still further improved by combining the zinc and aluminium chemically to form a spinel. In the Petrochemicals Division of ICI work is progressing on an improved catalyst for the isomerization of mixed xylenes to *p*-xylene used in the production of Terylene. Indeed, research into catalysis could be one of the most fruitful and important fields of chemical research at this present time, and without question the papers to be presented at the forthcoming International Congress on Catalysis will be carefully studied by the industry.

Another example of a different way of saving energy in a catalytic reaction is provided by the work of J. A. Barlow of B.P. Chemicals. The oxidation of a light hydrocarbon feedstock to mixed acids is an exothermic reaction and the heat of reaction is, in the new process, removed by heat exchangers and, together with the heat in the hot gases that are discarded, used to generate steam to operate the compressors. The process is not only self-supporting, but yields an excess of energy for use in other parts of the plant.

In other sectors, unwanted by-products are being converted into useful materials instead of being burnt, and ICI for example converts C_5 olefinic by-products from the naphtha cracker units into petroleum resins, and the dibasic acid by-products from adipic acid manufacture into esters for plasticizers and lubricants.

Finally, attention is already being given to the energy required to produce industrial chemicals and there are some astonishing differences (Table 2). For example, acrylic fibre and nylon 6 fibre require respectively 6.9 and 5.2 tonnes of

Table 2 *Energy required in the production of various chemicals, expressed in tonnes of oil equivalent per tonne*

Acrylic fibre	6.9	Poly(vinylchloride)	1.9
Nylon 6 fibre	5.2	Ethylene/propylene/butenes	1.8
Acetylene	4.3	Benzene/toluene/xylenes	1.7
Nylon salt	4.0	Vinyl chloride	1.6
Polyester fibre	3.9	Ammonia	1.1
Polyethylene	2.2	Methanol	1.0
Terephthalic acid	2.1		

oil equivalent per tonne compared with polyethylene and poly(vinylchloride) which require respectively only 2.2 and 1.9 tonnes of oil equivalent per tonne. Clearly where a choice of materials is possible preference should be given in future to those that require the smaller input of energy.

12 The Decline of Oil

But suppose that a decision is taken to use North Sea oil as a fuel because this gives the most rapid return on the investment by Government and the oil industry, ignoring the fact that conversion into chemicals gives a high 'value added' element, what type of feedstock can the chemical industry use?

The obvious one is coal, and ICI in its international operations already uses a great deal of coal in countries where it is cheap, so the know-how is already available. In the past, coal has yielded aromatic chemicals, and the problem in this country will be to develop new methods of producing aliphatic chemicals from expensive British coal that will be competitive in world markets. Coal has disadvantages compared with oil. For example, whereas natural gas and light fuel oil contain 25 and 15% of hydrogen, bituminous coals contain only 7 or 8% and anthracite only about 3% of hydrogen, so that large amounts of hydrogen must be available for the production of aliphatic chemicals. Coal also contains sulphur, often much more than oil and this will have to be removed to avoid unacceptable levels of pollution. Several methods already exist and are in use in various parts of the world for converting coal into chemical feedstocks, for example, total gasification to produce synthesis gas for conversion into methanol and ammonia; pyrolysis or a combination of pyrolysis and gasification; and liquefication with liquid or gaseous solvents, followed by hydrogenation to produce lighter hydrocarbons. The capital cost of developing such processes in the U.K. will be about £1400m – much lower per kW of energy than the cost of nuclear energy or energy from the Severn barrage (Figure 8), but some 15 years will be required to reach full-scale production – just in time perhaps for the fateful 1990's.

For some purposes organic materials may be replaced by inorganic materials, and the possibility of using inorganic polymers is being explored not only as an insurance against the impending shortage of hydrocarbons but also because they would offer superior thermal stability and better resistance to oxidation; the use of inorganic polymers in buildings, furniture, and vehicles in place of organic polymers would considerably reduce the fire risk. Such a polymer is not yet in sight, but siloxanes, polyorganosiloxanes, aluminium polyphosphates, and boric

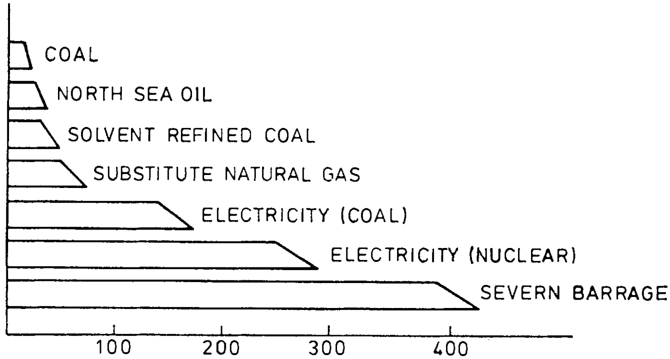

Figure 8 *Investment requirements for energy production*
(Reproduced by permission from *Chem. and Ind.*, 1975, 681)

acid–phosphoric oxide polymers are being tested. One of the more promising materials to date is an alkali borophosphate polymer (Figure 9) which is a thermoplastic, transparent, glass-like material as resistant to water as soda-lime silicate glass, but unfortunately just as brittle. The field should be a very attractive one for research by the inorganic chemist.

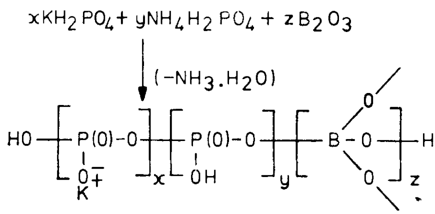

Figure 9

Inorganic chemistry of a different type that may help to solve a rather special energy problem relates to some interesting co-ordination compounds under investigation by Professor Chatt (Table 3). These compounds take up molecular nitrogen and by treatment with acid convert one molecule of nitrogen into two molecules of ammonia. The tungsten complex gives ammonia in 90% yield but the molybdenum compound only in 35% yield. Attempts to develop a low-temperature, low-pressure process for producing ammonia as an alternative to the high-temperature, high-pressure process used at present have not yet met with any success, but success could materially reduce the energy required for food production.

13 Enzymes

Another method of reducing energy demand is the production of useful chemicals by means of enzymes. Enzymic processes operate at normal temperatures and

Table 3 *Yield of ammonia and hydrazine from reaction of* H_2SO_4 *with tungsten and molybdenum complexes*

Complex	*Solvent*	$\%NH_3$	$\%N_2H_4$	$\%N_2$
cis-$[W(N_2)_2(PMe_2Ph)_4]$	MeOH	90	2	94
	MeOH	88	2	92
	MeOH–H_2O	63	3	67
	THF	46	13	59
	THF	42	23	64
trans-$[W(N_2)_2(PMePh_2)_4]$	THF	36	15	54
	THF	36	<1	34
cis-$[Mo(N_2)_2(PMe_2Ph)_4]$	MeOH	36	<1	40
	MeOH	30	<1	32
	THF	20	<1	28
	THF	35	<1	34
trans-$[Mo(N_2)_2(PMePh_2)_4]$	THF	4	<1	*ca.* 5

pressures. Undoubtedly in the first place micro-organisms of various types, would be used, then later natural enzymes isolated from such micro-oganisms, possibly attached to carriers to enable them to be operated continuously, and finally tailor-made enzymes in a cascade system that would enable complicated transformations to be carried out in one continuous process.

The substrates for these fermentation processes would be produced by solar energy – starches, sugars, celluloses, and lignins obtained from waste vegetable matter or from fast-growing plants specially cultivated for the purpose. Some 3×10^{24} J of solar energy reach the earth's surface, about 120 times the total known reserves of coal, gas, and oil, and this goes on in perpetuity without creating any pollution. The efficiency of conversion into fixed carbon compounds in tropical grasses is between 6 and 8%, although less than 1% in the temperate zone. It must not be forgotten that of the 5m tonnes of ethanol produced annually, 3m tonnes are still produced by conventional aerobic fermentation, and only 2m tonnes from ethylene. As the price of hydrocarbon feedstock increases, it would not be surprising if more and more ethanol were to be made by fermentation, probably in the tropics. Ethanol is as easily transported as crude oil and would find a ready market in industrial countries or even provide the basis for a local chemical industry, another example of a geopolitical complication.

Alternatively, anaerobic fermentation could be used giving a gas comprising 65% methane and 35% carbon dioxide. The former would be an excellent source of power and again a basis for industrialization in the tropics and thus a factor of potential geopolitical significance.

All the chemical developments that I have discussed should start now so that they could be fully operational by the 1990's. We need all the techniques we can think of to prolong the life of home-based energy, and coal with all its disadvantages will have to bridge the gap until nuclear energy can take over, and eventually it must become the main source of organic chemicals.

As new nuclear power stations come into operation, more chemists will be employed in monitoring the reactors and in recovering the spent fuel with a view to its ultimate re-use. More will become involved in research and development work on fast breeder reactors and in studying the technical feasibility of fusion reactors and, as increasing supplies of electricity become available, the chemical industry will probably become increasingly interested in electrochemistry, providing more opportunities for chemists. At present it is only used for electrosynthesis on a small scale as the engineering problems are formidable. But the advantages of electrosynthesis are considerable, for energy can be introduced into reactants in a highly selective manner, large amounts of energy can be used to activate relatively unreactive molecules, and electrochemical reactions are a pollution-free method of carrying out a variety of redox reactions. The production of hydrogen by electrolysis will become an economic possibility, and hydrogen could even become a serious competitor to electricity because electrical transmission is the most expensive method and the hydrogen pipeline one of the cheapest methods of transmitting energy (Figure 10). Hydrogen could also replace oil as a fuel for use in motor cars and aeroplanes, and will be essential when coal becomes the basic feedstock for the production of aliphatic chemicals.

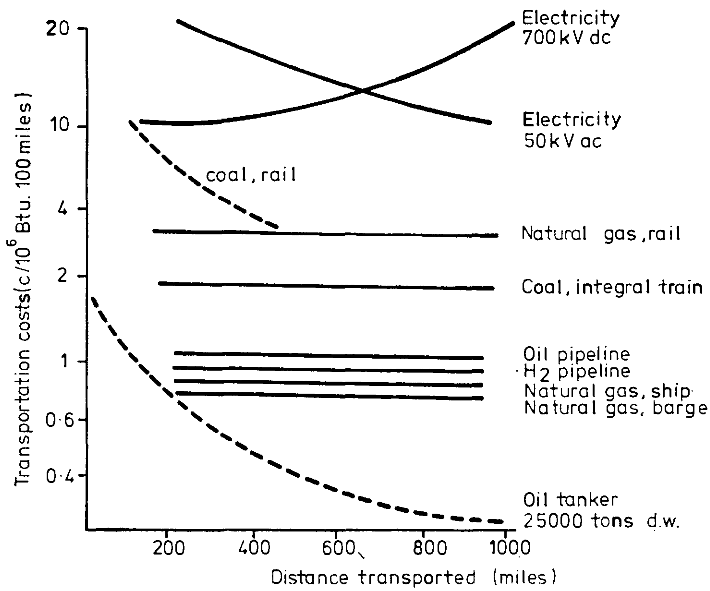

Figure 10 *Transportation costs for fuel*
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14 Demand for Chemists

For a number of years, the Chemical Society and the Royal Institute of Chemistry have been concerned over the declining numbers of students turning to chemistry as a career and many of those who become chemists seem reluctant to enter industry even though the Universities and the Science Research Council are anxious to pursue research activities that are relevant to the economic situation. I believe that we are now justified in pressing students to look at chemistry in a new way, namely, as one of the disciplines essential for the survival of mankind, emphasizing that our problems cannot be solved by the chemist alone but by teams of chemists, biologists and physicists, engineers and economists, working together.

The problems that lie ahead are so vast and complicated and expensive, and time is not on our side, that we must co-operate to the fullest possible extent with our friends and neighbours in Europe and the U.S.A. to avoid unnecessary overlap in our research efforts. Even more difficult to accomplish perhaps is the acceptance of the geopolitical fact that the Third World has control of much of the raw materials on which our own industries and high standard of living have depended, and they are already in process of converting these raw materials into goods previously made in the West. The Fourth World will not be slow to follow once it acquires the necessary expertise. The next generation of chemists may indeed find themselves in great demand in these countries to help in building local industries using indigenous supplies of energy and raw materials, thereby helping in the transfer of industry from the temperate countries to the tropics.

I will end by quoting Lord Ashby again:

> 'The problems posed by the "Second Look at Doom" require not only great expertise but also a consensus among millions. So they need not only multidisciplinary teams of research workers – a sort of geopolitical Los Alamos – they need also a stupendous programme of adult education to awaken people to what may be coming . . .' and finally:
>
> 'The formula for survival is not power: it is symbiosis.'

I wish to express my thanks to many people who have contributed ideas and information to this talk: first, to my colleagues on the Council of Environmental Science and Engineering, especially Sir Kingsley Dunham, who preceded me as chairman; to Dr. J. H. Chesters and Lord Hinton; to several members of the Atomic Energy Authority; and to many chemical colleagues, especially those in ICI.