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ERRATA

Page 53 (line 36)   *for* 15.10^{18} *read* 15.10^{16}

Page 56 (formula)   *for* $2.1\ 10^6 y$ *read* $2 \cdot 1.10^6 y$

                      for 3.210^6 barns   *read* $3 \cdot 2.10^6$ barns

Page 162 (line 32)   *for* U(VI)   *read*   U(IV)

THE ROLE OF THE CHEMIST IN THE ATOMIC ENERGY INDUSTRY

THE GROWTH OF THE INDUSTRY

THE growth of the atomic energy industry has been unique. At no other time in the history of scientific development have a few comparatively simple observations by a handful of scientists provoked such immediate world-wide repercussions. In less than a decade weapons of unparalleled destructive power were developed, and after a further decade the large-scale production of useful power from nuclear fission has become a practical reality. Such an achievement has called for the closest collaboration between men of nearly all the scientific disciplines; at all stages of development the chemist has had a vital contribution to make.

THE BEGINNINGS

No sooner had the process of fission of U^{235} by neutrons been demonstrated early in 1939 than scientists in Britain and the United States appreciated the potentialities of the process as a weapon, and made suitable representations to their Governments. By mid-1941, a small Anglo-French team had established the feasibility of constructing both a controlled chain-reacting pile and a weapon. At that time British Industry was strained to capacity by the war, and it was not possible to set up the necessary organisation for the development and production of a nuclear weapon. The responsibility for the development of a weapon rested therefore with the United States. Two groups of British scientists, working in the United States, contributed to the successful development of the weapon. In 1943 a joint Anglo-Canadian project was also set up to build the heavy-water moderated reactor at Chalk River. This team was later to lay the foundations of the post-war British project.

In the years 1942 to 1945 the American teams made great efforts to obtain the necessary basic information and to build up the complex industrial plant for producing the fissile materials U^{235} and Pu^{239} essential for a nuclear weapon. In August 1945 the

objects of the project were accomplished when nuclear devices were detonated over the cities of Hiroshima and Nagasaki.

At the end of the war the British teams were withdrawn from the United States and plans were drawn up for the British atomic energy programme. It was originally intended that effort should be directed towards the production of the necessary materials for weapons and power reactors, the development of the peaceful uses of atomic energy and the furtherance of fundamental research. In 1946, however, the *MacMahon* Atomic Energy Act was passed by Congress. This Act prevented collaboration with other countries, and it was therefore essential that work on the development of a British nuclear weapon should be initiated without delay. The years 1947–48 therefore saw a repetition of the rapid expansion which had occurred in the United States in the early 1940's. Under the auspices of the Ministry of Supply, two Research Centres were established in Berkshire; one, at Harwell, for fundamental research, and the other, at Aldermaston, for weapon development. The headquarters of the Industrial Group was set up at Risley in Lancashire; this Group was responsible for the rapid construction and operation of three factories for the production of uranium and plutonium. In October 1952 the first all-British nuclear weapon was successfully detonated on the island of Monte Bello, off the coast of Australia.

PEACEFUL USES

During these five years of intensive expansion for weapon development the peaceful applications of atomic energy were not neglected. It was becoming increasingly apparent that the development of some new source of power was vital to Britain's prosperity. Not only could a diminution of reserves of coal be anticipated in the foreseeable future, but the situation was aggravated by the growing demands for power. In an expanding industrial economy, with its increasing mechanisation, Britain's power requirements have been approximately doubling every eleven years for several decades. Other indigenous sources of power, such as oil shale or water power, are of only limited availability, and in recent years it has become increasingly apparent that too great a dependence upon supplies of imported fuel oils is politically undesirable. Nuclear fission offered the very real possibility of meeting the extension of our power requirements for many years. The nuclear fuels—uranium and thorium—are available in considerable quantities in several areas of the world, including parts of the Commonwealth.

So it was that in the late 1940's an extensive programme for the

development of atomic power was initiated, which culminated in the successful commissioning, in October 1956, of the world's first large-scale nuclear power-station at Calder Hall. In a decade the industry had developed into a nation-wide organisation, involving a capital investment of hundreds of millions of pounds, employing some tens of thousands of men and providing, indirectly, employment for many more.

~ The development of such a vast project *ab initio* calls for a massive research effort, but any such effort is completely impotent without the sound backing of several vital industries, mainly heavy, civil and electronic engineering. Extremely high standards are expected of these supporting industries, and extensive development work is often required.

Not only is a highly organised industry necessary for the successful development of nuclear power; a high level of capital investment is also required. These two factors—the cost and the necessary engineering backing—has confined the initial exploitation of nuclear power to the highly industrialised nations, namely Britain, Canada, the United States, the Soviet Union and France. Information on the basic technology is now becoming more generally available, and more countries are entering the field of nuclear development. These include India, Germany, Sweden and several European countries collectively under the Euratom and O.E.E.C. organisations. Some of these countries are, however, finding it necessary to build up the engineering background which is so essential to the successful development of a nuclear power industry.

THE UNITED KINGDOM ATOMIC ENERGY AUTHORITY

~ As the emphasis on the development of nuclear power increased it became apparent that the organisation within the Ministry of Supply was administratively unsuitable. The atomic energy project was becoming one of Britain's major industries, and called for an organisation working on industrial lines. Accordingly, in January 1954 the United Kingdom Atomic Energy Authority was set up by Act of Parliament under the auspices of the Lord President of the Council. The functions of the Authority may be divided into Research and Production.

Research

Fundamental work on the many aspects of nuclear power is primarily carried out at the Research Establishment at Harwell, and work is also undertaken on contract by Universities and

Industrial Research Laboratories. The Industrial Group, with headquarters at Risley, is responsible for the exploitation of any development arising from the work at Harwell, taking charge of the design and carrying out such applied research as may be necessary. The Group has research laboratories at each of the factories; in these the day-to-day problems which arise are met, and work on the development of existing processes is carried out. Problems of a more fundamental nature are referred back to the Research Group at Harwell.
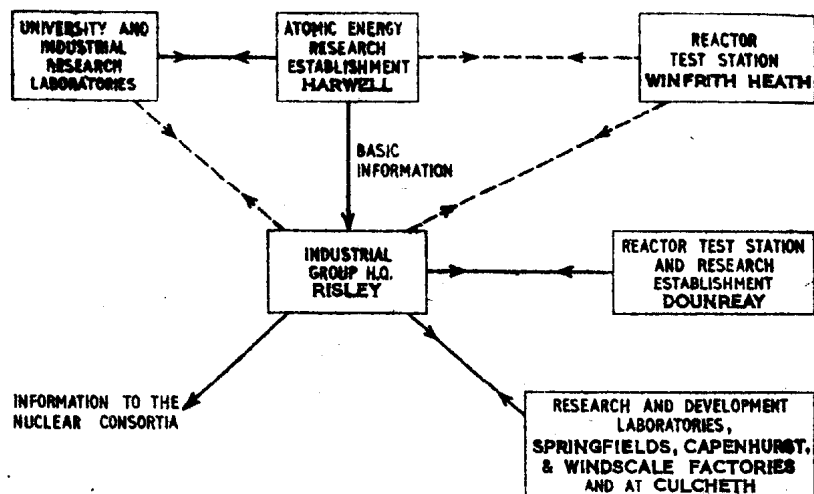

FIG. 1.   RESEARCH IN THE U.K.A.E.A.

Reactor research centres, at which advanced experimental reactors are to be built, have been established, one by the Industrial Group at Dounreay in Caithness and the other by the Research Group at Winfrith Heath in Dorset.

The relationship between the various research organisations is depicted in Fig. 1.

Production

The Industrial Group operates three large factories, located in the North-West of England.

At Springfields, near Preston, uranium ore concentrates are processed and converted to either the metal for reactor fuel elements or the hexafluoride for the factory at Capenhurst, near Chester. Here $U^{235}F_6$ is separated from the hexafluoride of natural uranium by gaseous diffusion. Some of the enriched uranium is returned

to Springfields for the replenishment of the uranium recovered from irradiated fuel elements and some is sent to Dounreay for fabrication into fuel elements for the research reactors, such as DIDO and PLUTO at Harwell and the experimental fast reactor at Dounreay.

At Windscale, natural uranium has been irradiated for plutonium production in the two reactors now shut down as a result of the accident on October 10th, 1957. Further irradiations are being continued in the four reactors at neighbouring Calder Hall, with the simultaneous production of electricity. The plutonium is separated chemically from the parent uranium and the fission products at the adjoining separation plant. The recovered uranium is returned to Springfields for refabrication into fuel elements. The Windscale processing plant, originally built to process the fuel from the two Windscale plutonium production piles, has sufficient additional capacity to carry out the reprocessing of the fuel elements from the U.K.A.E.A. reactors now in operation or under construction; a new plant is to be built to process the fuel elements from the civil reactors which are to be completed in the next few years.

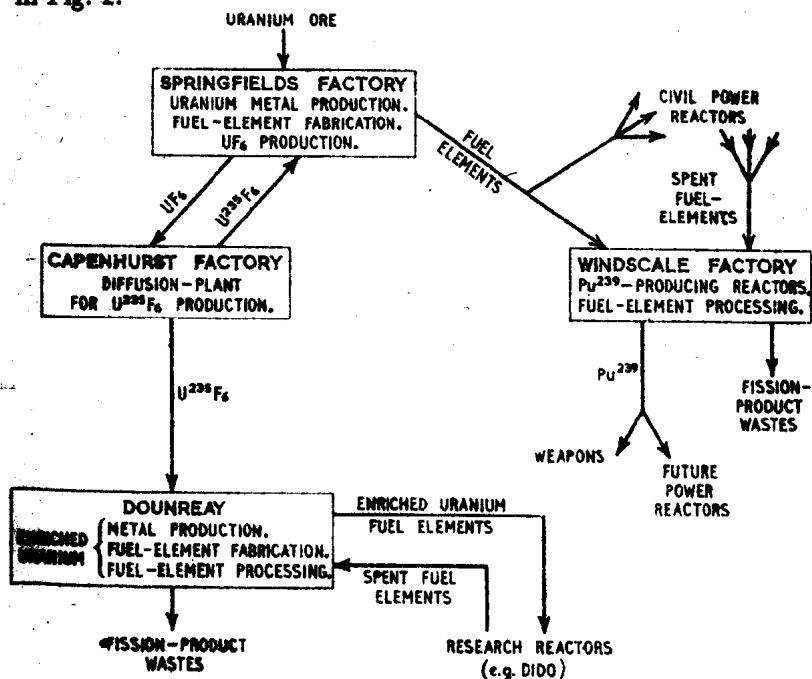The relation between the Industrial Group factories is shown in Fig. 2.

FIG. 2. PRODUCTION IN THE U.K.A.E.A.

THE IMPACT OF NUCLEAR POWER ON CHEMISTRY

STIMULATION OF INORGANIC CHEMISTRY

As a consequence of the exciting developments which took place in physical and organic chemistry in the first part of the twentieth century the study of pure inorganic chemistry fell into decline. In the early 1940's the pressing needs of the atomic energy programme stimulated a vast amount of new research in the inorganic field.

The chemist is called upon to help in the development of the technology of elements which, prior to 1940, were not widely used. These include zirconium and beryllium and even the nuclear raw materials themselves—uranium and thorium. Previously these latter elements were mainly used, as oxides, in the pigmentation of glass and glazes and in the manufacture of Welsbach incandescent gas mantles. The lack of fundamental knowledge of these materials is illustrated by the quoted melting point of uranium metal. As late as 1943 this was given rather vaguely as " less than 1850°C "; it is in fact 1132°C!

In the production of U^{235}, the volatile uranium hexafluoride was required in large quantities for the diffusion plants; this necessitated an extensive development in the chemistry of fluorine and fluorides generally. Interesting by-products of this research are the polyfluorohydrocarbons P.T.F.E. (polytetrafluoroethylene) and *Kel-F* (polychlorotrifluoroethylene). Both of these materials now find a wide application in the chemical industry as corrosion-resistant containers.

In general, there are very few elements which do not hold some interest for the worker in the field of atomic energy. The lighter elements (H, Be, C) are suitable neutron moderators; most of the elements near the centre of the Periodic Table appear as fission products; the heavier elements are either potential nuclear fuels or are produced by neutron capture in the fuel during operation of a reactor. Many of the transition metals make suitable constructional or container materials for nuclear reactors, and many elements, such as fluorine, as UF_6, find a unique application in the industry.

Besides being called upon to develop the chemistry of less known elements, the chemist has been presented with some new elements. Polonium and actinium, which are available naturally in only small quantities, can be produced by neutron capture on the irradiation of bismuth and radium respectively in a nuclear reactor. The transuranium elements—numbering at present ten in all—are

produced either by neutron irradiation or heavy ion bombardment of uranium and other heavy elements. The chemistry of one of the transuranium elements—plutonium—is of vital interest to the atomic energy industry as this element constitutes an important nuclear fuel. Gaps in the Periodic Table have also been filled by the isolation of the elements technetium (43) and promethium (51) from the fission products, and by the production of astatine (85) by the irradiation of Bi^{210} with high-energy alpha particles from an accelerator.

SEPARATION PROCESSES

An interesting chemical aspect arises in the separation of isotopes, such as deuterium from hydrogen, and of closely related materials, such as zirconium and hafnium which occur together in nature. Hafnium, because of its high absorption of neutrons, is an undesirable contaminant of the important reactor constructional material zirconium. The chemical properties of the two elements are so alike that it is not possible to effect an efficient separation by classical chemical methods. Separation is now achieved by processes of either ion exchange or solvent extraction.

The outstanding example of isotope separation is that of separating U^{235} from natural uranium, in which it occurs to an extent of only 0·7 per cent. The separation process relies upon the slight difference in the rate of diffusion through a membrane of the hexafluorides $U^{235}F_6$ and $U^{238}F_6$. Fortunately the situation is not complicated by varying isotopic weights of fluorine, since only one isotope (F^{19}) occurs naturally. Although this separation is a physical process, considerable chemical effort was required before any plant could be operated. An understanding was needed of the various methods of preparing uranium hexafluoride, its physical properties and, of particular importance, its rate of attack on possible plant constructional materials.

SOME NOVEL TECHNIQUES

In building up the atomic energy industry many techniques novel to inorganic chemistry were developed and applied on an industrial scale.

Solvent extraction is a well-established technique of organic chemistry. Applied to inorganic materials it has found an important use in the processing of spent fuel elements. Uranyl and plutonyl nitrates react with certain organic reagents, such as tributyl phosphate, to form complexes of the type

$$UO_2(NO_3)_2[(RO)_3PO_4]_2$$
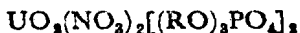
These complexes, presenting an organic structure to a solvent, are more soluble in non-polar solvents than in water, and so are extracted from aqueous solution. Other species, such as fission products and plutonium in the tetravalent state, do not form complexes and are therefore not extracted.

Inorganic ion-exchange materials have been used on an industrial scale for some time for the softening of water. Similar materials, such as certain clays, are at present being investigated as possible media on which to deposit fission-product cations prior to disposal. For more refined purposes, such as laboratory work or the deionisation of the cooling water for a nuclear reactor, synthetic ion-exchange materials can be tailor-made to specification. By incorporating into organic polymers suitable reactive groups, such as $-SO_3H$ or $-NR_2$, resins having cationic or anionic exchange properties can be produced.

A column containing a bed of fine particles of resin can be used to effect the separation of a mixture of ions. This can be achieved by, for example, forming a suitable anionic complex of the cation concerned, and absorbing this on an anionic exchange column. Cations which do not form anionic complexes pass through unabsorbed. Alternatively, a series of closely related elements may be separated by absorption on a cation exchange column followed by elution with a solution of a suitable complexing agent. Because of the slightly differing degrees of absorption on the ion-exchange resin and the varying strengths of complex formation, the different components are eluted successively from the column and may be collected separately. Such a technique is widely used for the rapid separation of mixtures of transuranium elements on a very small scale.

MICRO TECHNIQUES

The development of atomic energy, particularly in the early stages, required accurate measurements to be made on very small amounts of material. For example, at Chalk River the chemistry of plutonium was studied using no more than a few milligrams of the element, and the flow-sheet for the Windscale processing plant was based on these investigations.

To weigh the small quantities of material involved a quartz-fibre micro-balance is employed. The normal knife-edge of a balance is replaced by a fine, taut, horizontal thread of silica, which is firmly affixed to the mid-point of a light-weight beam. The turning moment of the sample on the pan is counteracted by a torque in the silica thread, applied by means of a rotating scale.

The balance point is indicated by an optical lever. Such a balance can be of very high sensitivity—10^{-9}g—but is limited to a maximum loading of a few mg by the strength of torsion thread. In an alternative design, this difficulty is overcome by supporting the beam and sample at the mid-point of the beam by a fine vertical silica thread, the torsion fibre still being retained as a means of balancing the beam. With such a system samples up to 5 g in weight can be accommodated without incurring any loss of sensitivity.

It is often desirable to carry out calorimetric measurements using small samples of material. A microcalorimeter has been developed at Harwell for the rapid estimation of small amounts of polonium. The method is based on a measurement of the heat liberated by the alpha decay of polonium, which amounts to 0·14 W/mg of Po^{210}. The sample, usually mounted on a foil or in an X-ray capillary, is placed in a small block of aluminium, the temperature of which is measured by means of a thermistor. The voltage across the thermistor is applied to a large-capacity condenser and the charging current is measured on a sensitive galvanometer. The observed charging current is proportional to the rate of change of e.m.f. across the thermistor, which, over the small temperature ranges observed, is proportional to the rate of change of the calorimeter temperature. Over the initial stages this is constant, and is directly proportional to the heat output of the sample. Thus, the quantity of polonium can be estimated by the observation of an almost constant galvanometer reading. The time taken for the measurement is about twenty minutes, compared with a matter of hours which is required to carry out microcalorimetric measurements by more conventional methods. By suitable design of the apparatus power inputs as low as 0·01 W can be accurately determined. This corresponds to only 70 μg of polonium.

The technique of polarography is well-established as a means of determining the concentrations of a mixture of cations in dilute aqueous solution, but the method lacks discrimination if two cations being determined have similar reduction potentials or if one is in large excess. A modified apparatus has been developed at Harwell and is now available commercially. In this instrument a small square-wave voltage, of the order of tens of mV, is superimposed upon the normal slowly-changing potential applied to the dropping electrode. The a.c. component of the current flowing is suitably filtered, amplified and displayed on a pen recorder. This technique not only eliminates the undesirable effects of the double-layer capacity current, but also in effect measures the

derivative of the current-voltage curve. The resulting polarogram consists, therefore, of a series of peaks occurring at voltages which are characteristics of each cation present. At concentrations as low as 2.10^{-5} M the peaks corresponding to the reduction of Cu^{++} ($\sim 0.25V$) Pb^{++} ($\sim 0.47V$) Tl^{+} ($\sim 0.52V$), In^{+++} ($\sim 0.64V$) Cd^{++} ($\sim 0.68V$) and Zn^{++} ($\sim 1.08V$) can be resolved, and the resolution is not impaired even in the presence of a hundred-fold excess of cupric ions.

NEW TECHNIQUES MADE AVAILABLE BY THE OPERATION OF NUCLEAR REACTORS

Besides prompting the extensive development of several novel chemical techniques the atomic energy industry has made its own unique contributions to the science of chemistry. These contributions arise largely as a result of the operation of research reactors.

ISOTOPIC TRACERS

The irradiation in a nuclear reactor of many naturally occurring elements results in the production of radioactive isotopes. These find a wide variety of uses in all branches of chemistry. For example, compounds labelled with C^{14} are used in organic chemistry, and particularly biochemistry, in elucidating reaction mechanisms. Flourishing isotope production branches, including the Isotope Division at Harwell and the Radiochemical Centre at Amersham, have grown up. From these centres, radioactive isotopes are shipped in ever increasing amounts to all parts of the world. The catalogues list over 100 radioisotopes which are available, besides some 150 organic compounds labelled with C^{14}. Unfortunately the interesting story of the application of radioisotopes is beyond the scope of this book and will not be discussed further.

ACTIVATION ANALYSIS

The same process of activation of elements in a nuclear reactor forms the basis of an extremely sensitive method of determining a wide range of elements. As an example we may take the method of estimating arsenic, for which this technique has been used to determine trace amounts of the element both in biological systems and in germanium in the development of transistors.

The sample, containing as little as 10^{-10} g of arsenic, is irradiated in a nuclear reactor alongside a standard sample containing a known amount of arsenic. After irradiation both the standard and sample are, if necessary, dissolved and a known large excess of

inactive arsenic added to act as a carrier for the minute amount of radioactive material produced in the reactor irradiation. The solutions are then purified from all other radioactive elements which may be present by suitable chemical techniques such as precipitation, distillation, chromatography and ion-exchange. Finally the sample is mounted on a counting tray and estimated by beta or gamma counting, and the quantity of arsenic in the sample obtained by comparison with the activity of the standard.

The high sensitivity which is obtained in activation analysis arises mainly from the very small activity required for beta counting. With standard equipment 100 disintegrations per minute can be measured with reasonable precision. The sensitivity of the method, however, varies considerably from element to element, since the counting rate obtained for a given weight of sample depends upon the degree of neutron absorption of the element and upon the half-life for the decay of the active product. The weights of various elements which can be estimated with a precision of 10 per cent are shown in Table 1. These apply to activations carried out in the BEPO reactor. In a reactor of higher flux, such as DIDO, greater activities are produced and the sensitivity is increased about fifty-fold.

TABLE 1.—ESTIMATED SENSITIVITY OF ANALYSIS OF SELECTED ELEMENTS BY RADIOACTIVATION METHODS USING THE BEPO REACTOR

Element	Estimated Sensitivity (g)
Arsenic	5.10^{-11}
Copper	1.10^{-10}
Gold	5.10^{-2}
Iron	1.10^{-7}
Lead	5.10^{-6}
Sodium	1.10^{-10}
Sulphur	5.10^{-11}
Uranium	1.10^{-10}

RADIATION CHEMISTRY

Prior to 1940 the only sources of nuclear radiation were X-ray tubes, comparatively weak naturally-occurring radioactive materials (e.g. radium) and particle accelerators (e.g. the Van de Graaff generator). The operation of nuclear reactors enables a wide variety of radiation sources to be prepared by the neutron irradia-

tion of suitable materials. Typical examples are listed in Table 2, in which radium is included for comparison.

It will be seen that some of the artificially-produced radio-isotopes are of much greater activity than the naturally-occurring radium, and furthermore they are available in considerably larger quantities.

TABLE 2.—RADIATION SOURCES PRODUCED BY NEUTRON
IRRADIATON IN A NUCLEAR REACTOR

Material Irradiated	Product	Principal Mode of Decay, and Energy (MeV)	Half-life for Decay	Approximate Strength of Source (curies/g)
Naturally occurring	Radium + daughters	a, 5 γ, 0·2	1 590 y	1·0
Cobalt	Co^{60}	γ, 1·3	5·2 y	up to 10
Uranium 235	Fission products, including:—			
	$\begin{cases} Cs^{137} \\ Ba^{137} \end{cases}$	$\left.\begin{array}{l} \beta, 1·18 \\ \gamma, 0·6 \end{array}\right\}$	30 y	60
	Sr^{90}	β, 0·5	28 y	64
Uranium 238	Pu^{239}	a, 5·1	24 300 y	0·07
	Am^{241}	a, 5·5	470 y	3·8
Bismuth	Po^{210}	a, 5·0	138 d	4700

The nuclear reactor itself is a large, intense source of radiation, consisting primarily of neutron and gamma radiation. The use of a reactor as a radiation source is hindered by the necessary presence of a flux of slow neutrons, which can give rise to intense radioactivity in the irradiated materials by neutron activation. This radioactivity can hamper the subsequent handling operations. However, although high gamma doses can be obtained in, for example, a Co^{60} source, a nuclear reactor is the only source of a high flux of fast neutrons.

By incorporating a quantity of certain materials into the irradiated sample the nature of the irradiation can be completely changed and the amount of energy deposited within the sample increased by as much as several orders of magnitude. With an impregnation of U^{235}, for example, fission occurs in the neutron flux of the reactor and the sample is effectively irradiated by fission fragments. In BEPO the rate of energy deposition in water is increased by a factor of 10^5 when uranyl sulphate is dissolved in the water to give a concentration of 1 g U^{235} per litre. Alternatively,

incorporation of lithium or boron results in irradiation by high-energy alpha particles arising from the reactions

$$B^{10} + n \to Li^7 + \alpha \quad \text{and} \quad Li^6 + n \to H^3 + \alpha$$

THE CHEMIST'S CONTRIBUTION TO THE DEVELOPMENT OF ATOMIC ENERGY

Analytical chemistry is of vital importance at all of the atomic energy factories for the purposes of the control of purity and the prevention of excessive losses of valuable material in the plant effluents. In addition, at Capenhurst and Windscale potentially dangerous fissile materials are processed. Here the plants are in the main constructed in such a way that no combination of circumstances could give rise to an inadvertent nuclear chain reaction, with resulting damage to plant and injury to personnel. A most careful analytical accounting is still necessary, however, to ensure that excessive amounts of fissile material do not accumulate within the plant, for example as sludges.

The chemist has an important contribution to make in the research involved in the development of a reactor project and the associated processes. The fields of research fall broadly into five categories.

(i) Reactor Materials

A power-producing reactor requires between tens and hundreds of tons of highly purified materials, the exact nature of which depends upon the reactor type. For example, the Calder Hall reactors require uranium for the fuel, graphite for the moderator and carbon dioxide for the coolant. In some circumstances considerable quantities are required of materials, such as zirconium or beryllium, which until a few years ago were little known outside the laboratory. This has involved the development of processes for the refining of the ores and the reduction to the metals.

(ii) Reactor Development

The first reactors to be constructed are operated at low temperatures (below 200°C) and present comparatively few chemical problems. The higher temperatures which now occur in power-producing reactors mean that chemical reaction rates are very much increased, and problems of the compatibility of fuel, moderator and coolant arise. These problems are often aggravated by the presence of the intense radiation field within the reactor core. The

development of novel high-temperature reactor systems, involving liquid metals, fused salts or aqueous solutions of uranium also presents formidable chemical problems, mainly of compatibility and radiation decomposition. Furthermore, to be economic a reactor must operate for many years, so that even very slow reactions (for example corrosion reactions) are therefore of importance in the successful running of a reactor.

In contrast to more conventional corrosion studies it is often extremely difficult, and sometimes impossible, to reproduce exactly the conditions which would be met in actual service. For example, the neutron flux in a power reactor might be substantially greater than can be found in even the most powerful research reactors. The chemist must therefore be prepared to carry out experiments of several months' or years' duration, and to devise methods of measuring the small changes which occur during the early stages of the reaction.

(iii) Processing of Spent Fuel Elements

After a certain period of irradiation fuel elements are removed from the reactors and processed in order to remove plutonium and the fission products. Obviously, this aspect of reactor technology lies very much within the domain of the chemist. A solvent extraction process was selected for the Windscale factory, but before the design could be started the chemistry of plutonium—an entirely new element—had to be investigated. Research is now being directed towards improving this process and developing radically different processes which promise to have several advantages over solvent extraction.

(iv) Disposal and Utilisation of Fission-product Wastes

The fission products, which are removed in the processing of spent fuel elements will be produced in increasingly large amounts as time goes by. It is necessary that these be disposed of safely, or, preferably, put to some useful purpose. Several methods of achieving these objects are being actively investigated.

(v) Fundamental Work

The Atomic Energy Authority encourages research work of a fundamental nature, much of which is centred at Harwell. For example, the fundamental chemistry of many of the processes used in the factories, such as solvent extraction, has been investigated to provide adequate information for the satisfactory design and

operation of the plants.   Attention is not only confined to topics closely related to the factory processes.   At Harwell unique facilities are available;   these include such expensive items as nuclear reactors, particle accelerators and buildings designed for the handling of toxic radioactive materials.   Chemists make wide use of many of these facilities in studying the fundamental chemistry of the process of fission and of the transuranic elements, and in studying the chemical effects of high energy radiations.

Developments in each of these fields will be elaborated in later chapters of this book.

THERMONUCLEAR REACTORS

At sufficiently high energies light nuclei, such as H, D or Li, fuse with the release of a large amount of energy.   One means of achieving the necessary particle energies is to heat the light atoms to extremely high temperatures, of the order of millions of degrees. Such a fusion process is achieved in the thermonuclear bomb, where a fission bomb is used to provide the necessary temperature, and it is believed to be the source of energy in the sun and stars. Temperatures of 5 million degrees have been achieved in the experimental thermonuclear apparatus ZETA at Harwell.   Here deuterium gas at a low pressure is heated by passing through it a high electric current.   Although fusion has not been observed at these temperatures, it is anticipated that considerably higher temperatures will be obtained after suitable modifications to the apparatus.   At present the high temperatures can be sustained for only a few milliseconds and the energy released is insignificant compared with the energy input required.

Extensive development, possibly over several decades, will be necessary before a power-producing reactor can be considered. Even in such an event, the economics of the system are at present completely unknown.   Although the fuel, deuterium, is abundant and can be extracted fairly cheaply from water, the capital costs of a thermonuclear reactor are likely to be high.   The time-scale involved in developing an economic system, even if this does become a practical reality, is such that nuclear reactors based on the fission of U^{235} and Pu^{239} will remain an important feature of the industrial scene for many years to come.

It is not possible to define, at such an early stage, the part the chemist will play in the development of a thermonuclear fusion reactor.   Very likely his contribution will be limited to the production of pure fuel materials and possibly the development of suitable

materials resistant to high temperatures, for the walls of the system. In the process of fusion itself chemistry has no meaning, for at the temperatures involved (up to $10^8°C$) molecules do not exist (the product RT is of the order of 2.10^5 kcal, compared with chemical bond-energies of 10 to 100 kcal). Even at the temperatures attained so far ($5.10^6°C$) hydrogen and deuterium are fully ionised, and oxygen and nitrogen are ionised to the $+4$ and $+5$ states respectively. Moreover, unlike the fission products, the products of fusion (e.g. He^4) are not radioactive and therefore will not necessitate elaborate chemical separation and disposal processes.

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