HARWELL

Research Laboratory of the United Kingdom Atomic Energy Authority

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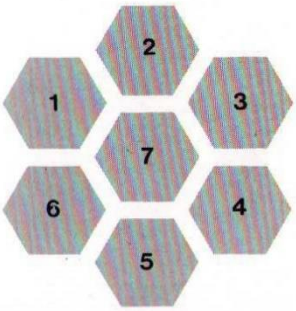

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Introduction

The Atomic Energy Research Establishment was set up by Dr. (later Sir) John Cockcroft on Harwell airfield in January 1946 to undertake research and development on "all aspects of the use of atomic energy" and to organise, with the atomic energy production organisation at Risley, the practical realisation of nuclear power. Today Harwell is a multidisciplinary research laboratory with many broad objectives in applied science, but nuclear power development remains our dominant programme and the reason for our characteristic technical orientation.

Harwell became part of the newly formed UKAEA in 1954; by that time the reputation of the laboratory as an international centre of nuclear research was already established. Much of the UK nuclear development was pioneered at Harwell and many of the leaders of the nuclear industry spent part of their careers here. As the programme expanded, parts of the work were transferred to other sites or organisations. High energy nuclear physics and the necessary accelerator engineering moved to the Rutherford High Energy Laboratory on an adjoining site in 1958; the Reactor Physics Division moved to Winfrith in Dorset in 1958; radioisotope production and sales were transferred to the Radiochemical Centre at Amersham in 1960 (leaving a small unit at Harwell to supervise production in the Harwell reactors) and the physics of nuclear fusion moved to the nearby site at Culham in 1961.

Harwell remained, and is today, a laboratory equipped to carry out research on all the materials needed in reactor development and indeed on every aspect of the nuclear fuel cycle from the separation of isotopes through fuel production and testing to fuel reprocessing and radioactive waste management. The laboratory has two versatile materials testing reactors, DIDO and PLUTO, a variety of accelerators, of which the latest is the 136 MeV linear accelerator completed in 1979, and facilities for experimentation on every grade of radioactive materials.

A great change in Harwell's character was brought about by the Science and Technology Act (1965) which provided the framework for the UKAEA to diversify its research and development into non-nuclear fields, subject to formal "requirements" from the then Minister of Technology. The exacting demands of nuclear technology had led to Harwell's building up a broad competence in the physical and engineering sciences, together with a smaller but important biological programme. These capabilities could now be applied to many other problems for the benefit of British industry and the Government.

The acid test was whether customers wanted Harwell's services enough to be willing to pay for them. Today, Harwell is the largest contract research organisation in Europe earning more than half its total expenditure from nuclear and non-nuclear research and development contracts from industry and from Government Departments; many examples are given in the chapters which follow. The broad aim has been to use the same base of technical skills and facilities for both nuclear and non-nuclear developments. This leads to strong technical capabilities with greater scientific depth and wider experience in chosen fields than would otherwise be achieved, to the benefit of our customers in both the nuclear and non-nuclear industries. The more widely-based technologies which result have often been fed back to solve operational problems in the nuclear power programme from which they originally sprang.

Prediction is always fraught with some uncertainty and what Harwell will be doing in detail in ten years time will depend on the demands made on us. About two-thirds of our efforts are presently devoted to nuclear topics, either on the AEA's own programme or on contracts for the nuclear industry, and this will remain a dominant interest. The provision and use of energy, and safety and environmental protection will remain major non-nuclear interests and we shall seek to develop and consolidate our present role as a multi-disciplinary laboratory with a strong, market-led industrial orientation. We have built up close and good relationships with numbers of firms and groups of firms, which we shall strive to develop further. It is necessary, however, to maintain a careful balance between the short-term commitments which are typical of industrial requirements and the longer-term generic investigations which can provide the seeds of future technology. Harwell will seek to maintain a reputation for first-class research work as well as an emphasis on practical application and an awareness of the many conditions on which the successful industrial exploitation of ideas and results depend.

This booklet has been produced to illustrate the scope and flavour of our work by the inclusion of some up-to-date examples. Very many members of Harwell staff have contributed and I thank them all, but the main credit is due to Dr. John Putman who provided the final text and undertook all the editing.

Lewis Roberts

L. E. J. Roberts, Director.

The Nuclear Power Programme

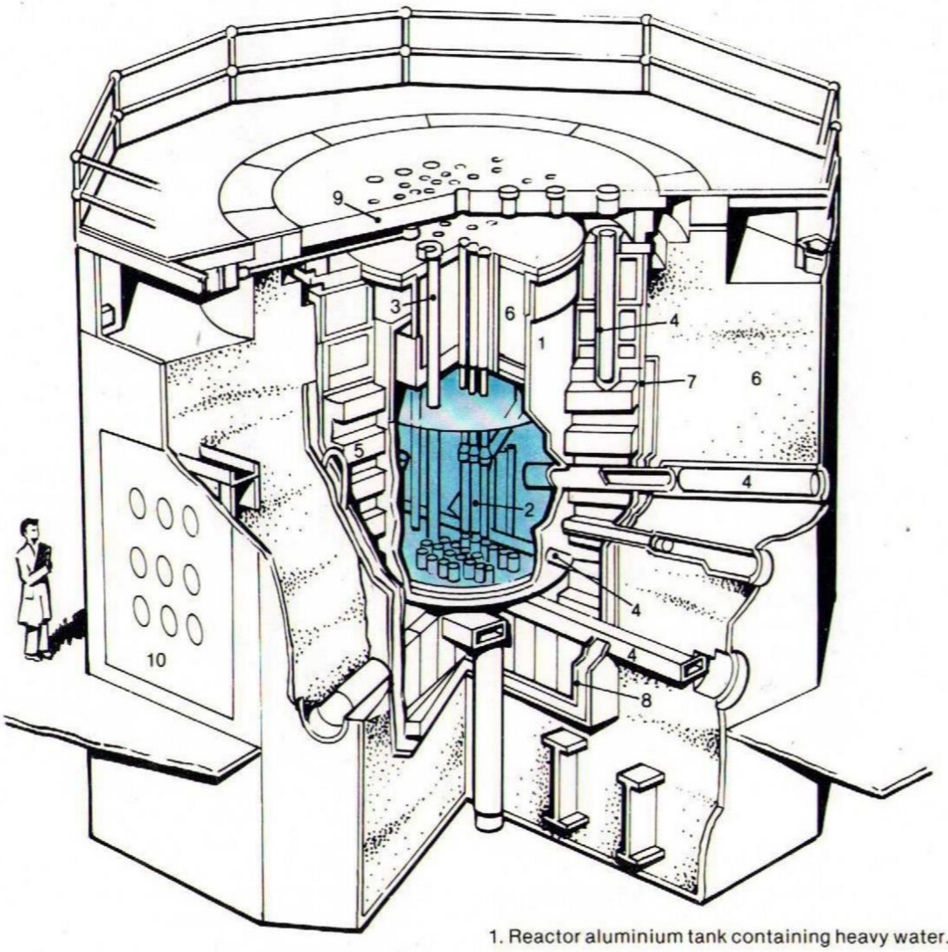


Figure 1
DIDO Reactor

Harwell's largest and most important task is to support the UK nuclear power programme by research undertaken for the UK Atomic Energy Authority and directly for the British nuclear industry. Such research, aimed at continual improvement of the economics and safety of nuclear power, will remain central to its exploitation, just as analogous research is deployed by the coal, gas, oil and electricity industries. Over a period of thirty years, the Laboratory has worked on every reactor system introduced or contemplated in the UK, on almost every aspect of the fuel cycle and on the interaction of nuclear power generation with the environment.

The choice of reactor systems for the UK power programme has been narrowed considerably in recent years and for the foreseeable future we are concerned with only three main types – gas-cooled reactors, pressurised water reactors and fast reactors. The essential features of these are described briefly in Appendix 4, and it is evident that, in the long term, fast reactors will make the best use of available supplies of uranium. This was realised in the early days of nuclear development; 'Zephyr', the first assembly of fuel to test the design of a fast reactor was built here in 1953.

Our nuclear programme followed the UKAEA's requirements during the 1970's by reducing effort on the examination of specific reactor systems to provide resources for new work: on reactor safety and reliability, on the management and disposal of radioactive waste and on fuel handling and reprocessing. A part of the new work concerns aspects of the safety of American-designed pressurised water reactors (PWR) which are being considered as an alternative to advanced gas-cooled reactors (AGR) for UK power stations. This safety appraisal is part of an Authority-wide programme.

In the following account, some contributions to the development of more effective techniques of design, safety assurance, fuel utilisation, reprocessing and waste treatment, based on thorough scientific understanding are outlined. In parallel, research and development is undertaken directly for the UK nuclear industry – particularly for British Nuclear Fuels Limited (BNFL) and for the Central Electricity Generating Board (CEGB). This work is generally shorter-term in nature, arising from operational problems in nuclear power generation and fuel processing. It complements very well the longer-term predictive research for the UKAEA. An appreciable amount of work is also done on repayment for the nuclear power programmes of other countries, notably for organisations in the USA, Canada, Germany, Japan and the EEC.

RESEARCH REACTORS

Since the first experimental piles GLEEP and BEPO were built in the late 1940's, Harwell has always been a reactor site, operating and maintaining its own reactors to test the materials and components of other reactor designs and as a source of high neutron intensities for research.

The original, low-powered GLEEP is still used to check the neutron-absorbing properties of reactor materials, but the main materials testing reactors are DIDO and PLUTO, built in 1956 and 1957. These reactors are of identical basic design and operate in a staggered programme of 24 days on and 4 days off for maintenance, so that one or other is always operating.

Fig. 1 is a cut-away diagram of DIDO showing the reactor core and the arrangement of fuel elements. The reactor uses heavy water both as a moderator and coolant and the fuel is a uranium-aluminium alloy, highly enriched (about 80%) with uranium-235. The core is surrounded with graphite which can accommodate larger specimens for irradiation with thermal neutrons, but the main feature of DIDO as a test reactor is that the 26 fuel elements are hollow, *Fig. 2*, being made up of concentric cylinders between which the cooling water circulates. Within a central thimble of each fuel element are sealed experimental 'rigs' up to 5 cms in diameter exposed to the high neutron and gamma radiations of the fuel element, but otherwise isolated so that their temperature, pressure and contents can be adjusted over a wide range to simulate conditions in other reactors.

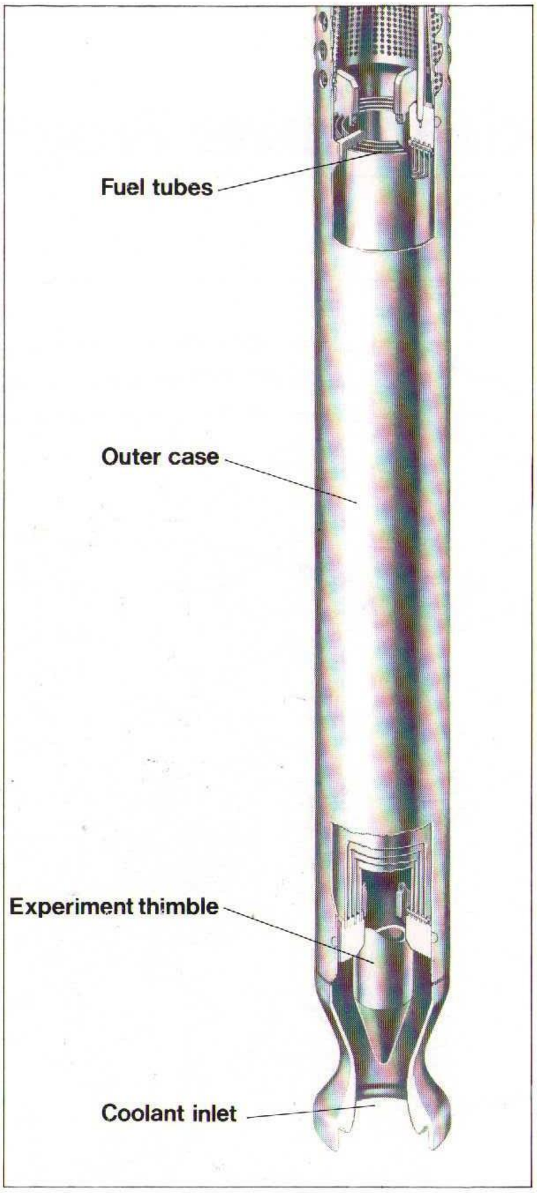


Figure 2

Fuel element for resarch reactor

Although the basic design is now more than twenty years old, the reactors are extremely versatile and can be used for tests of reactor conditions of all kinds. The total power generated – 26 megawatts per reactor – is low compared with a power reactor, but this corresponds to about 1 megawatt per fuel element and inside the fuel elements the radiation intensity is high: at 2×10^{14} neutrons/cm^2/sec, the neutron flux is ten times that normally found in an AGR. Long-term effects of radiation on materials in an AGR can thus be induced in a tenth of the time, providing advance knowledge of what is likely to happen in the power reactor. Moreover, conditions in the experimental reactors are easier to control than in a power reactor and detailed behaviour of the latter can often be inferred by reproducing particular phenomena in the research reactors under controlled conditions.

An average of 35 to 40 experiments are in progress at any one time in each of the reactors and some of the rigs which carry them are very sophisticated. For example the 'creep' of fuel container materials has to be measured to an accuracy of 1/100 micron over three-month periods at temperatures of 700°C and this remotely in a 19 mm diameter tube. The design, building and insertion of a rig into the reactor may take 12 to 18 months and this work is the responsibility of a team of specialist engineers. Over the years that DIDO and PLUTO have been operating, some 1100 different rigs have been designed and some of them used many times.

Loops

Inside the experimental rigs, conditions are generally static, in that the environment is not changed during the period of the experiment. For closer simulation of reactor conditions or for introducing transient changes (e.g. to simulate reactor malfunction), 'loops' are used in which gas or water is circulated through the experimental area and controlled and monitored from the outside. Both DIDO and PLUTO have gas loops which are of particular value in studying the carbon dioxide coolant for AGR's under operating conditions. DIDO also has two high pressure water loops which can reproduce conditions in a PWR. The equipment controlling these loops is large and complex but the vital components in the reactor core are mounted in the 5 cms diameter experimental thimble of which *Fig. 3* shows one example.

Loops like this take years to design and build and the expertise gained is used to satisfy the needs of other customers world-wide. Design and construction of a loop for use in a Euratom reactor started in 1979 under a contract valued at £6 million. Other overseas approaches for commercial design and construction are under consideration, within the limits set by the UKAEA's requirements.

Uses of DIDO and PLUTO

Although a great majority of the effort in operating the research reactors is concentrated on provision of irradiations for the power programme, the reactors are also used as a source of neutrons for basic research on materials, of which we shall say more later, and for commercial irradiations. These three main uses are about equal in their consumption of reactor neutrons.

The commercial irradiations are largely carried out to produce radioactive isotopes for use in medicine and in industrial research and process control, many applications of which Harwell pioneered in its early years. Today the customer is the Radiochemical Centre Ltd (TRCL), who process and market the radioisotopes world-wide. The continuous availability of reactor space afforded by the alternate use of DIDO and PLUTO is essential

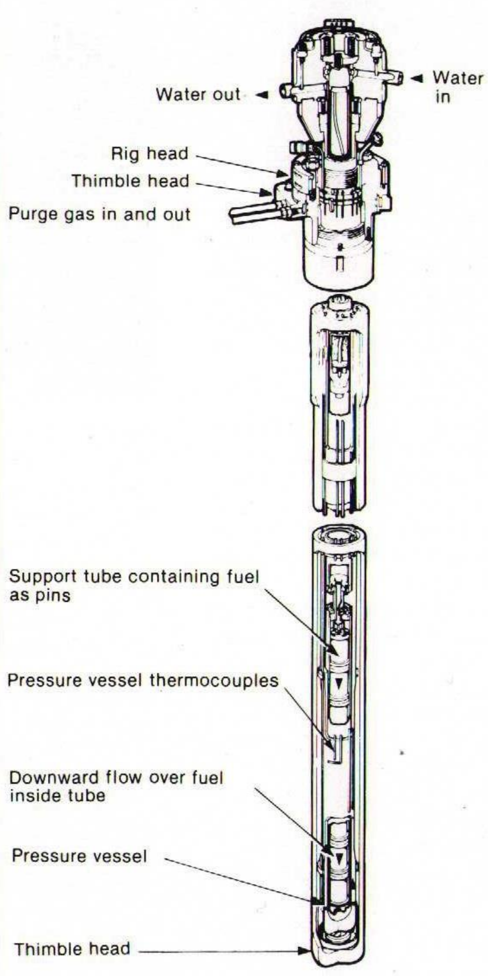


Figure 3

Water loop: test section in reactor

This is an experimental thimble, as indicated in *Figure 2.*

to the reliable supply of short-lived radioisotopes, some of which only last a few days, and three quarters of TRCL's primary production is in these reactors. Cobalt metal, used as a control absorber of neutrons, is converted to cobalt-60, a longlived gamma-ray emitter and this too is sold through the Radiochemical Centre.

In addition, several tonnes of silicon metal are irradiated annually with thermal neutrons for manufacturers of semi-conductor materials in Europe and Asia. By absorbing the neutrons, a small fraction of the silicon is transmuted to phosphorus. This has proved the most uniform and controlled method of 'doping' the metal with phosphorus to induce its semi-conducting properties.

Commercial irradiations do not compete with the power programme for valuable space inside the fuel elements but can be carried out elsewhere in the reactors. They therefore complement the research projects very well in making fuller use of the facility and they earn more than £1 million a year towards the running costs of the reactors.

REACTOR AND GENERATING PLANT MATERIALS

Fuel and fuel elements

Fuel element performance is central to the reliability and economics of a nuclear reactor. Of all the reactor components the fuel is exposed to the most hostile conditions including high temperatures and intense irradiation.

Harwell has studied the preparation, fabrication and in-service performance of most reactor fuels investigated by the UKAEA. The work involves irradiation of fuel samples in the research reactors DIDO and PLUTO followed by metallurgical and chemical examination in radiation-shielded cells *Fig. 4*. Metallic, oxide, coated-particle and carbide fuels have all been investigated, together with a variety of cladding metals used in canning the fuel. The understanding thus gained of fuel swelling and the release of fission product gases was a vital contribution to the design of fuel elements for the Magnox and AGR reactors.

Because the fuel element is designed to be readily replaceable, improvements in the light of experience or of changing demands can continue throughout the life of a reactor type. For example, as nuclear power stations supply an increasing part of the national electricity demand, they can no longer be restricted to base-load operation and must be capable of power adjustment to reflect the varying load on the electricity grid. This so-called 'power cycling' will produce new stresses in the fuel elements of the commercial AGR's.

In a four-year programme completed in 1980 for the UKAEA and the CEGB, the effects of power cycling on fuel cladding were tested in a gas loop of PLUTO. Power cycling was simulated by surrounding specimen fuel pins with a neutron absorbing gas (helium-3) and by varying its pressure, power ratios of about two to one were accomplished without much affecting the power level of the test reactor itself. These experiments confirmed that power cycling did indeed cause earlier failure of the fuel elements and that increasing the thickness of stainless steel cladding did not much improve their lifetime. However, a higher-strength variant of the standard cladding alloy was found to be very effective in increasing endurance under these conditions. Fuel elements clad with this new alloy are now being loaded in the commercial AGR's for more extensive evaluation.

A common aim of these developments in cladding and of others in fuel element fabrication is to increase the useful life of the elements before they have to be removed for expensive reprocessing, because this effectively reduces the cost of nuclear power.

Fast Reactor fuel

A fast reactor fuel pin *Appendix 4* is typically a 5 mm bore stainless steel tube 2½ metres long, containing a central 1 metre length of mixed uranium-plutonium oxide fuel, with 0.4 metre of uranium 'breeder' above and below it. The remaining length provides space to accommodate gases released as fission products

Figure 4

Shielded cells for post-irradiation examination

Research into the effects of radiation on materials is done in high activity handling cells with thick protective walls of lead or concrete. Those shown here have concrete walls 1.67 metres (5ft 6ins) thick and remotely controlled manipulators. Operations are viewed through glass-fronted tanks of the same thickness, filled with zinc bromide solution.

from the fuel. The conventional method of fuel manufacture is to make dry uranium and plutonium oxide powders, mill them together, press them into hollow cylinders and then sinter (i.e. heat) to produce dense, hard pellets about 8 mm long which can be slid into the fuel cladding tubes.

Since the fuel is radioactive and toxic, these processes are carried out in glove boxes with an outer enclosure which is entered only for maintenance. However, dry processing gives rise to a fine dust which settles on the windows of boxes and emits gamma rays, thus increasing the radiation to which operators are exposed.

Harwell chemists have developed a new process, gel precipitation, which eases these problems. The starting material is a solution of uranyl and plutonium nitrates, which is mixed with a gelling agent. This solution is forced through jets rather like the spinnerets of a nylon-producing plant. The jets are vibrated to break the liquid stream into droplets *Fig. 5*, whose very uniform size depends on the frequency of vibration. The droplets fall into an ammonia solution where they gel and after washing, drying and sintering at high temperature, they form hard, dense spheres of intimately mixed uranium-plutonium oxide. The spheres can be poured and flow easily with no dust. A fuel element can be filled rapidly with 0.8 mm followed by 0.08 mm spheres, to a packing density of about 80%.

Unfortunately the gel sphere fuel conducts heat less efficiently than do the solid oxide pellets and this, together with the limiting density of 80%, is a potential disadvantage in advanced fuel designs for high power concentrations. Present work is investigating these limitations and the possibility of pressing gel spheres directly into pellets.

Fuel cladding and radiation damage

Next to the fuel itself, the most intense exposure to radiation and high temperature gradients is borne by the material in which the fuel is enclosed. In the fast reactor this means the fuel pin cladding and the wrappers which contain the fuel clusters in the reactor core *Appendix 4*. Harwell shares in the evaluation and development of steels and nickel-base alloys for these components.

An effect identified some years ago in the experimental fast reactor DFR at Dounreay is the swelling of cladding and wrapper materials under intense irradiation, which leads to distortions in the reactor core assembly. Examination with an electron microscope shows that this neutron-induced swelling arises from the formation of small voids in the cladding material.

It took about 3 years to produce this effect in DFR although it will appear much more quickly in larger fast reactors of higher neutron intensity, like the Prototype Fast Reactor (PFR). The rate of experimental investigation would therefore have been very slow. However, research on radiation damage suggested that the neutron-induced effects could be simulated in thin metal foils bombarded with charged particles from an accelerator or with high energy electrons. The Variable Energy Cyclotron (VEC), using an intense beam of carbon ions, can simulate in a few hours *Fig. 6* the effect of a year's exposure to neutrons in a Fast Reactor, without the disadvantage of making the samples radioactive. Although the damage processes are not identical, the quicker tests allow a wide range of reactor materials to be compared and selected under controlled conditions of temperature and radiation dose. The work is in close collaboration with Dounreay Nuclear Establishment where the most promising materials are subjected to confirmatory tests with fast neutrons in the Fast Reactor.

For example VEC tests showed that the addition of silicon to steels and other alloys can reduce radiation swelling by an order of magnitude. A Nimonic alloy, PE16 (produced by Henry Wiggins & Company Limited) was shown to suffer very little swelling under nickel ion bombardments. Neutron irradiation at Dounreay confirmed this property and was the

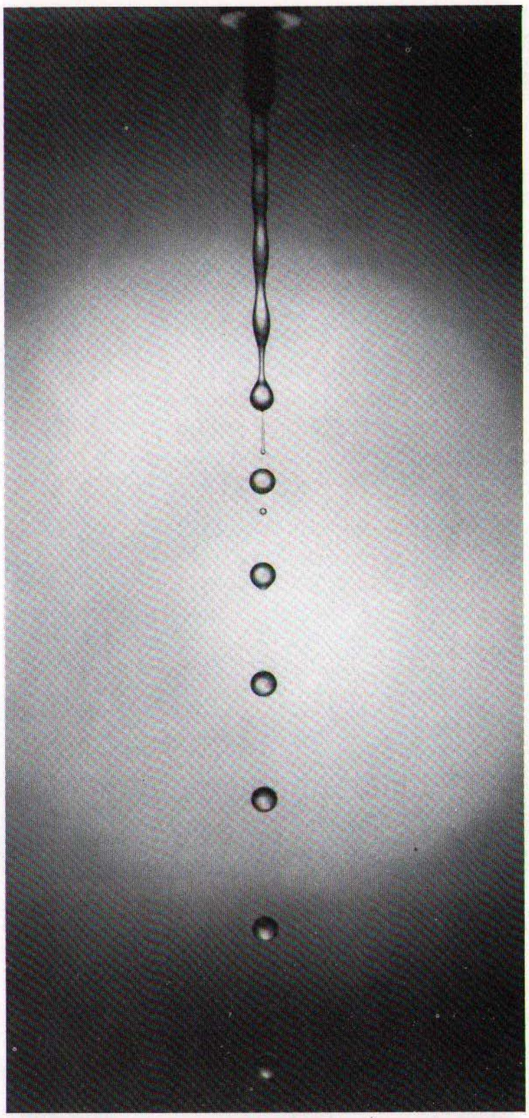


Figure 5

Gel precipitation for fast reactor fuel

The stream of nitrate solution from a vibrating jet is seen breaking into droplets. The tiny, subsidiary droplets are overtaken by the larger ones as they fall through the ammonia solution, to form regular single spheres.

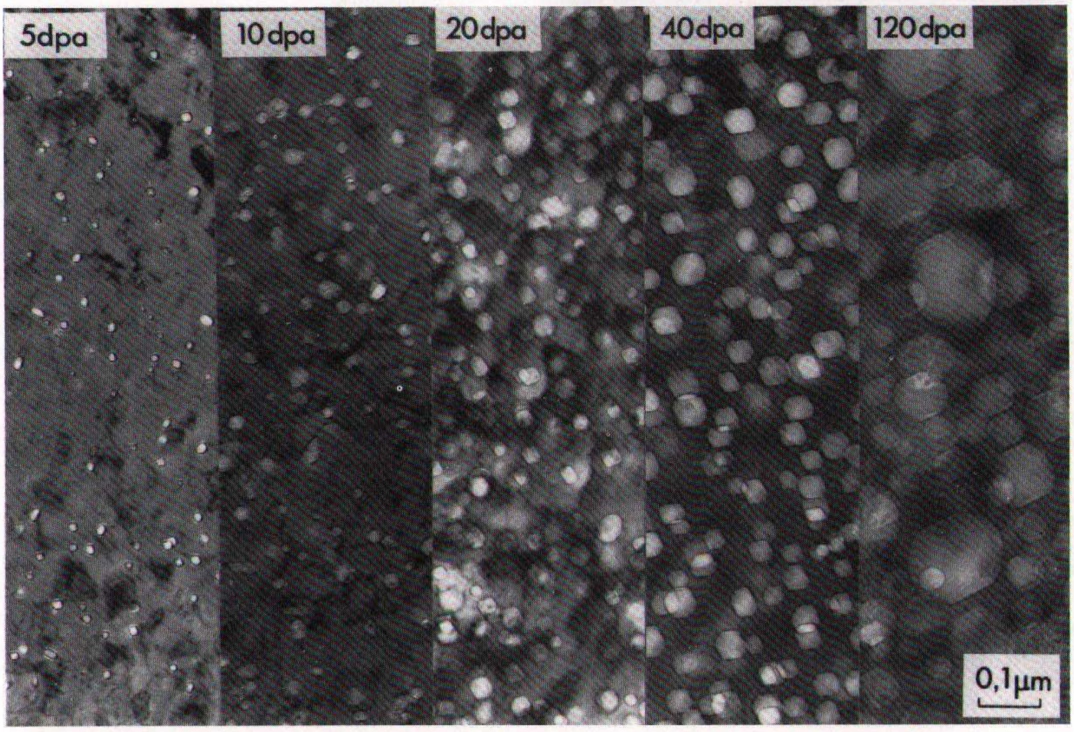


Figure 6

Radiation damage in stainless steel

The electron micrograph shows progressive formation and growth of voids and fine precipitates in a solution-annealed austenitic steel typical of fast reactor fuel cladding. Specimens at 600°C were irradiated in the Variable Energy Cyclotron with 22 MeV carbon ions. Each atom is displaced many times from its position in the metal and the 'dose' of radiation is shown in d.p.a. (displacements per atom of target material). In a fast reactor, neutron doses to the fuel element cladding are typically up to 90 or 100 d.p.a.

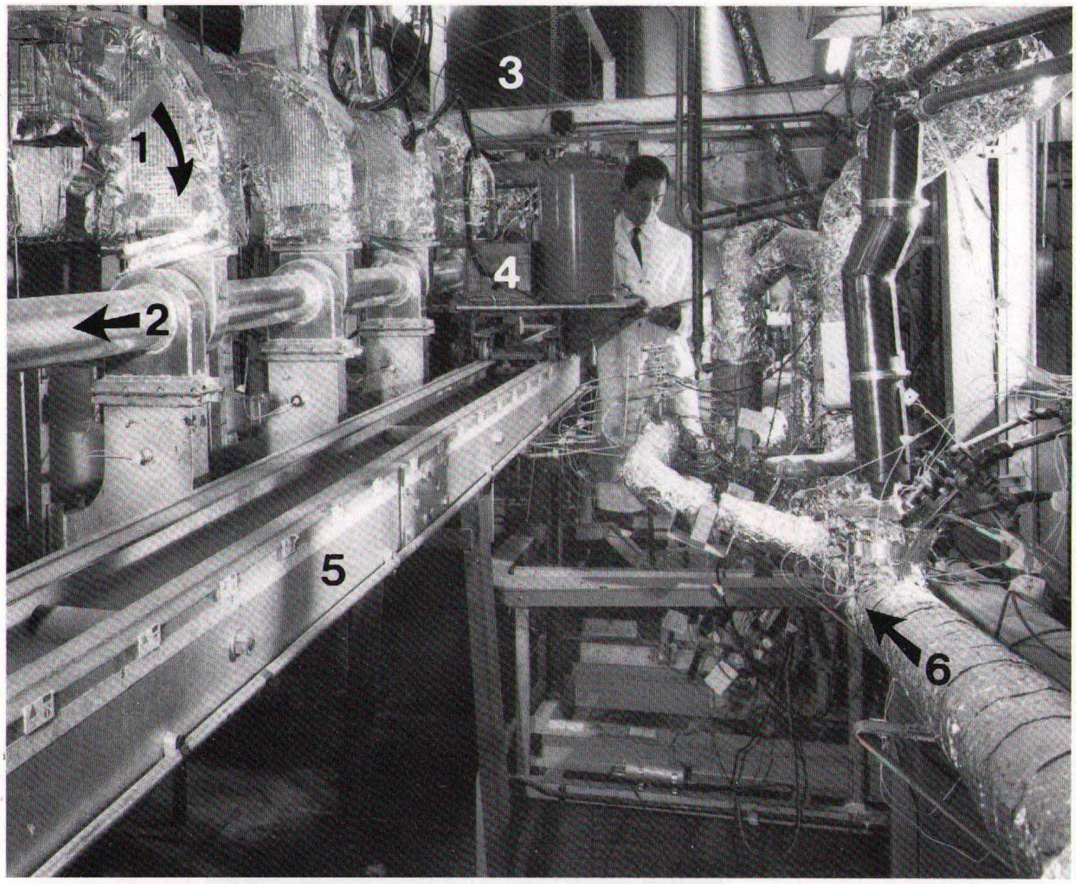


Figure 7

Active mass transfer loop

1 Cooling air to duct surrounding cold leg.
2 Sodium flow in cold leg.
3 Casing for preheater.
4 Mobile detector head.
5 Track for mobile detector head.
6 Sodium return flow to preheater.

basis of a decision to use PE16 instead of stainless steel for wrapper material in the Fast Reactor core.

Although the fast reactor fluxes in DIDO and PLUTO were too low for the voidage investigation, the very high availability of the research reactors compensates for this limitation in experiments designed to remain in a reactor for a long time. An example already quoted is the use of a PLUTO rig for studying irradiation creep under controlled conditions. This form of creep is a slow, continuous extension of material under stress which is induced by irradiation. The work is complementary to studies of specimens irradiated in the much higher neutron flux of PFR, but measured only when the reactor is shut down.

The reactor operator needs to know how the core components will deform and what forces will build up if they are distorted into contact with one another. A theoretical model, CRAMP (Core Restraint Analysis and Modelling Programme) has been developed for this purpose; the reactor temperatures and neutron fluxes are fed into the model, together with swelling and creep data and the operator can then use the system to plan his core loading and unloading schedules. This programme is now being used and further developed in operation of the Prototype Fast Reactor at Dounreay.

Work in this area will continue for some years, concentrating on materials of critical importance to fast reactors. Looking further ahead, development of fusion reactors will call for similar investigations into their components and fast reactor experience will be highly relevant.

Coolant chemistry

The reactor coolant makes contact with a wide variety of materials over a considerable range of temperature and radiation levels. Chemical reactions with the reactor components, stimulated by intense radiation in the core, can result in localised corrosion in one area and deposition elsewhere. Since the coolant is circulating continuously, the effect is cumulative over long periods. Moreover, limited changes can be made in the coolant composition at any time and studies of coolant chemistry are therefore worthwhile right through the operating life of the reactor.

The coolants of greatest concern at present are carbon dioxide (for Magnox reactors and AGR's), water (for PWR's) and liquid sodium (for fast reactors). Special rigs in the research reactors expose these fluids to specific reactor components under controlled temperature and irradiation and their reactions are followed by experts in radiochemical analysis, surface examination, tracer technology etc. Laboratory experiments, with coolant loops outside the reactor, use radioactive tracer techniques to follow corrosion and transfer of specific materials in very small quantities.

The chemistry of carbon dioxide interactions with graphite under irradiation conditions has been a major study over many years. Pure carbon dioxide reacts with the carbon of a graphite moderator to produce carbon monoxide and in time the moderator graphite is corroded. An intensive attack on the problem in the late 1950's revealed that the effect could be inhibited by the addition of methane; the carbon dioxide coolant of an AGR is now typically admixed with carbon monoxide, methane and water vapour.

However, too high a concentration of methane leads to a build-up of carbon deposits on the fuel elements which insulates them from the coolant gas and causes overheating of the fuel. The effect was tracked down to radiation breakdown of the methane in the presence of iron and nickel, both of which are constituents of the cladding material.

In addition at temperatures over 700°C carbon dioxide oxidises the outside of the fuel cladding and the irradiated oxide may break away and circulate with the coolant gas, causing radiation hazards at the heat exchangers (unless trapped, as at present, by an inertial collector).

A potential operational solution to both problems is a barrier coating of ceria and silica on the fuel elements. Such a coating can be deposited by a sol-gel process similar in principle to the gel precipitation method described above for preparing fast reactor fuels. Tests in DIDO for 2 years have confirmed that both oxidation of the cladding and carbon deposition are reduced and coated fuel pins are now undergoing trials in Windscale's experimental AGR.

In a sodium-cooled Fast Reactor hot sodium in the core corrodes the metal components. The radioactive corrosion products are deposited in the cooler parts of the sodium circuit and radioactivity is thus spread throughout the primary circuit. This behaviour is studied in the Active Mass-Transfer Loop shown in *Fig 7*. Previously irradiated metal specimens are corroded in the hot zone and the transport of active corrosion products around the sodium circuit and their ultimate deposition in the cooler parts are measured.

Pressure vessels and boilers

The safe and reliable operation of power reactors depends on the integrity of pressure vessels and particularly on those which enclose the reactor core. The UKAEA's safety development programme on Pressurised Water Reactors (PWR) has renewed interest in the ductility of pressure vessel steels and especially in the embrittling effects of exposure to fast neutrons, a subject which has been pursued here for many years.

Studies of the mechanisms of embrittlement and fracture involve a detailed understanding of the microstructure of the metals and of the effects of radiation damage and high temperature annealing which can take place under operating conditions. There is a strong demand for pressure vessel steels of high fracture toughness and for more information on the way in which the fracture toughness varies as a function of ageing at the operating temperature of the vessel, as well as on the effects of fast and thermal neutron irradiation.

Since temperature and pressure cycling in an operating power station can produce fluctuating stresses in pressure vessels, the combined effects of fatigue and corrosion have to be examined. Tests are being made in DIDO on the corrosion fatigue of pressure tubes from a water-cooled reactor core. Meanwhile fatigue machines in the fracture laboratory are used to study crack growth and the mechanisms of corrosion fatigue for specimens of pressure vessel steel in controlled environments simulating operational conditions.

A model of PFR boiler conditions, including liquid sodium heating, is used to study the behaviour of steam-water mixtures at the heat transfer surfaces and the ways in which boiling processes are influenced by the nature of these surfaces. A separate miniature boiler loop is used with radioactive tracers to study the behaviour of dissolved salt impurities at very low concentrations in the boiler water. A collaborative project with Dounreay examines the mechanisms by which leaks might develop in sodium systems and the techniques by which early warning of such leaks can be given.

Nuclear data

An essential requirement for design and performance calculations on a nuclear reactor is a background of knowledge about the atomic nuclei of its components. Of chief concern is the way in which the fuel and other constituents of the reactor core interact with the neutrons which sustain the reaction – the rate at which neutrons are generated by fission of the fuel nuclei, the rate at which they are lost by unproductive absorption and the rate at which fresh fuel is built up by the production of fissile materials like plutonium 239. To plan the fuel replacement schedule, the build-up of fission products in the fuel elements and their effect on reactivity by neutron absorption must also be predictable.

The cross-section for most nuclear reactions, a measure of the probability of their occurrence, depends very critically on the energy of the particles which cause them – in case the neutrons. *Fig. 8* shows the cross-section of plutonium 239 nuclei for fission produced by neutron collisions and it can be seen to vary with the energy of the colliding neutrons in a very complex way. This sort of information is required for all the fissile nuclides in the fuel, and must be combined with knowledge of the energies of neutrons from the fission process. Absorption cross-sections of similar complexity have to be measured to determine the rates at which neutrons will be lost in the fuel, in the cladding materials and in each of the fission products.

Daunting as the provision of this information may be, the relevant data on cross-sections of the principal nuclides in the core of a thermal reactor have been available for some years with sufficient accuracy (±½%) for operating the reactor – that is for 'thermal' neutron energies up to about 1eV (electronvolt).

For fast reactors, similar data is needed for neutron energies up to 1 MeV (1 million electron-volts) and the problem is further complicated by further fissionable actinide

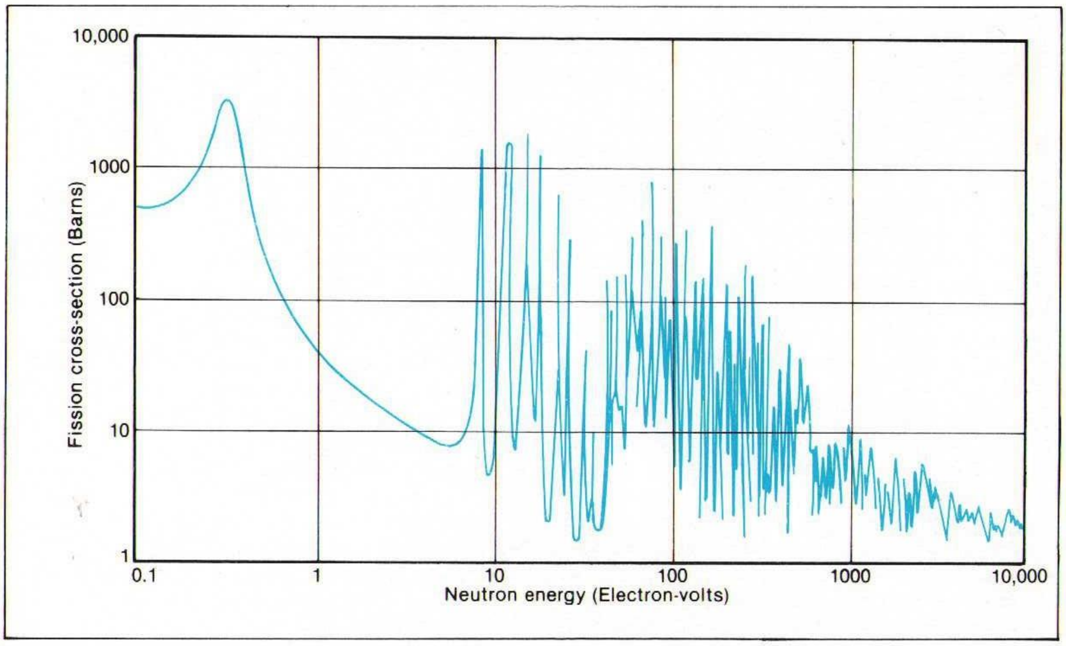


Figure 8

Neutron fission cross-section of plutonium-239

The fine-structure variations between ten and a few hundred electron-volts are progressively smoothed out at higher neutron energies by poorer resolution in the measuring system; in fact this kind of structure is expected to persist well above 1 MeV.

elements which built up in the fuel during high burn-up. Considering the complexity of which *Fig. 8* is an example, the amount of data now required is immense and could not be provided from UK resources alone. The UKAEA depends heavily on international co-operation in this field, principally with the USA and with significant contributions from the USSR and the rest of Europe.

Harwell has always provided the principal UK contribution in nuclear data and has built up an extensive range of charged particle accelerators and other facilities needed to make the measurements. Notable among them are three Van de Graaff generators and the electron linear accelerators, of which the 136 MeV machine completed in 1979 will be described later.

The programme of nuclear data measurement is based on requests by a Working Group representing all of the UK's nuclear power interests and its priorities change to meet the developing needs of the reactor progamme. Emphasis at present is on fast reactor data and on the consequences of higher fuel burn-up for fuel handling and recycling.

SPENT FUEL PROCESSING

The fuel elements in a nuclear reactor have to be processed periodically to remove the fission products and renovate the fuel. At present rates, about 1000 tonnes of fuel from UK power stations is processed each year. The 'spent' fuel is transported in shielded containers to a central plant at Windscale, Cumberland, where British Nuclear Fuels Limited (BNFL) fabricate and reprocess reactor fuels on a commercial basis. At Harwell about 50 scientists and engineers provide support in process development and control instrumentation under contract to BNFL.

A team of similar size is engaged on research in support of the Dounreay Nuclear Establishment, where the reprocessing of fast reactor fuels is under development. The basic processes of fuel treatment are similar in principle to those for thermal reactor fuels; the main differences in fast reactor fuels arise from the much higher plutonium and fission product concentrations and their different physical shape.

Reprocessing

On arrival at the reprocessing plant, the fuel elements are first stored under water in a 'cooling pond' to allow time for the shorter-lived fission products to lose their radioactivity. After some months, the cladding of fuel from Magnox reactors *Appendix 4* is removed by remote-handling equipment. The fuel pins from other reactor types (water reactors, AGR's and the Prototype Fast Reactor) are sheared into short lengths to expose the fuel.

Next the fuel is dissolved in nitric acid. The cladding of the sheared fuel pins, being of zircaloy or stainless steel, is insoluble in the acid and remains behind in the dissolver with certain other insolubles. The solution, containing uranium, plutonium and most of the fission products, passes to the solvent extraction plant. Here the uranium and plutonium are separated from the fission product wastes and from each other and are then purified ready for use in fresh reactor fuel.

Harwell is involved in the development of all aspects of reprocessing. The following recent examples will illustrate the diversity of this work.

Cooling ponds

The 6-metres deep cooling ponds effectively screen operators from the radiations of the fission products; the fuel elements at the bottom are handled with long tongs and viewed through the clear water. However, the cladding is liable to corrode under the intense local irradiation and the water needs to be cleaned or changed periodically. An ion exchange plant has been developed for installation at Windscale, to clarify cooling pond water and remove radioactive contaminants. The work was sponsored by BNFL.

Dissolver development

In the dissolver, the fuel from AGR's or fast reactors, clad in insoluble stainless steel, is only exposed to acid at the ends of the sheared pins. This can severely limit the rate of acid access, which is also hampered by the gas generated in the reaction. Chemists have devised a novel technique to speed up gas removal and acid penetration which greatly increases the rate of dissolution and is being further developed in collaboration with Dounreay.

At present all dissolvers which have to discharge zircaloy or stainless steel cladding hulls are operated on batches of fuel. This could limit the efficiency of a processing plant mainly geared to continuous operation. Methods of continuous operation are therefore being developed, based on special techniques of hydraulic transfer and these have reached an early design stage.

Solvent extraction plant

The basic process for separating uranium and plutonium from the fission products is solvent extraction. Essentially this consists in shaking up the aqueous acid process stream with an immiscible solvent, which extracts the uranium and plutonium, leaving the fission products in the aqueous phase. The solvent generally used is tributyl phosphate (TBP) diluted with odourless kerosene.

In the solvent extraction plant continuous separation is achieved in vertical 'contactor' columns through which the aqueous solution and the solvent pass in opposite directions *Fig. 9*. Each ten-metres long column contains an array of perforated plates through which the liquids are forced up and down by a pulsed air-pressure system, breaking up the aqueous stream into small droplets for intimate contact with the solvent. A single pass through the contactor removes the uranium and plutonium very efficiently, leaving the fission products in the aqueous phase as it emerges from the bottom of the column. The uranium and plutonium are back-extracted separately in a similar column by adjusting the acidity of the aqueous phase. Passage through several successive contactors produces extremely high purity. The TBP solvent from each column is cleaned and re-used in the extraction process.

Solvent extraction research is increasingly orientated towards the processing of fast reactor fuel having a high plutonium content. An instrumented pulsed-plate column rig is being used for chemical engineering studies of the solvent extraction process as applied to fast reactor fuels.

Higher radiation intensities in the processed fuels cause increased chemical degradation in the solvent and methods of cleaning it for re-use are being reviewed. An important aim is to reduce the bulk of contaminated waste for disposal by changing the reagents used. In parallel a detailed study has been made of the radiation degration of the solvent, the behaviour of individual breakdown products and their effects on the solvent extraction process.

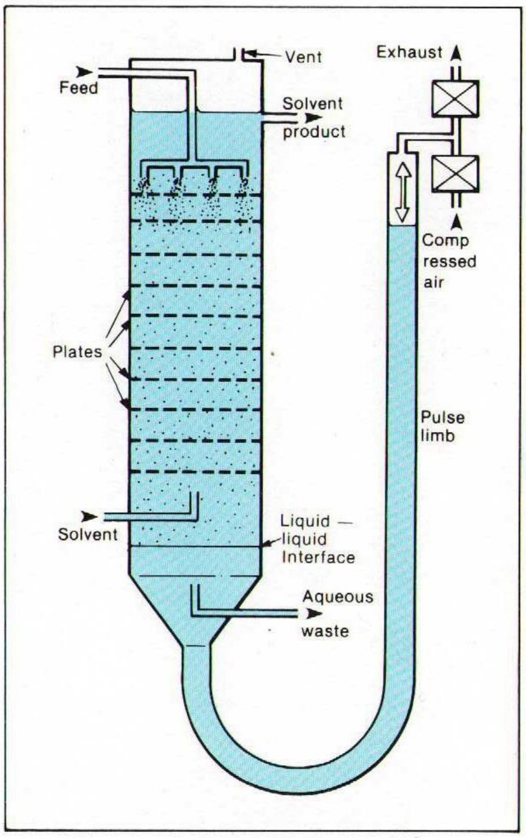


Figure 9
Solvent extraction
Air-pulsed plate column.

Remote control engineering

Because of the high levels of radioactivity in all stages of fuel reprocessing, the operations have to be monitored and controlled remotely. A feature of the engineering work is the planning and development of systems for handling and transporting radioactive materials. Advanced manipulator systems for fuel reprocessing plants are under continual review by an Authority Committee. Remote handling cells and remotely operated manipulators like that shown in *Fig. 10* are designed and developed.

Plant instrumentation

Since its earliest days, Harwell has been involved in the design and development of electronic equipment for radiation monitoring and chemical analysis, both for reactors and processing plant. Although its more widely used designs are manufactured by the electronics industry under licence, the development of special equipment for monitoring and control of liquid levels, flow rates, concentrations and radiations and the presentation of data in a usable form to the operator represents a major commitment.

Ultrasonic techniques have been shown valuable for determining interface levels between liquids in enclosed containers and for measuring heavy metal concentrations in tanks, pipes and settlers. Ultra-sound can readily penetrate stainless steel and is particularly appropriate for use in reprocessing plants,

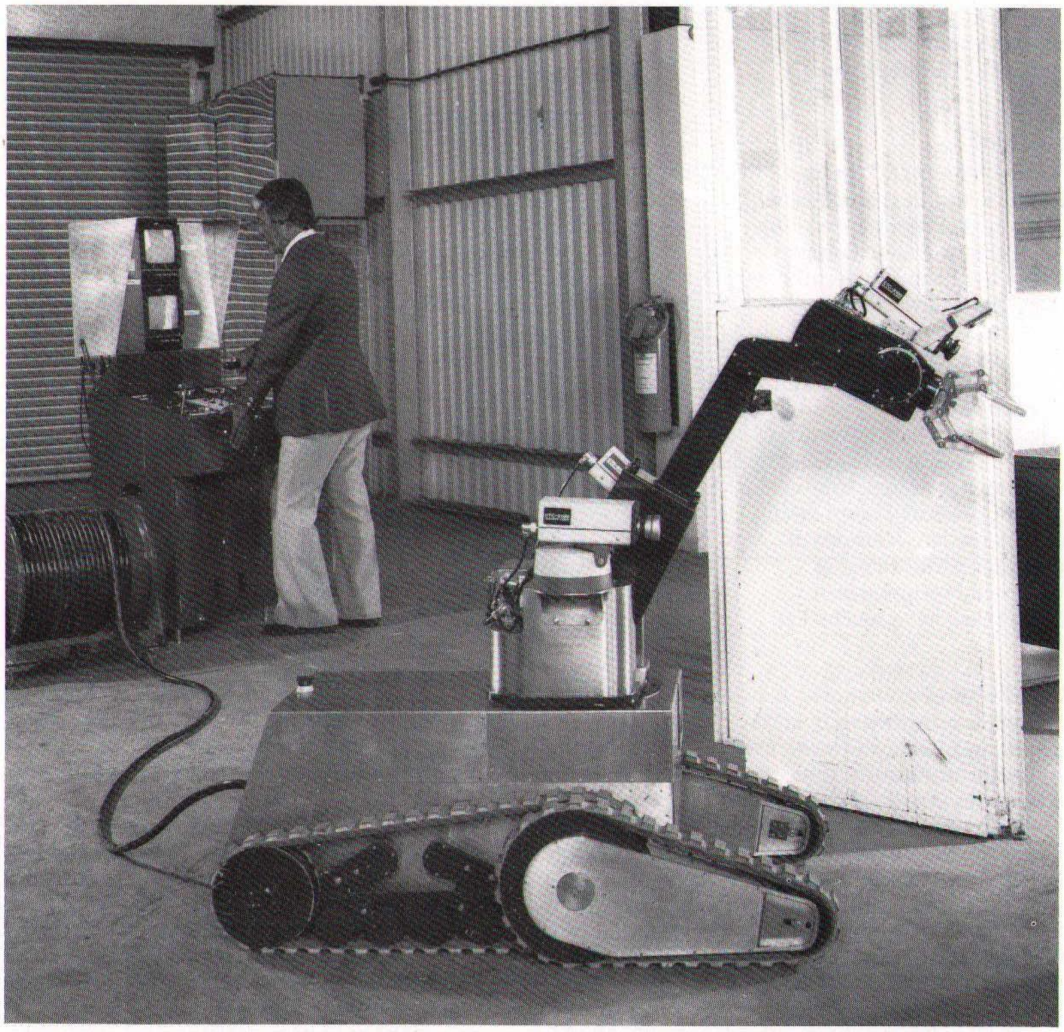


Figure 10

SPIDER: a remotely operated manipulator

Developed for British Nuclear Fuels Limited

where the equipment can be mounted outside the containers, greatly simplifying installation and maintenance. Both the velocity and the attenuation of ultrasonic pulses in passing through liquids are measured and the combination provides much detailed information about conditions in process solutions.

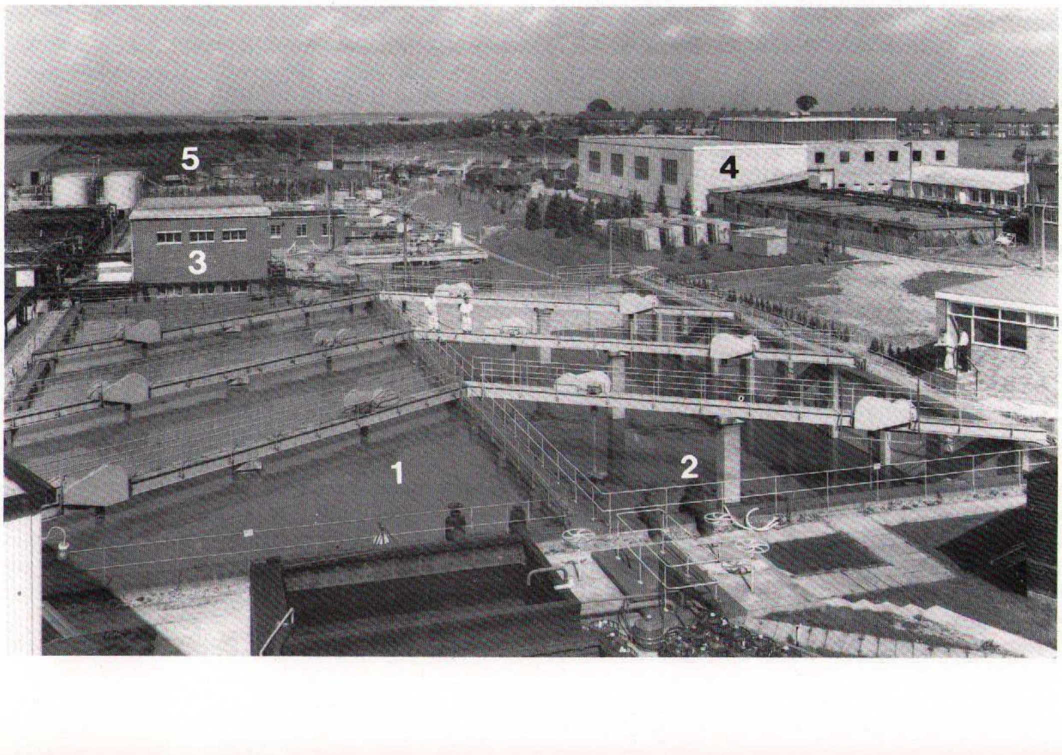


Figure 11

Tank farm for processing Harwell effluent

Low-level radioactive drains discharge alternately into two $1800m^3$ tanks **1**, **2**. The wastes are treated chemically in building **3**. (Building **4** is for higher levels of radioactivity.) Most of the radioactive materials are then extracted as sludges and the clarified water passes to holding tanks for final analysis before discharge. Inactive trade wastes are purified in another part of the tank farm and checked for radioactivity and noxious chemicals before discharge. Sewage is treated separately **5** in the far distance.

Use and re-use of the fuel: enrichment

The reprocessing plant recovers pure uranium and plutonium as uranyl and plutonium nitrates and these are the starting materials for making new fuel elements.

All thermal reactors now being built in Britain use 'enriched' uranium fuel, that is uranium containing more of the U-235 isotope than is found in nature. Most of the world's supplies of enriched uranium are produced by gaseous diffusion but this process of enrichment is expensive in energy consumption. During the last decade, a major programme has been established in isotopic enrichment techniques using gas centrifuges, exploiting carbonfibre and composites technology to develop faster machines of higher efficiency. The programme, which has been supported by CENTEC (a British/German/Dutch consortium) through BNFL is now moving into a commercial phase with BNFL's centrifuge enrichment plant at Capenhurst.

More recently, the underlying research programme has included a study of the possibility of separating isotopes using lasers. The principle is that atomic and molecular energy levels of materials containing the isotope uranium-235 will have slightly different values from those containing the heavier isotope uranium-238 and can thus be excited selectively by a laser beam at the appropriate frequency. The work involves a wide range of disciplines including physics, chemistry, metallurgy and theoretical physics.

RADIOACTIVE WASTE MANAGEMENT

Any power programme based on nuclear fission leads to the production of radioactive waste, from uranium mining, reactor operation and from the reprocessing of nuclear fuel. From the outset of the UK nuclear programme it was realised that the safe handling and disposal of this waste was an essential long-term provision. Most of the necessary research and development was done at Harwell.

Since 1978, responsibility for the policy on radioactive waste management rests with the Department of the Environment (DoE) and with the Secretaries of State for Scotland and Wales. Our involvement in the waste management programme is now largely (83%) funded by the DoE. Other work is supported by contracts to BNFL, CEGB and the Commission of European Communities.

Types of radioactive waste

The radioactive wastes are conveniently categorised according to the level of radioactivity involved. High level waste is a liquid concentrate of the fission products in nitric acid, arising from the solvent extraction plant in fuel processing. It contains about 98% of all the radioactivity produced, concentrated into small volume – currently about 70 cubic metres of liquid per year from the whole nuclear power programme. Management of high level waste is obviously the prime consideration.

Intermediate level waste includes the fuel element cladding, various ion exchange resins and concentrates from cleaning up the process streams and some reactor and laboratory equipment. Although the quantity of radioactivity involved is relatively small, it is still too high to be released to the environment and the bulky contaminated material has to be stored. It is important to reduce such bulk to a minimum.

Finally, low level waste includes laboratory and plant trash and liquids which, after treatment, can be discharged to the environment to limits prescribed by the authorising Departments. This is possible because quite significant levels of radioactivity are found in nature. The 'permitted levels' for the release of radioactivity are such as to increase the natural levels only marginally.

Low level waste

Harwell has a 'tank farm' *Fig. 11* for processing its own effluent before discharge into the river Thames and elaborate precautions ensure that releases are always well below permitted levels.

The natural radioactivity of the oceans is very large (totalling about half a million million curies) and sea disposal of low level radioactive wastes is permitted up to clearly defined limits. The UK is one of the four countries now using this method in the North Atlantic. Harwell prepares wastes from its own sites and BNFL and organises the disposal of these and similar wastes from industry, hospitals and other UK establishments in an annual operation some 500 miles off Lands End. The sea is 2½ miles deep in this area and there are no fishing grounds or submarine cables. The operations are rigorously prescribed by the International Atomic Energy Agency under a treaty known as the London Convention. The wastes are enclosed in concreted steel drums designed to reach the seabed intact. The total activity disposed of last year by the UK was 108,000 curies in 2,700 tons of material.

These methods, relying on dilution and dispersal of radioactivity in the environment are confined to low level wastes for which it can be demonstrated that the return to human populations through reconcentration in food chains is negligible. All other radioactive waste management methods rely on containment until the radioactivity has decayed to a safe level.

High level waste

The high level waste, containing almost all the active materials contained in the spent fuel rods, apart from the plutonium, arises only at Windscale and (in much lower quantity) at Dounreay. All the high level waste resulting from the UK nuclear power programme over the last 25 years is contained in less than 1,000 cubic metres of acid liquor, currently stored in ten stainless steel tanks at Windscale. The heat associated with the radioactivity is such that artificial cooling is required.

Storage in tanks is safe so long as they can be adequately maintained and supervised. However, there is wide international agreement that high level nuclear wastes should be converted in the longer term to a solid form for ease of storage and eventual disposal. Some reduction in volume is also achieved. A great deal of time and effort has therefore been spent in appraising suitable solids, and developing the methods of conversion.

The idea of solidifying high level radioactive waste is not a new one. During the 1950s the Atomic Energy Authority had already selected glass as a suitable host material and by the early 1960s Harwell's 'Fingal Project' had confirmed the feasibility of converting fission product wastes into glass, the final volume being about one-fifth that of the concentrated liquid. Glasses have a number of advantages for the long term storage of radioactive wastes and can incorporate, essentially in one structure, all the different elements in the fission products. The technology of glass-making is well understood, and glasses can be designed to be very resistant to heat and to radiation damage.

A range of borosilicate glass compositions have been developed at Harwell to incorporate the particular chemical compositions of high level waste. A considerable effort has been devoted to measuring those properties of the glasses which will determine their long term stability. Leaching rates have been measured in various natural waters and in salt water, as well as the variation with temperature and acidity/alkalinity. In general, higher melting-point compositions show the lowest leach rates. Some glasses with quite moderate melting points (about 1000°C) have leach rates comparable with those of common rocks such as basalts. These leaching rates are not altered significantly by artificial crystallisation of the glass, induced by annealing at temperatures about 700°C, nor by radiation damage equivalent to that which would be suffered in 100,000 years by glasses incorporating wastes of the compositions stored at Windscale.

British Nuclear Fuels Ltd. plan to install a full-scale vitrification plant to deal with the high level wastes stored at Windscale by 1990. The active glass will be cast into steel cylinders *Fig. 12* and will still require artificial cooling for a further period. Conceptual designs of suitable stores – which may be above or below ground – are being developed currently in work at Harwell and at Risley. In such a store, the blocks of active glass can be monitored and overclad if necessary. So long as the glass remains dry, there is no mechanism by which the activity can get back to man.

Storage of vitrified high level waste will therefore be a safe and comparatively simple procedure. However, research is going on, as described in the White Paper (Cmnd 6820) published in 1977, to determine the feasibility of eventual disposal either in deep underground repositories, or in or underneath the bed of the deep ocean, where no further surveillance will be required. The necessary geological and oceanographic research into these options is being carried out for the Department of the Environment by the Natural Environment Research Council, through the Institute of Geological Sciences and the Institute of Oceanographic Sciences.

Harwell's work for the Department includes studies of materials suitable for canisters in which the active glass would be protected from the environment for long periods, and conceptual studies of repository designs. These materials and the glasses are being tested under conditions which approximate to those in repositories. Theoretical studies are being made of the rate of migration of dissolved species through natural rocks and of the effect of heat evolution from the waste on the patterns of groundwater flow. Field measurements include determination of the conductivity of natural rocks and of liquid migration through them.

Intermediate level wastes

The management and eventual disposal of the intermediate level wastes pose no new problems of principle. The aim is to treat each particular category in order to concentrate the active component into a small volume which can be stored, or disposed of, in the same way as already discussed for high level waste, although the engineering will be simpler because the rate of heat evolution is lower. The rest of the material can then be treated as inactive or low-level waste.

Typical processes under development at Harwell include a chemical dissolution and separation process to deal with Magnox (magnesium alloy) fuel sheaths and scrap, and acid leaching and electrolytic methods of decontaminating stainless steel reactor components. Controlled incineration of combustible waste containing plutonium residues can leave an ash from which the plutonium is readily leached and recovered.

A novel process has been invented at Harwell for the immobilisation of fission product gases, such as Kr^{85}, if their discharge is limited in future. Using the principles of ion implantation *Chapter 3* Krypton ions are imbedded in successive layers of sputtered metal to build up a block which can accommodate 200 times its volume of krypton gas; a half-scale pilot plant has been built for demonstration and trial.

Figure 12

Section of vitrified waste in stainless steel container

In this specimen, the radioactive constituents of high-level nuclear waste are simulated, using inactive materials to form the glass.

UNDERLYING RESEARCH

The Atomic Energy Authority has always maintained a continuing programme of nuclear and allied research in which carefully selected topics, relevant to the longer-term development of nuclear energy, are pursued in greater depth than would be justified by the immediate demands of the power programme and in which innovative ideas, likely to generate future technology can be followed up. This programme has been much reduced in recent years, but still comprises a substantial effort in the nuclear and materials sciences, the physics and chemistry of surfaces, studies of heat transfer and fluid flow, new techniques of instrumentation and control and in those aspects of theoretical science which can coordinate the research and relate it to world-wide scientific progress.

Many of these topics have been illustrated in the preceding paragraphs. We report here some items of exploratory nuclear and materials research which have not been mentioned earlier. They relate to the special facilities for work on neutrons and nuclear physics and to the behaviour of materials under conditions of irradiation and stress typical of the power reactors.

Neutrons and Nuclear Research

Nuclear studies

The scope of the underlying nuclear programme comprises all the reactions of nuclei with charged particles, neutrons and gamma rays and the effects of the reactions on matter in bulk. Within this wide range, the energies and the types of reaction studied are constrained by the likely future requirements of the nuclear power programme.

The general study of nuclear structure using charged particle accelerators is now largely left to the Universities. Harwell's accelerators are applied more and more to studies of nuclear materials, especially to a more quantitative understanding of the interactions of charged particles with matter. These interactions are fundamental both to radiation damage investigations and to the development of charged-particle techniques for thin-layer analysis of fuels and canning materials. Proton scattering is already well established for near-surface analysis and a variety of analytical techniques are being developed, based on selective nuclear reactions of the bombarding particles with the species to be determined.

The area of nuclear physics most relevant to the development of nuclear power is the study of neutron reactions from low to relatively high energies (about 20 MeV), especially those related to the fission process and to the production of actinide elements. The provision of nuclear data for the power programme has already been described and the underlying progamme is largely related to this work.

With its research reactors, DIDO and PLUTO, recently augumented by pulsed-neutron facilities in the 136 MeV electron linear accelerator, Harwell is uniquely equipped with high intensity neutron sources. Not only will the linear accelerator provide the means for the future underlying programme on neutron reactions, but it will also be the basis for establishing the detailed neutron cross-section data needed for the Fast Reactor Programme.

The linear accelerator (LINAC)

The 136 MeV electron linear accelerator, completed in 1979 by Radiation Dynamics Ltd., of Swindon, is the fourth in a series of LINAC's: previous models had energies of 4, 15 and 45 MeV. The main function of the accelerator illustrated in *Fig. 13* is to act as the driver of a pulsed source of neutrons. Pulsed sources are especially useful for the accurate

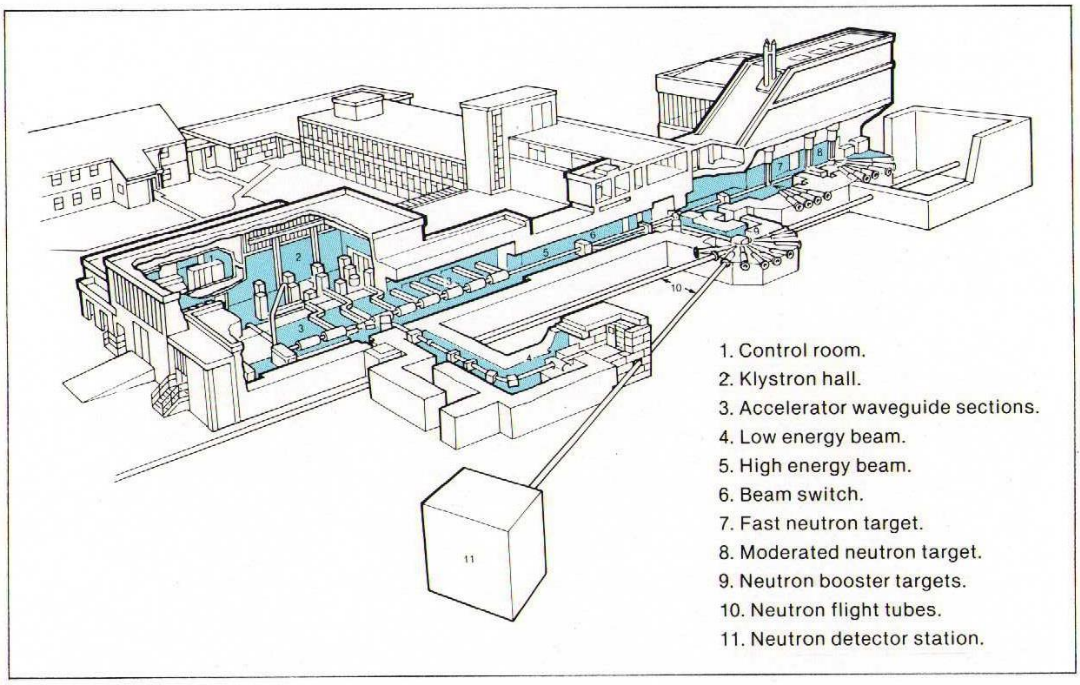


Figure 13

136 MeV Electron Linear Accelerator

Buildings in the background house the earlier 45 MeV LINAC and experimental laboratories.

determination of neutron energies by timing their passage along a flight tube. Long evacuated flight tubes are a feature of all neutron research facilities and are seen radiating from the LINAC target cells in the illustration.

The linear accelerator is of the travelling wave type, in which a pulse of electromagnetic radiation is transmitted down a wave-guide from four powerful klystrons. The wave guide is broken up with irises into sections arranged so that the electromagnetic wave passes through with the correct velocity to accelerate the electrons, which travel at the wave crests like surf riders on a sea wave.

The resulting beam of accelerated electrons is directed to strike one or more of a range of heavy metal targets and here the neutrons are generated. First the stopping of electrons in the target produces secondary gamma rays with energies up to those of the electrons. The gamma rays then interact with nuclei in the target in a photonuclear reaction that produces neutrons.

The 136 MeV LINAC has about 30 times the neutron output of its predecessor, in shorter pulses – a combination which will be valuable in suppressing background when studying neutron reactions on radioactive fuels and actinides. Some typical outputs of the present targets are shown in *Table 1,* indicating that this is the most powerful short pulsed neutron source in Europe and one of the most powerful in the world. Experience in the design of this facility has been useful to the Science Research Council in its plans to construct and utilise the Spallation Neutron Source which will be an even more prolific source of pulsed neutrons.

Neutron beams

The properties of thermal neutrons have special advantages for materials research on atomic and molecular scales:—

- They are scattered in collisions with atomic nuclei and the energy they lose in such collisions is greater for atoms of lower atomic weight, especially hydrogen, whose atom has about the same mass as the neutron. Thus lead is fairly transparent to neutrons and hydrogenous materials quite opaque.
- They are strongly absorbed by some nuclides in a manner which does not depend systematically on atomic weight. A neutron radiograph shows these materials in strong contrast to elements of similar atomic weight.
- There are diffracted from crystals as X-rays are, with characteristic wavelengths from 0.1 to 10 Angströms, depending on the neutron energy.
- They are very penetrating in most structural materials, so can be used to examine large samples in thick containers, permitting work at high temperatures and stresses.
- Their energy is characteristic of thermal vibrations in solids and liquids, so measurements of energy exchange between neutrons and samples give direct information on chemical binding and atomic motions.
- Their magnetic moment can be used in detailed investigations of the structure of magnetic materials.

These features allow neutrons to be used in a wide range of materials investigations for which other methods are unsuitable. In particular neutron techniques supplement those of X-ray crystallography, because neutron beams are less attenuated at the longer wavelengths.

The neutron beam programme is concerned with the study of atomic and molecular structure by various diffraction and scattering techniques. It ranges from a study of inhomogenities on the scale of 10 to 1000 Angströms, through conventional studies of crystal structure and the location of atoms in molecules of amorphous materials to measurements of the diffusion of atoms and molecules in solids and liquids and the vibrational excitation of molecules. The work contributes to most of the materials sciences, particularly to metallurgy and solid state physics, to crystallography and the structure of glasses and to the study of surfaces and the behaviour of catalysts. In this last field, the neutron is proving a unique probe for scanning catalyst materials under operational conditions. For the investigation of reactor materials and radiation damage, for examining the properties of waste-storage glasses and for studying such mechanisms as the sol-gel process and the reactions of catalysts, neutron beam research is an essential background to the nuclear power programme.

The reactors DIDO and PLUTO are the principal sources of neutron beams for probing materials in the UK and the Linear Accelerator provides a powerful new source of neutrons for materials research. There is a strong university interest in using these installations for fundamental research and the neutron beam

Target	Electron Pulse Duration	Mean Electron Energy (MeV)	Pulse Repetition Frequency (pps)	Peak Current (A)	Beam Power (kW)	Neutrons Per Pulse	Peak Neutron Output During Pulse (n/s)	Neutrons Per Second
Fast Neutron	5 ns	94	2000	6	5.6	1.1×10^{10}	2.2×10^{18}	2.2×10^{13}
Booster	100 ns	128	390	1	5	7.6×10^{11}	7.6×10^{18}	3×10^{14}
Condensed Matter	5 μs	60	300	1	90	1.2×10^{12}	2.4×10^{17}	3.6×10^{14}
Low Energy	2 μs	18	500	1	18	—	—	—

Table 1. Typical target outputs of 136 MeV LINAC

facilities are now made available to the Science Research Council who contribute to the running expenses.

Industrial interest is growing too, both in the study of catalysts for chemical reactors and in the development of neutron radiography. *Fig. 14* shows the distribution of lubricating oil in a working helicopter engine. The near-transparency of steel to neutrons and the opacity of hydrogenous materials like oil make radiographs like this possible through up to two inches of steel casing. Changes in oil flow with engine speed can be observed as they occur by displaying the image on a television screen. Rolls-Royce is co-operating in this development.

Materials Sciences

The underlying materials programmes are directed to a better understanding of the materials used in constructing reactors and fuel processing plant – especially of their behaviour under irradiation and their fracture properties in normal and corrosive environments.

Radiation damage

The operational problems caused by swelling and creep of fuels and canning materials have already been described, with an account of the use of charged particle beams for rapidly simulating the effects of exposure to neutrons.

The materials in the core of a nuclear reactor exposed to irradiation by fast and thermal neutrons can suffer three different types of structural change: displacement of atoms by fast neutron collisions, transmutation of elements following neutron capture in the nucleus and electron excitation. The following account deals only with the first of these phenomena, which is the origin of much of the radiation damage in metals.

Collisions of fast neutrons or charged particles with atoms in a solid can knock them out of their normal sites with such energy that the displaced atoms in turn suffer a series of collisions, which displace further atoms, forming a collision cascade. The displaced atoms eventually come to rest in abnormal, interstitial positions. Charged particles and

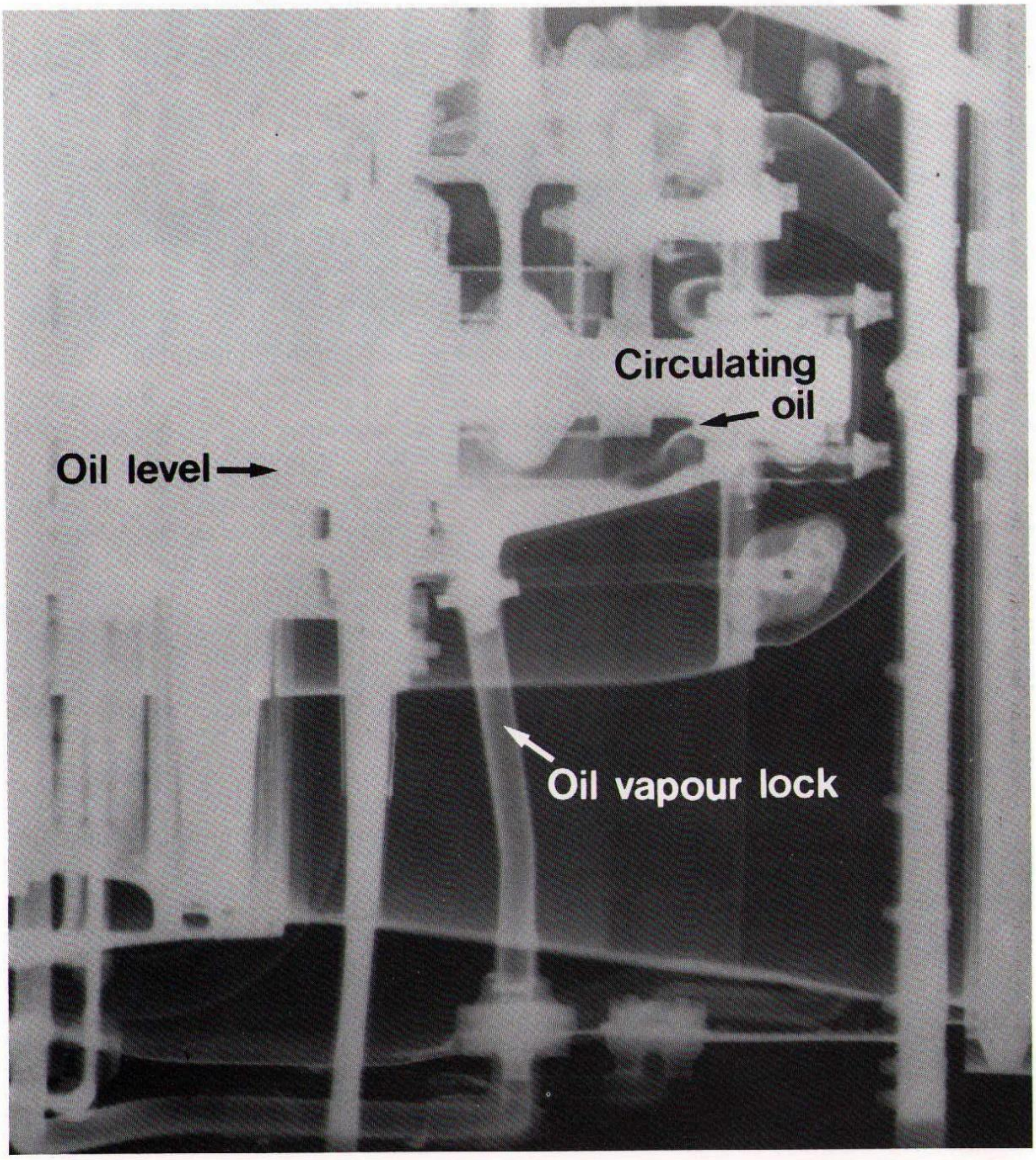


Figure 14

Neutron radiograph of helicopter engine

Rear bearing assembly of 'Gem' helicopter: radiograph displayed on a television screen with the engine running shows the distribution of circulating oil.

By courtesy of Rolls-Royce (1971) Ltd.

neutrons differ in the size of collision cascades they produce and this has recently been demonstrated by examing ordered alloys, in which the disturbances resulting from individual cascades can be seen with an electron microscope.

The vacant sites left by collisions and the interstitial atoms both form point defects which are mobile at certain temperatures. The interstitial atoms usually are mobile at well below room temperature whereas vacant sites become mobile in the range at which the cores of nuclear reactors normally operate. The point defects usually form clusters but under certain conditions an excess of vacancies can cause the growth of voids and hence an increase in volume of specimens. Theories to explain the growth of voids under irradiation are well developed but those for predicting nucleation are less well understood. For quantitative prediction of void swelling in nuclear reactors we seek a clear account of the atomic mechanisms involved in void formation and accurate measurements of the microstructural changes which result.

Atomic displacements can also give rise to radiation creep and radiation growth. The contributions of these two phenomena to total strain have been separately determined using a textured zirconium specimen. The method has been used to determine the temperature coefficients of both phenomena and the temperature coefficient of total strain.

The ion implantation technique enables the experimenter to deposit alloying constituents or impurities at precisely defined depths in a sample. Studies of diffusion, when these implanted specimens are exposed to radiation, yields interesting new information about the drift of solute materials in a vacancy flux. Diffusion models have been developed which can account quantitatively for the observations – an important factor in the understanding of radiation annealing or embrittling processes.

Radiation investigations with non-metals include the study of neutron and heavy-ion damage in oxide ceramics such as the insulators used for instrumentation in reactor cores and the effects of gamma radiation on the mechanical and electrical properties of organic polymers.

Fracture

Earlier studies of fracture were concentrated on the problems of materials in regions of high irradiation, such as the embrittlement of AGR cladding by helium arising from nuclear reactions and the rise in the ductile-brittle transition temperature of pressure vessel steels exposed to fast neutrons. More recently the fracture studies have been concerned with components less subject to irradiation effects. Emphasis has been placed on primary containment circuits of thermal reactors including the main pressure vessel, the pipework and the heat exchangers. Underlying research has concentrated very much on the metallurgical aspects of flaws and fracture in these components. Special aspects studied include the effect of segregation in large ingots on the distribution of mechanical properties in the final product, localized segregation processes leading to embrittlement and environmental effects on crack propagation including exposure to liquid metal and water.

The accepted methods for predicting failure conditions in engineering structures are mostly based on comparatively simple models, such as linear elastic fracture mechanics and simple rules for damage summation. A basic weakness of existing predictive methods is that they are not generally based on an understanding of the fracture mechanisms likely to occur in service. It is an aim of the underlying fracture programme to extend this knowledge, especially for reactor materials and pressure-vessel steels.

The Environmental Programme

2

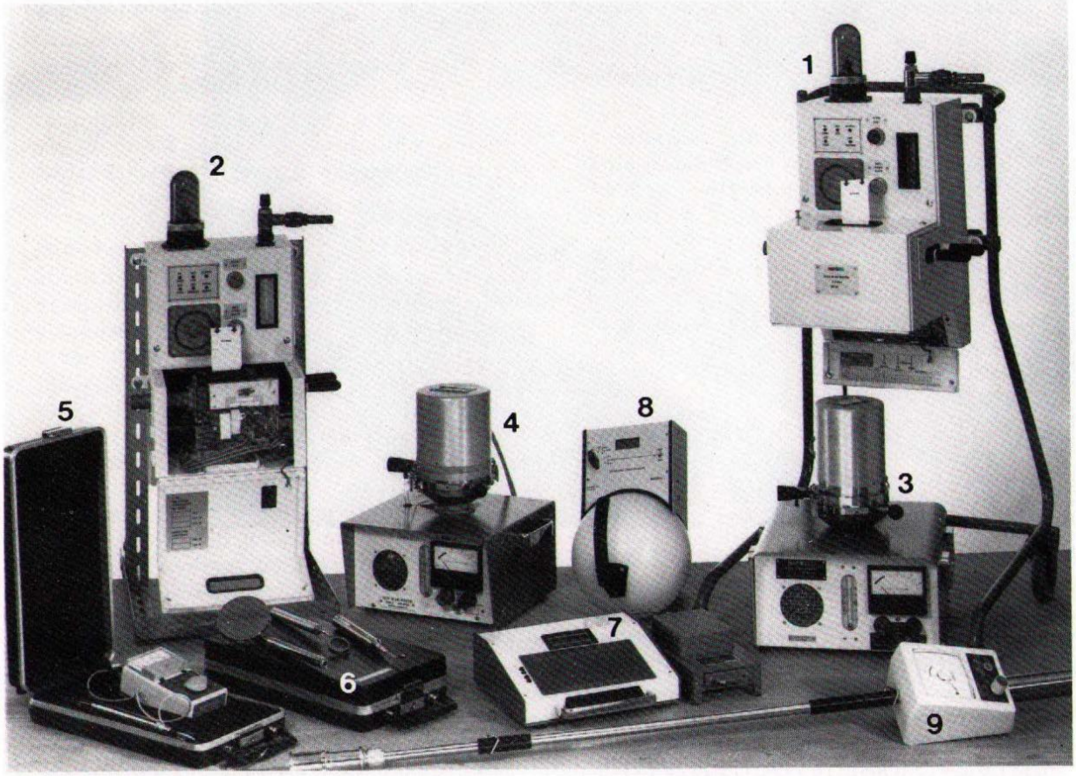


Figure 15

Radiological protection instruments developed at Harwell

Plant surveillance systems for measuring air borne radioactivity:
1 for alpha particles
2 for beta particles.
Transportable air monitors:
3 for alpha emitters
4 for beta emitters.
5 Miniature alpha particle probe and portable counting ratemeter.
6 Selection of semiconductor probes for alpha particles
7 Portable counting system for alpha particle sources
8 Portable neutron monitors, using helium −3 detector and digital display.
9 'Hot-spot' monitor for gamma radiation, using energy-compensated Geiger counter.

Background

The Atomic Energy Authority has a statutory obligation to protect the health and safety of its staff and to ensure that its activities cause no harm to the public. Specifically it is required not to exceed permitted limits of radioactive emission from any of its plants or laboratories and these limits are controlled by the Department of the Environment and other Government bodies. To satisfy both requirements, reliable systems of radiation measurement and control are needed. The first systems were developed and implemented in the 1950's and the provisions are continually reviewed and updated to meet present and foreseen situations.

The Authority's research and development programme in Radiological Protection and the nuclear environment is centred at Harwell. For staff protection it comprises the development of improved methods of radiation dosimetry, the establishment of safe procedures and studies of some of the biological effects of radiation and the pathways of radioactive materials in man. For public safety it provides the means of measuring and controlling all emissions, such as radioactive liquids and stack gases, together with a detailed appraisal of their dispersion, deposition and subsequent movements in the environment.

A relatively small team of experienced health physicists serves the regular needs of the site for surveillance of radiation areas and monitoring of personnel. Scientists and engineers as a whole are expected to provide a fund of knowledge on radioactivity-handling procedures, to try to foresee and plan for nuclear emergencies (however unlikely) before they arise and to support the operational services nationally should the need arise. The bulk of this specialist backing is available from the staff engaged in research on radiological protection and nuclear environmental investigations.

However, the studies which have been necessary to explore the behaviour of radioactive substances in air, sea and land can be adapted to apply to most of the common pollutants like lead or dieldrin, some of which are very toxic. The extreme sensitivity of radioactivation analysis and the specificity of radioactive tracers make them invaluable tools for studying conventional pollutants. Research teams were already experienced in this work when the diversification of 1965 allowed them to be employed more generally in environmental protection. About half of the effort in environmental research is now engaged in this way, keeping the specialists fully exercised in work very relevant to a

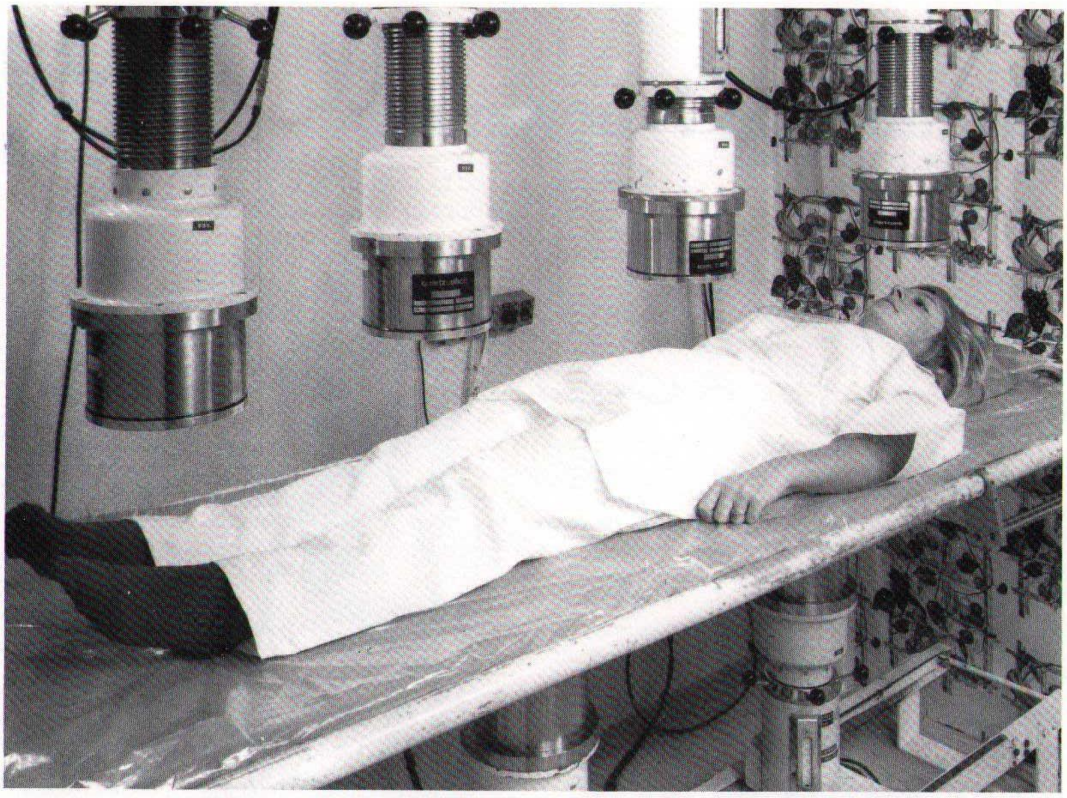


Figure 16
Whole body monitor

nuclear contingency and at the same time making a positive contribution to the safety of the environment as a whole.

RADIOLOGICAL PROTECTION

Instrumentation

Although the instruments which are required in quantity for radiological protection are manufactured by the nucleonics industry, many of the basic designs originate here and Harwell is responsible for developing improved methods of dosimetry and instrumentation to enable the UKAEA to meet their statutory obligations.

Indeed, it is our job to provide the means of measuring the intensity and the characteristics of all nuclear radiations and a central core of some 40 professional staff is engaged in developing detectors and the associated electronics. Radiological instrumentation is one aspect of this work; the programme is guided by an Advisory Committee on R P Instrumentation, representing the Authority's Establishments and other users. *Fig. 15* shows some of the nuclear instruments and systems designed and developed in recent years.

In detector development, the conventional gas-filled detectors and scintillation counters are supplemented by semi-conductor detectors such as diffused junction silicon diodes. These provide compact and rugged probes especially suitable for measuring alpha-particle activity in very small samples and for intra-cavitary measurements – such as the detection of alpha-emitting – contamination in nostrils. Some of these devices are also of medical value for internal dose measurements during radiotherapy.

The use of newly available silicon chip circuit components sets a trend towards smaller, cheaper instruments and more sophisticated devices can be produced at competitive prices. We foresee a new generation of micro-processors and several microcomputers are already being developed for specific purposes.

Recent work includes the monitoring of air-borne particulates, especially for alpha-particle emitters (which include uranium and elements of higher atomic number). Sensitivity to low levels of alpha-activity has been greatly increased through better discrimination against the background arising from natural radon and thoron gases and their radioactive daughter products in the atmosphere.

Installations for measuring beta and gamma radiation levels have always been used for monitoring in processing plants. Present development is towards the display of such information centrally for greater efficiency of radiological protection. The central display can also analyse trends in changing radiation levels and highlight any local increases for immediate attention by the responsible officer. It saves shoeleather too!

Personnel monitors are increasingly used to measure the exposure of workers in radiation areas. The smaller and lighter detectors now available and the improvements in data handling make possible a more detailed analysis of individual exposure.

Radiological protection research

Radiological protection is of international concern and there is world-wide interchange of information on the researches carried out in radiobiological laboratories and nuclear establishments. Harwell's work in the field is a contribution to this general pool of knowledge, relevant to the special interests of the UKAEA; much of it is undertaken as part of a European programme coordinated through the European Economic Community.

Our emphasis in this area has always been on applied research and the instrumentation relies on a background of research into dosimetry. A lot of attention is concentrated at present on the measurement of neutrons which will arise in the reprocessing of fast reactor fuel, especially on those of intermediate energies (1KeV to 100KeV). Better methods are needed for measuring the neutron flux and dose received by individuals. More practical data is sought on the variety of interactions of these intermediate energy neutrons with living cells and body tissue.

To be fully effective, radiological protection must be correlated with the effects of radiations on man. Although the main-stream of research in this direction is in medical and radiobiological establishments, Harwell has contributed much to the understanding of radiological hazards through studies of the metabolism of radioactive species in human volunteers.

Most of the measurements are made with the whole-body counter shown in *Fig. 16*. Essentially this consists of six large scintillation counters surrounding a couch on which the subject lies. It can detect gamma-ray emitters in quantities very much lower than maximum permissible levels, analyse their radiation energies and give some indication of their distribution in the body. The primary use of this facility is for investigating suspected cases of internal radioactive contamination, but whilst kept available for that purpose it is also used for radiological and metabolic studies.

Notable among these researches are the inhalation studies which examine where inhaled particles of different sizes are deposited in the lung and respiratory tract and how efficiently they are cleared. This work is part of a wider programme of inhalation toxicology which embraces industrial dusts such as asbestos. Basic information about the physiological processes of lung clearance and their dependence on particule size is gained by inhaling inert polystyrene particles of controlled sizes incorporating a short-lived radioactive gamma emitter, so that their subsequent movements can be followed.

A capability to detect inhaled plutonium in the lung is of special importance for radiological protection. Since this emits low-energy (17KeV) X-rays, the whole-body counter can detect it in the lung if present in sufficient quantity. However, at this low energy, the X-rays are strongly absorbed in body tissue and the response to a given level of radioactivity depends a lot on the size and shape of the man or woman concerned. Calibration of any measuring system is an international problem: for comparison, phantoms – i.e., plastic models – of the thorax are generally used, with materials chosen to simulate the absorption and scattering of radiations by human tissue. As a contribution to the calibration problem, three volunteers of small, medium and large physique inhaled polystyrene particles containing palladium-103, to simulate the emissions from plutonium-239. The particles were also labelled with a gamma emitter, so that the total quantities were accurately known. The three men then visited 13 laboratories in Europe and North America for comparative measurement of their lung contents. Discrepancies by a factor 3, which were then typical, have largely been resolved by improvements in the materials of construction of phantoms, to which this initiative has led.

Mechanisms of radiation damage

The 'permissible levels' for radioactive ingestion and radiation exposure, on which national limits are based, are set by the International Commission on Radiological Protection. These levels are established using evidence from radiobiological research throughout the world and form a rather limited accumulation of evidence on human tissue (e.g. from radiotherapy patients) which has received radiation doses at a high rate. For these purposes it is assumed that damage is related only to the total radiation dose, independently of the rate at which it was received.

There is some evidence that this is not so and that radiation received over a long period at low dose-rate may be less harmful than the same dose administered in a short, intense burst. The arguments depend both on the effectiveness of multiple 'hits' on single cells and on biological repair mechanisms and selective cell propagation after the event. At present the nature of dose-rate dependence is uncertain, though these possibilities suggest that present restrictions may err on the safe side. A related problem concerning the relative biological effectiveness of short-range radiations like alpha particles is also being re-examined.

A small exploratory programme of research is examining the mechanisms of cell damage by radiations at different exposure rates and the way in which this damage is propagated in cell division. The time is propitious, because a supply of 'clone cells' is now available, cultured from a single original animal cell. A number of strains of clone cells, including human cells, are available. These provide a uniform starting material free from biological variations which might mask small effects. Computer data processing is used to handle the statistical information arising and to compare the validity of different theoretical models. Close links are maintained with the Medical Research Council, whose researches are of course on a much larger scale.

Occupational risk

It is to the credit of radiological protection that there is a dearth of human material on the damaging effects of radiation. On the principle of leaving no possibility unexplored, Harwell has engaged the Medical Research Council to make a retrospective epidemiological study of all present and past employees of the UKAEA. The mortality records of some 45,000 persons, together with their detailed history of radiation exposure and other conditions of employment, will be analysed for any correlations. This study is not expected to detect any hazard from radiation unless these risks are substantially greater than is currently estimated. However, it will indicate an upper limit to possible risk on an independent statistical basis and establish whether dose limits have been seriously in error. It supplements and will be incorporated into the continuing data submissions to the N.R.P.B's National Register of Radiation Workers which was launched in 1976.

THE NUCLEAR ENVIRONMENT

Environmental monitoring

The planning of nuclear waste disposal requires a study of the physical movement and chemical reactions of each species in the environment and of the physical and metabolic pathways back to man. Much of this work is predictive, because the high-level waste is still in storage. However, controlled low-level radiation emission from the power programme has now been occurring for quarter of a century and careful measurements can indicate how well the early predictions of environmental dispersion are borne out in practice. Harwell is therefore determining concentrations of nuclear pollutants in the environment by taking samples of land, sea, air and rain in selected areas. This involves chemical analysis and radioactive assay at concentrations well below the safety level defined by the National Radiological Protection Board.

A survey now in progress is examining the concentrations of plutonium and fission products in the soil of Cumbria, where the Windscale fuel processing plant is situated. In addition, sea, air and rainfall are sampled near the coast to determine the mechanisms of transfer from one environmental medium to another, such as that from sea to land by windborne spray.

Atmospheric contamination is of special interest, because the air is the most mobile vehicle for environmental pollution. Filter samples of the local atmosphere have been taken continuously since 1954: the air and rainwater sampling station at Chilton is one of a world network originally designed to monitor radioactive debris from distant nuclear weapons tests. Seven of these stations are in the UK, providing a continuing record of air-borne material from all sources.

In interpreting all of these measurements of nuclear contamination it is important to distinguish that which is of natural origin, that which arises from nuclear power operations and that due to past nuclear explosions. Many of the fission products are common to the last two, but from a comparison of the relative abundances of some nuclides, the contribution from each source is deduced.

THE ATMOSPHERE

Non-nuclear atmospheric research

Some of the early atmospheric monitoring is directly applicable to wider pollution problems.

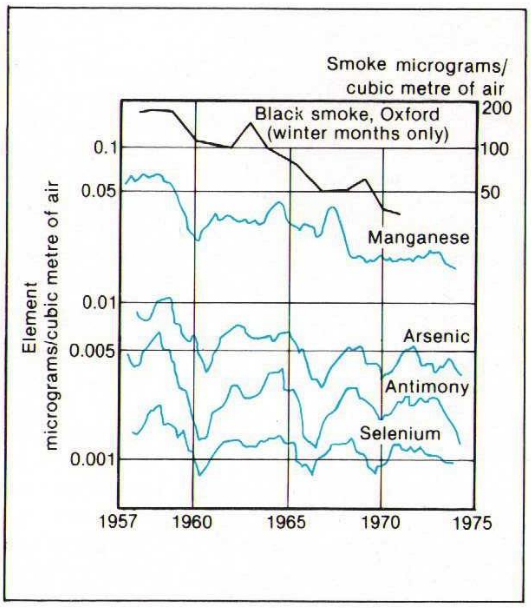


Figure 17

Trace element concentrations in air 1957 to 1974

Selected data from air sampler at Chilton, Oxon. The black smoke concentrations shown for comparison are winter concentrations at Oxford, 20km north of the Chilton site, from 'National survey of air pollution', by Warren Spring Laboratory, HMSO 1972. The trace element measurements were made at Harwell in 1977 to 1978.

For example, the stored filters from Chilton contain a quantitative record of the concentrations of air-borne particulates in Southern England over more than twenty years. A retrospective analysis of these filters, by a variety of methods including radioactivation analysis, showed the varying concentrations of 27 trace elements and compounds in airborne suspension over the years from 1957 to 1974. The selection in *Fig. 17* show a marked decrease over the period: this may be correlated with a reduction in black smoke emission by improved methods of burning fuel, following the 'Clean Air' Act of 1956. The concentrations of black smoke over Oxford during part of this period, taken from a national survey by Warren Spring Laboratory, are shown for comparison. Nearly half the mass of the Chilton aerosol was made up of ammonium sulphate and nitrate and their concentrations increased over the period.

The techniques developed for tracing the dispersion and deposition of possible emissions from nuclear stations have been applied more generally to study the physical and chemical behaviour of conventional air pollutants and their life cycle in the atmosphere. This work is now funded by the Department of the

Figure 18

Lead pollution investigation

Subjects inhaling exhaust aerosol on hard shoulder of M4 motorway.

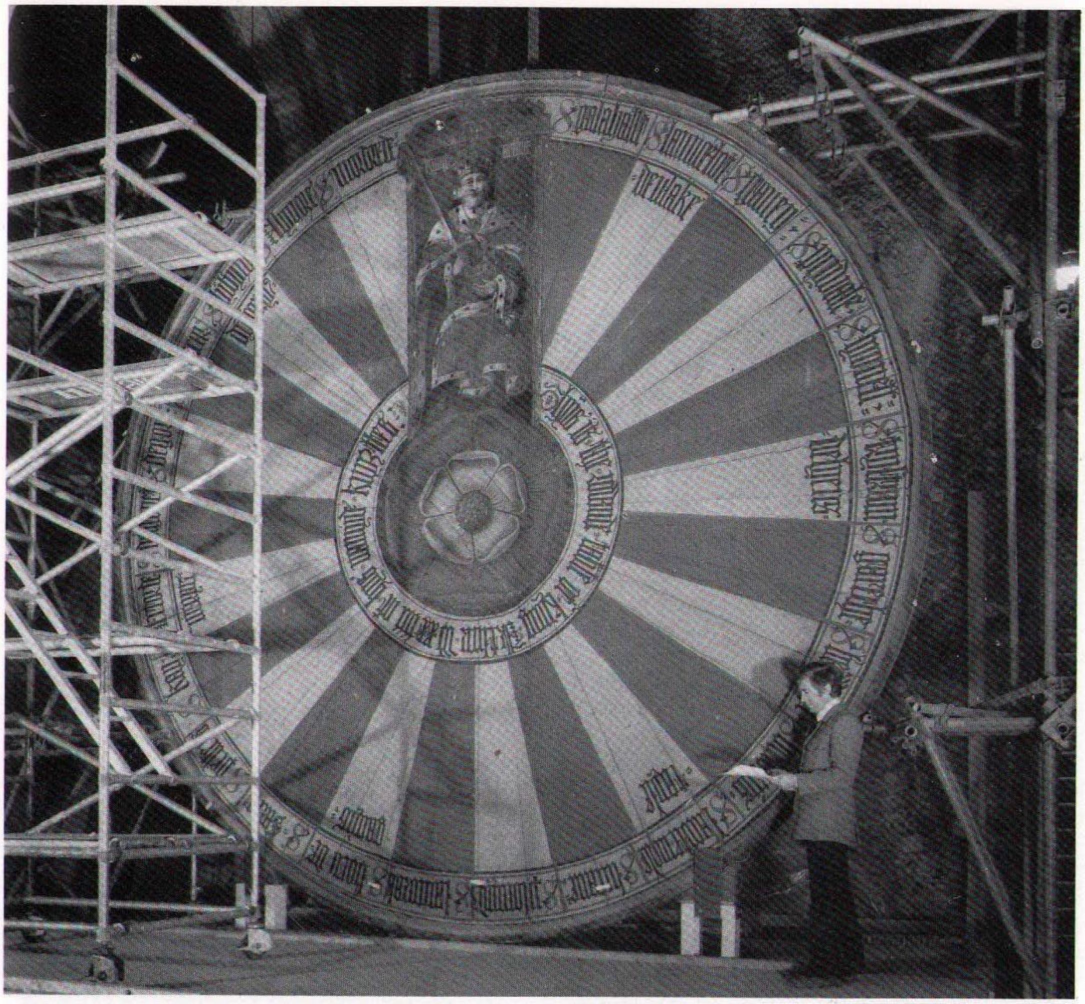


Figure 19

The Round Table, Winchester

This ancient table from the Great Hall, Castle Yard was a subject for radiological dating.

Environment (DoE) and provides a scientific basis for the Department's pollution control policies. Specific environmental problems involving atmospheric emissions are also investigated for industrial companies.

One recent programme examined the behaviour of sulphur dioxide, produced by burning coal, oil and other fossil fuels, and studied the various mechanisms by which it is removed from the atmosphere and its relationship with smog and acid rain. Another study of photochemical pollution examined the irritants produced by the action of sunlight on hydrocarbons and nitrogen oxides emitted by motor vehicles and power stations. The rates of chemical reactions concerned were measured in the laboratory and used in computer models to predict the effects of various emission control strategies on the reduction of this form of pollution.

An international investigation of longer term significance concerns the effect of man-made pollutants on the ozone in the atmosphere which protects the earth's surface from damaging ultra-violet radiation from the sun. It is suspected that some contaminants, notably chlorofluorocarbons used as aerosol propellants and other chlorocarbons, may seriously deplete the protective layer if not controlled, leading to a higher ultra-violet intensity at the earth's surface and possibly an increase in the incidence of skin cancer. Harwell's contribution to this progamme is to determine atmospheric concentrations of the chemical species concerned, to measure the rate constants of some important chemical reactions and to calculate the likely effects on stratospheric ozone in future decades, using computer models.

Environmental toxicology

A feature of the work with environmental toxins is that for many pollutants the behaviour can be followed not only in the atmosphere, but also after inhalation or ingestion in the human body. A survey of the distribution of airborne lead, principally from motor vehicle exhausts, included its passage to the population. As well as field determinations of atmospheric concentrations, chemical forms and particle sizes near motorways and busy streets, the uptake and retention of both natural and radioactive lead in the lungs of human volunteers was measured *Fig. 18* and studies were made of the mechanisms of transfer to blood and bone and removal from the body by excretion. The work was sponsored by several government departments and the petroleum industry. It showed that under present conditions the contribution of airborne lead to total uptake is about ten per cent on average, though the proportion is up to fifty per cent for people living very close to busy motorways.

Radioactive trace measurements of lung retention are also used in examinations of clearance and toxicity of dusts in factory environments, such as asbestos and glass fibres and the wood-dust arising in furniture manufacture. A study undertaken for the tobacco industry has shown that the patterns of particle deposition in the lung are quite different for smokers and non-smokers.

Radiological age

The atmosphere contains small quantities of a number of radioactive materials of natural origin. One of these is carbon-14, produced by the action of cosmic rays on nitrogen. Because growing plants absorb carbon dioxide from the air, carbon-14 forms a well-defined proportion of the carbon in all living bodies. American scientists showed that the remaining radioactivity in dead wood or bone is a measure of the time since it was part of a living tree or animal; as the half-life of carbon-14 is 5730 years, this can be used to determine the ages of archaeological specimens up to about fifty thousand years. Harwell is one of 130 laboratories in the world which measure carbon-14 at the very low levels required. Among the 400 samples a year with which it deals, the round table shown in *Fig. 19* and for many years attributed to King Arthur was found to have originated in the 13th century A.D.

Tritium (hydrogen-3), present in even smaller concentrations in atmospheric waster, has a half-life of about ten years. Its concentration in ground water is a measure of the time since this fell as rain and the low-level laboratory makes about 1000 determinations a year, mainly for hydrology research centres and water authorities. Nuclear weapons tests in the early 1960's gave a temporary boost to activity levels of tritium and fission products in the atmosphere. This peak of activity is still recognisable in the tritium of ground water and in the caesium-137 found in lake sediments of that period and is used as a specific date label.

WATER AND THE SEA

Hydrology

Conservation of public water supplies requires a knowledge of the movements of water through rainfall to the soil, through rivers to the sea, its storage in porous rock strata and its transpiration through living plants. In the past, the use of radioactive tracers has added greatly to the knowledge of underground water movements and in collaboration with specialist hydrological laboratories, Harwell has contributed much to this work. However, the present philosophy is to disturb the natural balance of stable and radioactive isotopes as little as possible. In nearly all applications, the natural radioactivity is used to indicate patterns of movement over an area rather than to estimate the 'age' of a specific sample, but the time scales can be very long.

Natural and 'bomb' tritium provide effective markers over some 10 or 20 years and their absence indicates older deposits. Carbon-14 is measured in the carbonates dissolved in water from deep-lying strata as an indicator of movement over thousands of years. This has been used to determine the replenishment rate of the greensand aquifier under the Thames Basin for the Water authority as a basis for controlling water extraction rates. A longer time-scale still is provided by the balance of dissolved uranium isotopes where these occur in water, and they can indicate movements over a million years. Their concentrations are measured in the laboratory by distinguishing between their alpha-particle energies.

The hydrology team carries out all of these measurements for Water Authorities and other users and interprets them as required. A capability is thus maintained which is valuable to the Atomic Energy Authority, for the behaviour of ground water is of crucial importance in selecting sites for radioactive waste disposal: much of the current work on the hydrology programme is directed to the appraisal of rock formations for this purpose.

Silt, sediment and the seabed

Short-lived radioactive tracers can still be used to investigate the dispersal and recycling of industrial effluent and sewage outfalls in rivers and the sea. In the past, investigations of sand and silt movements in river estuaries and on the seabed have led to dramatic improvements in dredging procedure, especially in the Thames estuary and the Firth of Forth. Although these facilities still exist, they have largely been taken over by other organisations.

With the design of sensitive radiation detectors for use on the seabed, operations moved further out to sea. It was found that a survey of natural radioactivity could be correlated with the geological nature of the bed. More sophisticated analysis of the gamma-ray energies identified specific elements such as uranium and potassium. When small neutron sources were attached to the detectors, the gamma rays they induced in sea-bed material enabled other elements to be determined. The team is now engaged with the Institute of Geological Sciences in a survey of radio-geology in the North Sea *Fig. 20* under contract to the Natural Environment Research Council.

THE LAND: HAZARDOUS MATERIALS

Experience in handling and treating radioactive materials and in industrial chemistry is being applied to the more general disposal problems of toxic industrial chemicals. The work is organised in the **Hazardous Materials Service,** established in 1968 after a recommendation by the Key Committee on toxic waste disposal. The service, now supported by the Department of the Environment as well as by the income from its commercial activities, occupies some 15 professional staff, whose main commitments are as follows:

The Waste Research Unit is wholly financed by the Department, to advise on the characterisation and disposal of wastes.

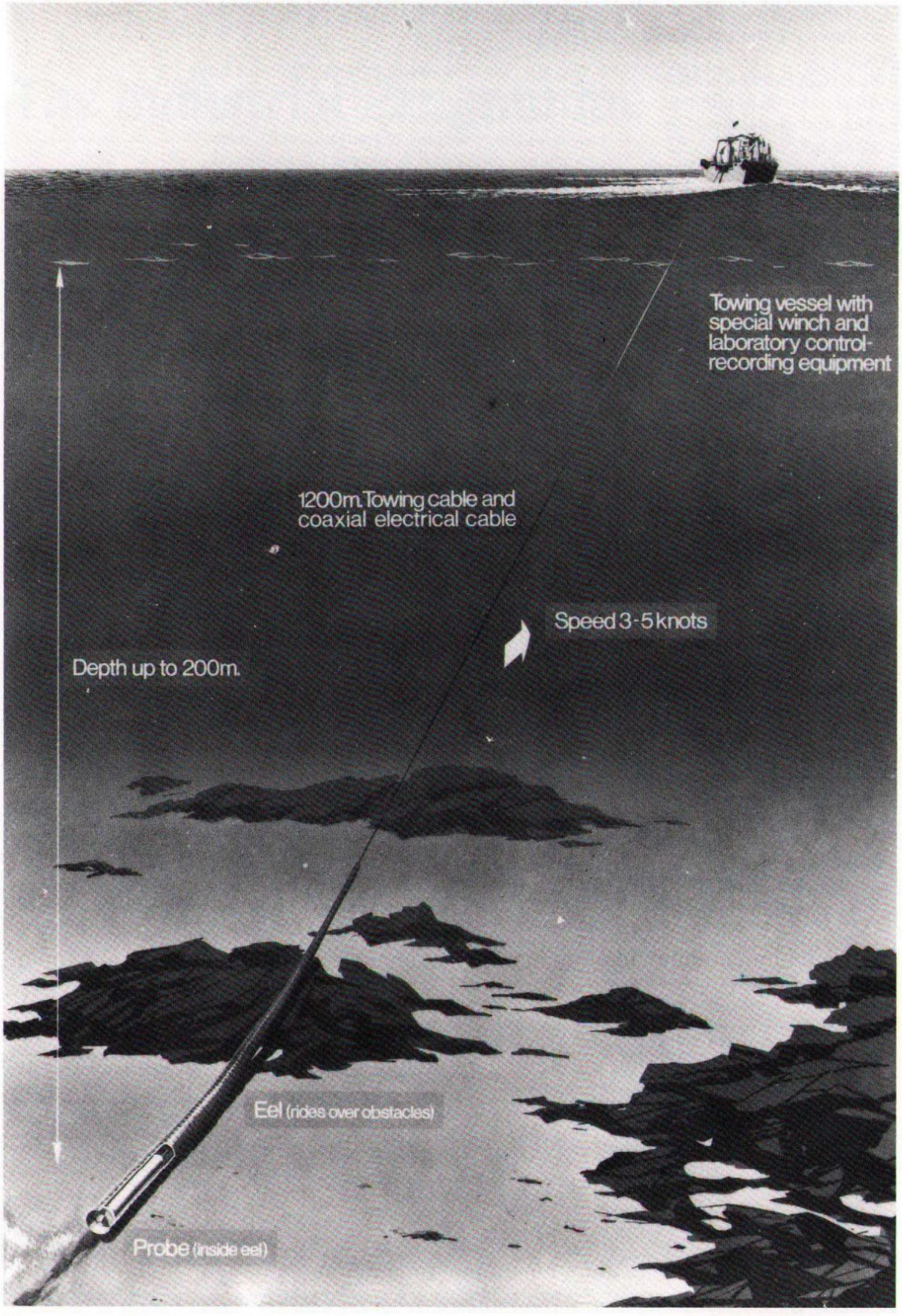


Figure 20

Radiogeological measurements at sea

Research and development is undertaken into the problems of disposal for specific types of waste, such as pesticide residues, cyanides and mercury, and their impact on the environment.

The Waste Management Information Bureau provides advice and information on request, mainly to local authorities and industry and publishes a monthly information bulletin. It is backed by a computerised data bank containing a large collection of published material and exchanges information with overseas nations, particularly with the EEC.

The Landfill Programme aims to rationalise and manage scientifically the filling of holes left by opencast mining or quarrying operations and thus to recover the land for agriculture or building. Harwell is involved jointly with the Water Research Centre and the Institute of Geological Sciences in investigating the effects of waste treatment and disposal practices on ground water quality and in examining novel procedures for some particular types of industrial waste.

The Hazardous Materials Service is often consulted about the toxic hazards of planned, existing or derelict sites, and gives advice on safe methods of decontamination, land reclamation and future use of the sites. When required, the Service plans and supervises the whole operation through selected contractors and itself collect hazardous materials for disposal.

The Chemical Emergency Centre gives assistance to the emergency services who attend accidents involving dangerous chemicals. It is part of a nation-wide scheme (Chemsafe) organised by the Chemical Industries Association to give prompt advice and assistance. Harwell is the long-stop when the manufacturer cannot be contacted, or can be made the first point of reference for companies which subscribe to the Chemical Emergency Agency and display the appropriate telephone number on the vehicle. A duty officer is on call 24 hours a day and has at his disposal a computerised data bank of chemical properties and hazards, as provided by the manufacturers of some 11,000 products. A specially equipped vehicle stands ready to travel to the site of any incident within 50 miles.

The public fire services now have on-line access to information on hazardous chemicals through 'Hazfile', a data bank set up with the BOC Datasolve computer bureau, to which 47 county fire authorities subscribe. 'Hazfile' is updated regularly by the Chemical Emergency Centre.

NUCLEAR INSTRUMENTS FOR THE MINES

For a number of years nuclear techniques have been developed for exploration and mining. The absorption and scattering of nuclear gamma rays and the reactions of neutrons with a body of rock are measured to assess the expected yield of mineral ores or the impurities in mined material. This ability to assess ore quality quickly in a bulk of heterogeneous materials, without chemical analysis, is important to the efficiency and profitability of mining operations. By cutting down the mining of unproductive dross, it also reduces the size of resulting spoil tips and so contributes to environmental conservation, but the primary objective is an economic one.

The work, which involves both mining laboratory research and instrument development, is supported by contracts from the mining organisations.

Portable instruments have been developed to evaluate the ores in working faces and boreholes by gamma-ray scattering, neutron reactions and X-ray fluorescence analysis. Fixed installations measure the ash content of coal on conveyor belts as it leaves the mine, enabling it to be graded for different markets or for optimum efficiency as boiler fuel. Applications are being developed further in contracts which range from the multi-element analysis of coal to the interpretation of oil-well logging data.

The Industrial Programme

3

PROGRAMME DEVELOPMENT

The industrial programme aims to use capabilities developed for the nuclear programme to serve wider needs of British Industry and Government. There is thus a very close relationship between the nuclear and non-nuclear programmes, through the common areas of expertise which they employ *Table 2*. Often the same people are engaged at different times on nuclear and non-nuclear work, using essentially the same technologies to pursue different objectives.

Harwell has always had a close relationship with the electronics and nucleonics industries in the development of instrumentation. More generally, the applications of radioactivity – which the Laboratory pursued under its original terms of reference – led to its involvement in diverse industrial problems and to a small but significant programme of contract research and development. Thus when the Science and Technology Act in 1965 permitted the UKAEA to diversify its activities into non-nuclear fields, there was already some commercial experience on which to build.

The industrial programme is wholly funded by its earnings, which are mainly from industrial clients and from Government Departments. Much of the work is of wide application, aimed at sectors of industry rather than specific firms and supported either by groups of companies with similar interests or by the Requirements Boards of the Department of Industry. Research of this kind forms a seed-bed out of which grow more specific research and development projects commissioned by individual firms. Most parts of the programme are planned to combine the more general and the specific components, with an increase in direct industrial funding as a project matures.

The programme now is very diverse, ranging from materials research and fabrication techniques, through process technology and production control to nondestructive testing and chemical analysis. This short account cannot do justice to all of its projects, but a selection of recent activities will illustrate the kind of work undertaken.

MATERIALS AND FABRICATION

The safe development of nuclear power has always necessitated research into structural materials and their mechanisms of failure at high temperatures, under acute thermal stresses and in corrosive environments. This experience and many of the special materials developed have found important applications outside the nuclear industry. Materials work for the non-nuclear industries is concentrated mainly in the Ceramics and Composites Centre and in the Metals and Chemical Technology Centre. The following are some examples of their recent activities.

Harwell's Role in Nuclear Power	Areas of Expertise	Main Receipt Earning Activities
Expertise & facilities for investigation of in-core conditions	Use of accelerators reactors and special nuclear facilities	Sale of accelerator time Uses of neutron beams – by SRC; by Industry Irradiations Isotope production (for Radiochemical Centre)
Development of processes required for fuel production and reprocessing	Process Development New materials	Ceramics and Composites Centre Metals and Chemical Technology: Fecralloy Steel Catalysts Corrosion and Fatigue
	New processes	Gel processes Biochemical processes Electrochemical processes; Batteries
	Improved plant design	Heat Transfer and Fluid Flow Service Separation Processes Service
Studies related to safety and reliability of nuclear plant; and research on environmental problems of nuclear power	Analysis, surface examination, NDT, instrumentation	Analytical Research and Development Unit Solid State Instruments Service Non-Destructive Testing Centre Nuclear-based instruments for Industry Laser instruments: I.C. Engines
	Environmental Sciences	Atmospheric pollution research Hazardous Materials Service Hydrological Tracers
Engineering Development of Rigs Computing and Data handling	Engineering Computing Other	Engineering Design Systems design and data processing Computer modelling and optimisation Energy Technology Marine Technology

Table 2. Relationship between Harwell's nuclear power work and receipt-earning activities

The Ceramics and Composites Centre

Established in 1967, the Ceramics and Composites Centre brings the disciplines of materials science, chemistry and process engineering to the development of new and improved products and processes for exploitation by British industry. The Centre is funded by the Engineering Materials Requirements Board to pursue applied research in selected areas of materials technology and it undertakes a wide range of developments for industrial firms under contract. The work includes the preparation of materials by gel processing, surface coating techniques and the development and fabrication of ceramic electrical materials and insulation products.

Gel processing

The preparation of fast reactor fuel spheres and the application of surface coatings have already been mentioned as examples of gel processes. These are a group of chemical procedures which involve gels as intermediates and so achieve close control of the properties and forms of inorganic oxides. Three main forms of product have been developed for specific industrial uses – liquid sols for coating applications, spherical gel particles and spherical oxide particles with controlled size, porosity and pore size distribution. Oxide-based catalyst materials are under development: some are already used industrially by Johnson Matthey Ltd. Absorbent silica and alumina particles have been developed as chromatographic support materials and are now marketed world-wide by Phase Separations Ltd under the trade name of 'Spherisorb'. Some uses in high-speed biological processing will be described later. Many other uses of gel processed materials and techniques are being explored including ceramic pigments, free flowing powders for plasma spraying, improved processing for metal carbides, and controlled release of pharmaceuticals from gels. In this last application, pharmaceutical compounds are introduced at an early stage in the gel processing and thus become uniformly distributed through the spherical pill into which the gel is then made. Experiments with simulated gastric fluids have shown that the period of release of a typical drug can be adjusted from ten minutes to several hours by varying the conditions of preparation.

The use of gel processing described in *Chapter 1* for coating AGR fuel pins to inhibit oxidation and carbon deposition is one of many instances in which a technology originating from the nuclear power programme and developed for industrial uses has been fed back to solve a pressing problem of nuclear power.

Surface coating techniques

Among the surface coating methods being pursued, apart from gel processing, the leading technique is sputter ion plating, which transfers material in an electric field applied to a simple glow discharge system under low vacuum. The method is particularly suited to the deposition of electrically conducting ceramics and metals, especially complex alloy coatings with good oxidation resistance at high temperatures. The techniques developed produce strongly adherent coatings of high integrity. They are being used to apply coatings of three main types important to industrial development – heat resistant coatings for high temperature fittings such as gas turbine components, corrosion resistant coatings for chemical applications and hard-wearing coatings of titanium carbide or nitride. Similar methods can be used to form adherent deposits of nickel on ceramic or glass surfaces, which can then be joined to other metals by conventional soldering.

Thermal spraying is widely used by the Centre in industrial work. Deposits up to 1 mm or more in thickness of ceramics, metals and some plastics can be applied rapidly to a wide range of materials. The method can also be used for fabrication, either by plasma spraying onto a fibre mat or by building up the deposit on a removable mandrel. A number of components made in this way are illustrated in *Fig. 21.*

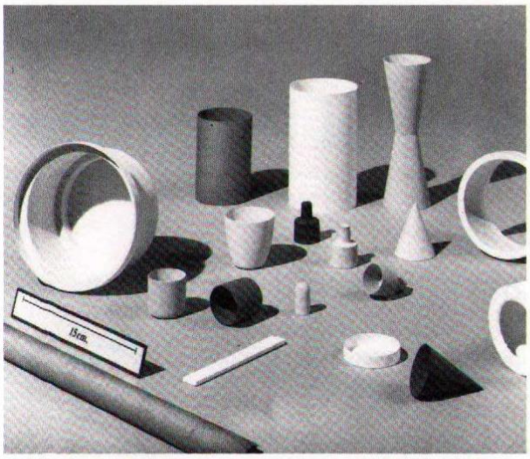


Figure 21

Fabrication by plasma spraying

A selection of products formed by spraying onto mandrels.

Electrical materials

Many ceramic materials have electrical properties which can be exploited for industrial uses and a current project is the development of sensor applications for the detection of gases in industrial furnaces. Another new product is the porous ceramic heater. This is a heating element composed of electrically conducting

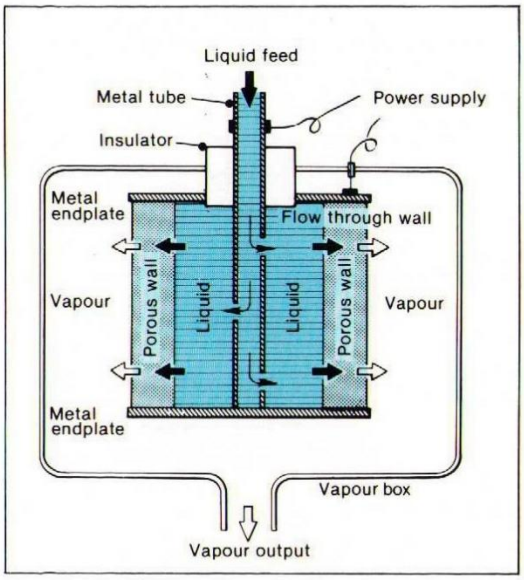


Figure 22

Porous element fluid heater

Principles of use as a vaporiser. Liquid is vaporised as it passes through the porous walls of the heater tube.

porous materials such as carbon or silicon carbide, though which fluids can pass for heating. *Fig. 22.* The high contact area of the pores, compared with conventional immersion-type heaters, makes for very efficient heat transfer: in favourable cases temperature rises of 500°C can be achieved in a few milliseconds transit time through the element. Because of the small size of the heating device, very rapid start up and shut down characteristics can be achieved.

Originally developed for improving heat transfer from a nuclear fuel element to the reactor coolant, this technology has a wide market in the chemical processing industry and in fluid heating generally. Collaboration with Edwards High Vacuum International Ltd, SIGRI Elektrographit GmbH and with E Fogarty and Co Ltd in the development of heater elements has proceeded for some years and the latter company has now formed Porous Element Heating Ltd as a wholly owned subsidiary to exploit the technology.

Thermal insulation

The Ceramics Centre is developing a range of inorganic materials for use as heat insulators. A particular development in this area is 'Cenolite'* material made by bonding together the microscopic hollow glass 'cenospheres' which form a part of the pulverised fuel-ash (p.f.a.) from coal-burning power stations. The resulting product, can be moulded into a variety of shapes and panels, can be drilled, sawn and nailed into position and withstands temperatures up to 1000°C. The material has been developed under joint sponsorship with the Central Electricity Generating Board, specifically for the fire protection of structural steel-work. Fire test evaluations have been carried out by FIRTO (Fire Insurers Research and Testing Organisation) and industrial installation trials have been made. Further developments using p.f.a. include improved building products to meet new regulations on thermal insulation for homes.

More generally, the Ceramics Centre has completed a study of the use and development requirements of thermal insulation materials in the high temperature processing industries, including pottery, cement, refractories, non-ferrous metals, iron and steel. Sponsored by the Department of Energy, this is part of a national energy conservation programme which will be discussed in the next chapter.

Composite materials

Harwell has long been interested in reinforced plastic materials, starting with a small group concerned with glass fibre reinforced plastics. It was, in the 1960's, one of the laboratories working on the development of carbon fibres based on a process invented by the Royal Aircraft Establishment. Carbon fibres were developed originally with aerospace applications in mind, but many other possible industrial uses have since been identified. In the nuclear field they are being used in wear resistant bearings for water-circulating pumps in the DIDO and PLUTO reactors and they are of potential interest in the construction of high-speed centrifuges for uranium enrichment.

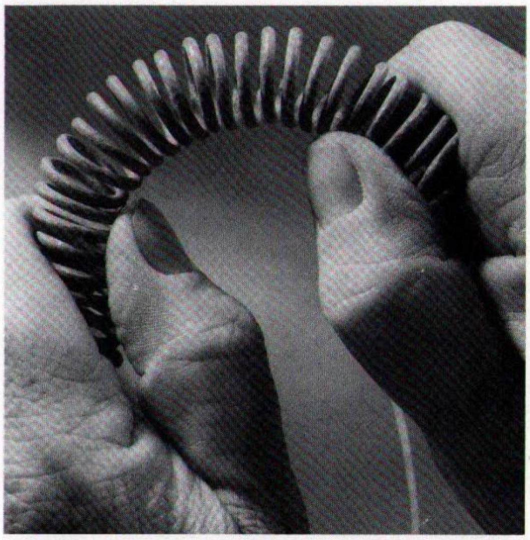


Figure 23

Fecralloy steel applications: furnace winding

Remains ductile after 1000 hours at 1000°C.

The properties of fibre reinforced composites depend on the direction and disposition of the fibres. The advantage is that fibres can be placed in appropriate directions to match the principal stresses and the present emphasis in the composites work is to develop techniques for the design and fabrication of components for specific engineering requirements. The main thrust is market-led, especially by the car industry, where emphasis on lightness and strength for fuel economy makes a substantial opening for fibre-reinforced materials.

In an investigation for the Commonwealth Secretariat, jute has been found promising as a reinforcing fibre, almost as stiff as glass and less than half the density. Markets for components made of jute-reinforced plastics are being explored in the aerospace and automotive industries. The successful introduction of jute into reinforced plastic components would result, not only in energy and cost savings, but in export opportunities for developing countries such as India and Bangladesh.

Metals and Chemical Technology

'Fecralloy' steels

A family of high-temperature, corrosion resistant steels, originally developed as fuel cladding materials for gas-cooled reactors is now registered under the trade name of 'Fecralloy'. These ferritic steels, containing chromium, aluminium and yttrium in proportions tailored to the application required, have exceptionally good oxidation resistance at temperatures up to 1200°C. Their further development as a new product for industrial use was funded by the Chemicals and Minerals Requirements Board (CMRB) and was undertaken in close collaboration with the steel industry. Messrs Firth Brown Ltd and Resistalloy Ltd., both of Sheffield are now licensed to produce the steels in quantity and new applications are still being explored with the Harwell team.

'Cenolite' is a Trade Mark of the UK Atomic Energy Authority

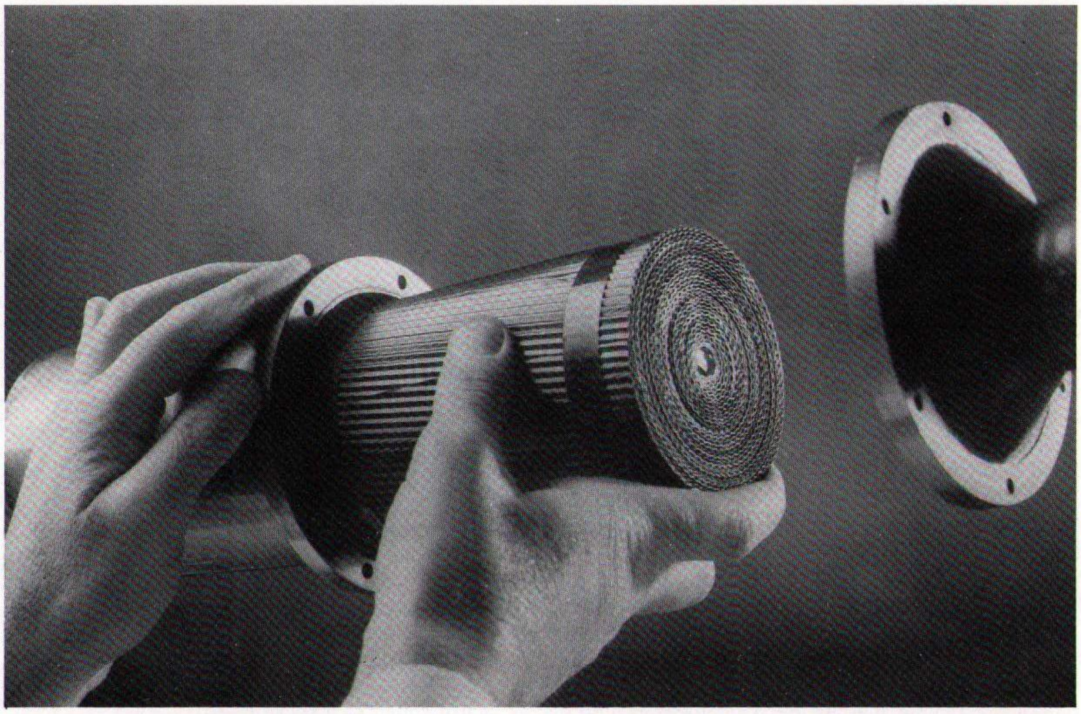


Figure 24

Fecralloy steel applications: thin, corrugated strip

Resists corrosion in exhaust control unit for motor cars.

Fecralloy steels can be cold drawn to fine diameter wire or rolled into thin strip. *Figs. 23, 24.* As electrical resistance wires or industrial furnace windings they can undergo more than 1000 hours at 1000°C without becoming brittle and have twice the working life of most conventional furnace windings. They are resistant to corrosive atmospheres, especially to automobile exhaust gases at high temperatures. Their tenacious surface layer of alumina forms a good bonding surface for the application of other layers, such as high temperature catalysts.

Car exhaust emission control

A combination of these last properties made Fecralloy steel a very effective support for the platinum catalysts developed by Johnson-Matthey Ltd., for control of car-exhaust pollution. *Fig. 24.* Thin, corrugated Fecralloy steel strip is coated with the catalyst using the gel process described above. Fitted to a motor car exhaust, the system converts the polluting exhaust gases to harmless carbon dioxide, nitrogen and water. A large market already exists in the USA and Japan.

Industrial catalysts

The use of sol-gel technology to make catalytic materials with controlled porosity and surface area is the basis of further catalyst development for the chemical industry, using Fecralloy steel as the support. Harwell's wide range of surface analytical techniques, some of them using the accelerators and other large capital facilities already available on site, makes it particularly well equipped to supplement the industry's own extensive research and development. A number of joint programmes are in progress. The Catalyst Unit, set up in 1978 with initial support by CMRB, is now concentrating on this market. Its work includes the development of a nickel catalyst for steam reforming, the development of a lead resistant catalyst for motor vehicles and of a high temperature catalyst for an HCN reactor at 1200°C.

Ion implantation

Another form of surface treatment, arising from researches into radiation damage, is the bombardment of materials with charged ions from accelerators. It was found that ions implanted just beneath the surface of a solid target in this way could change the surface properties in useful ways. An early project to explore the ion implantation of semi-conductors at controlled depths pioneered the method by which most of the world's semi-conductors are now made and helped to establish British Industry in this field.

Dramatic reductions in the wear of steel surfaces under friction have been demonstrated after implantation with a variety of ions at energies from 50 to 100keV. Typically an implantation with nitrogen ions at 50 Kilovolts reduces the wear rate of steel tools by factors between 10 and 100. The treatment is beginning to be used quite widely by users of drilling tools, moulding nozzles and wire-drawing dies to extend their useful life. The work is supported by the Engineering Materials Requirements Board and Hawker-Siddeley Dynamics Engineering Ltd. have now been licensed to build machines for the surface treatment market.

Research has also shown that suitable implantations can change the chemical properties of surfaces, notably their corrosion rate. Oxidation rates in zirconium can be increased or decreased by selective implantation; cerium implants in the niobium steel used as cladding in reactor fuel elements significantly reduces the spalling described in *Chapter 1,* so these investigations are of interest to the nuclear as well as the non-nuclear industries.

The vigorous exploratory work which these discoveries have stimulated is not, of course wholly empirical. In parallel with the development of applications, careful studies of the mechanisms by which implanted atoms can modify surface properties are being made, in collaboration with solid state laboratories in the UK and overseas.

Interface technology

The interaction of liquid metals with ceramics is an important aspect of the programme, both in the brazing of alloys to unmetallised ceramic surfaces and in extending knowledge of the behaviour of foundry moulds: this generic research is funded by the Engineering Materials Requirements Board. Meanwhile a specific investigation for Rolls-Royce on the casting of nickel-based alloys for turbine blades showed how surface preparation of the ceramic crucibles could reduce the reject rate five-fold.

A wide range of research into metallurgical structure and fracture mechanisms is undertaken, using the examination techniques which are summarised in *Fig. 29*. Characterisation of the microstructure of surfaces is playing a major part in a joint study of weld metal toughness with BOC Murex.

PROCESS TECHNOLOGY

The research and development services and advice which are offered on industrial process plant build on experience in designing processes and plant for the nuclear power programme. The Heat Transfer and Fluid Flow Service (HTFS) and the Separation Processes Service (SPS) are two of the main projects in this area. Both are supported by the Chemicals and Minerals Requirements Board (CMRB) and by industrial subscribers who help to select the general research programmes.

Heat Transfer and Fluid Flow Service

HTFS, was established in 1967 to provide design and research information on applied heat transfer and fluid flow. Within this broad field, its design activities embrace: furnaces, boilers and pipelines systems; condensers, cryogenic systems, refrigerators and air conditioning; heat exchangers and heat transfer equipment of all kinds.

The service is jointly operated by the UKAEA and the National Engineering Laboratory, with headquarters at Harwell. Its 170 subscribers range from quite small firms to some of the largest companies in the UK and abroad. In return for an annual fee, these sponsors are given detailed design reports on specific equipment and processes, supplemented with computer programs where manual calculation is impracticable, and a design handbook which summarises methods in all the important areas. They also receive an information service based on world-wide literature and regular reports on the research done. A consultancy service is available to subscribers and contract research is undertaken on a confidential basis.

The general research programme is supported mainly by the CMRB and includes research into the mechanisms of heat transfer and fluid flow, with particular reference to the design of industrial equipment and prediction of its performance. Results are reported directly to subscribers and presented annually in research symposia which are attended by sponsors and invited members of academic institutions.

One example of the experimental work is that on boiling in tubes. As a part of its industrial test facilities, HTFS has installed a full-scale thermosyphon reboiler of the type used as vapour generators by the chemical process and petroleum industries. The installation has 104 boiler tubes and is fully instrumented to measure pressure, vapour quality and production rate. Its performance was predicted from the results of detailed laboratory measurements using a single electrically heated tube and showed good agreement with experimental trials using water, cyclohexane and iso-propanol as operating fluids. The calculation methods thus proven are embodied in a computer programme "TREB" which is now widely used by industrial designers.

One of the major uncertainties in heat exchanger designs is the thermal and flow resistance caused by fouling deposits which form on heat transfer surfaces. A survey estimated the cost to UK industry to be about £400 million per year. A joint programme of research with the National Engineering Laboratory is investigating the origins and mechanisms of the fouling process. The work is funded by CMRB.

Separation Processes Service

Set up in 1974, the SPS is jointly operated by Harwell and the Warren Spring Laboratory. Its subscribers range from small to very large companies. The main aim of the project is to improve the expertise of member firms in the selection, design and use of separation process equipment. Technology transfer is thus central to its activities.

SPS is working in five main areas – crystallisation, drying, filtration, gas-cleaning and liquid-liquid extraction. Each technical area is supervised by a panel of industrial members. The research and development programme in all of these areas is designed to supplement and strengthen the technology transfer role. Drying processes are the largest area of research. A wide range of equipment is studied, including fluid bed, pneumatic conveying (flash), rotary, spouted bed and spray dryers. Basic engineering principles are being applied to develop design procedures in an area where the traditional approach is entirely empirical.

Through the co-operation of subscribers, very extensive use is made of installed industrial plant, both for testing equipment and for validating design information. In a recent project, SPS prepared a generalised computer program to assist in the design of spray dryers. Before specific programs were issued for general use, five member companies took copies to test on their own computers and in their own areas. The validation of the programs was greatly speeded and their value to SPS

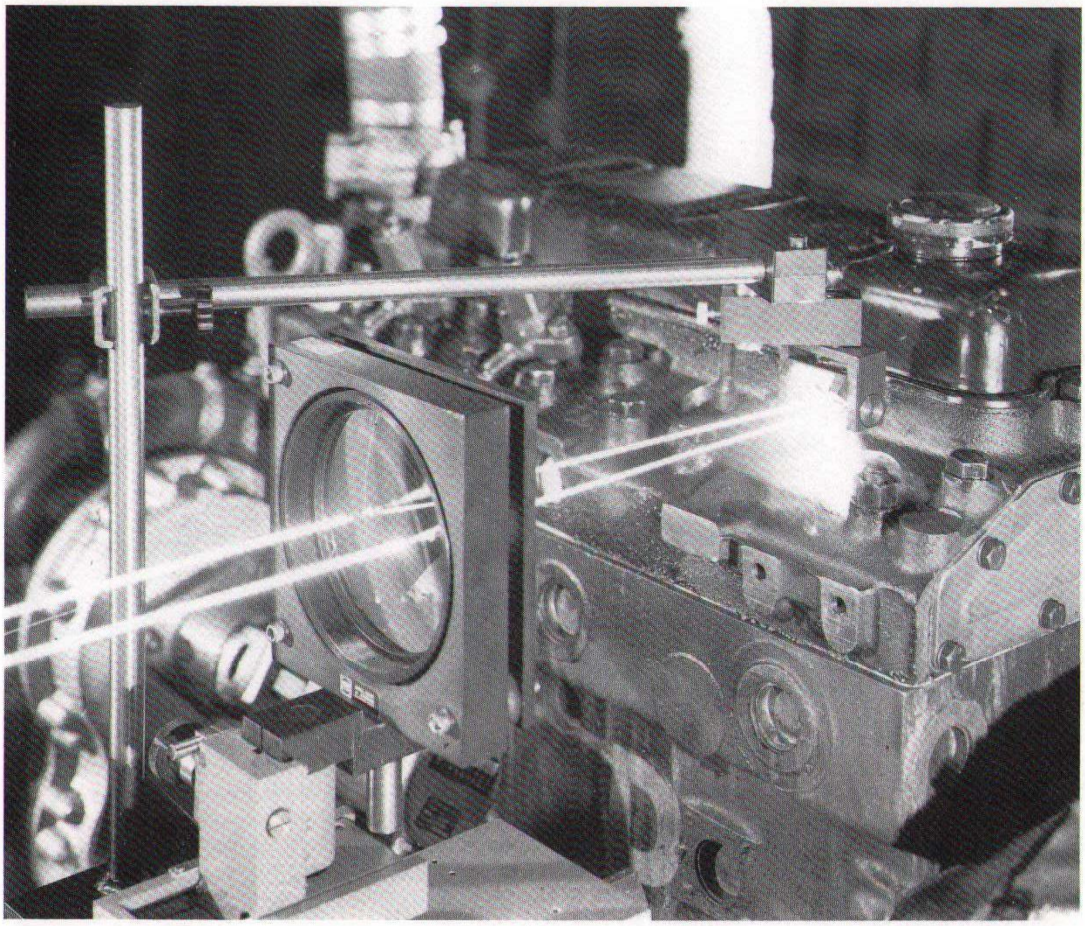


Figure 25

Laser anemometer used on a diesel engine

The laser beams are seen entering one cylinder of a Perkins high-swirl diesel engine via a focusing lens and an aiming mirror.

members considerably enhanced. This kind of close interaction with members is central to the SPS approach and the project could not succeed without the enthusiastic co-operation of its industrial participants.

Internal combustion engines

To improve efficiency in internal combustion engines and to reduce exhaust pollution, the designers need detailed information about the mixing and distribution of fuel and air in the cylinders of both diesel and petrol driven machines and the progress of combustion during the engine cycle. Since the cylinder is totally enclosed and any measuring devices placed in it can themselves disturb the combustion process, reliable practical measurements were difficult; designers had to work largely from empirical data and from theories of the mixing process. With this in mind, the Mechanical Engineering and Machine Tools Requirements Board (MEMTRB) at the end of 1976 sponsored the development of instruments for measuring the physical and chemical processes in commercial engines operating under normal test-bed conditions.

The laser anemometer, already being used by HTFS in furnace studies, was the first tool to be adapted for this purpose. Its use relies upon the fact that gases and liquids invariably contain small light-scattering particles whose movements follow those of the fluid. In operation the narrow, parallel beam of a laser is split into two components which are then focussed to cross at the point to be investigated.

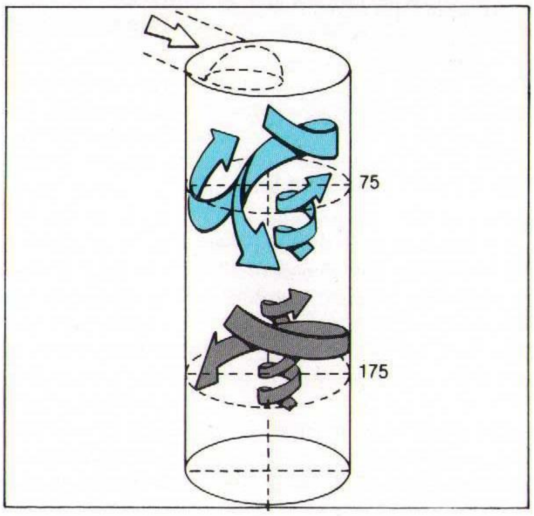


Figure 26

Air-flow in the cylinder of a diesel engine for two positions of the piston.

In the tiny volume (0.01 mm^3) illuminated by both beams, interference produces a fine pattern of light and dark regions. Any particle crossing this pattern is seen by a suitable detector as a fluctuating light signal whose frequency can be used to determine the direction and speed of the gas.

By adjusting the direction of the laser beams through a small window, measurements can be made throughout a combustion chamber or other parts of an engine without disturbing the conditions of operation. The resulting mass of data is computer-processed to give a complete picture of fuel and air motions at all stages of the engine cycle. In *Fig. 25* the anemometer is being used to make in-cylinder measurements on a Perkins high-swirl diesel engine. The result of some preliminary work, performed outside the engine *Fig. 26* illustrates the kind of airflow which has to be measured.

Laser techniques have achieved a breakthrough in flow pattern information for both diesel and petrol engines. Further developments are aimed at providing more sophisticated data to the designers. The laser anemometer is being extended to measure not only the velocities of fuel droplets, but also their size. Raman spectroscopy has been developed to provide localised measurements of temperature and of chemical composition inside working engines.

The I.C.E. project now receives substantial funding directly from the motor industry. Its forward programme is guided by an Advisory Committee of engineers from the manufacturers of internal combustion engines, together with MEMTRB, the original sponsor. Membership of the Committee's Diesel and Petrol Engine Working parties, on an annual subscription basis, confers the right to propose new types of work and forms a basis for co-operation in the development programme. Liaison is maintained with the National Engineering Laboratory, whose programme on fuel-air mixtures is also funded by MEMTRB.

Biochemical technology

A team of chemists, biochemists and chemical engineers is developing techniques for separating biological compounds on an industrial scale and processes for using them in the food and beverage industries as well as in the production of pharmaceuticals and medical products. The work is funded mainly by the Chemicals and Minerals Requirements Board (CMRB) and by industry, but some is supported by medical organisations.

One notable achievement is the development of a continuous electrophoresis system for separating a wide variety of biological materials. The high yields of biological activity obtained and the high throughputs possible (100 times more than the nearest equivalent system) represent a major advance. The Department of Health and Social Security has sponsored a development programme on fractionation of human plasma, from which can be obtained a number of clinically used fractions in very good yield (e.g. albumin, immunoglobulins and in particular anti-haemophilia factor (AHF). It is possible that the whole of the UK's needs for AHF could be met by a small number of separators. There is also a very large commercial market for human plasma fractions overseas, especially in the U.S.A.

By using the gel processes described above, inorganic powders have been fabricated into porous spheroids which can be penetrated by large organic molecules. Because of the relatively large surface area, physical rigidity, and chemical stability of these porous materials, large packed beds of them can be used for adsorption/separation processes at high flow rates with minimal back pressure. Thus, using 25 litre packed beds of porous titania particles it has been possible to recover functional protein from cheese whey (about 10,000 tons of protein suitable as human food could be separated from the two million tons of whey produced annually in the UK); to recover an enzyme suitable for use in the food industry in good yield from fruit juice and to purify virus vaccines. BDH Ltd. is now producing spheroidal calcium phosphate under licence for laboratory use and marketing it worldwide.

The team is also developing immobilised enzyme systems for food and pharmaceutical processing as well as for chemical conversions, on a production scale. A process for converting starch to glucose has been developed in collaboration with Tate and Lyle Ltd. who are now operating the process on a tonnage scale in a UK factory, and are actively seeking exploitation overseas. As an extension of the immobilised enzyme programme, the feasibility of using immobilised whole cells for the synthesis and transformation of high value chemicals is being examined under the sponsorship of CMRB.

INSPECTION AND ANALYSIS

An extensive range of facilities for non-destructive testing and for the physical and chemical examination of surfaces, established to promote safety and reliability in nuclear plant, are now applied more widely to problems of the non-nuclear industries.

Non-Destructive Testing

The focus of this service to industry is the Nondestructive Testing Centre, set up in 1967 to stimulate the use of NDT techniques in quality assurance. Supported by the Mechanical Engineering and Machine Tools Requirements Board (MEMTRB), the Centre is a national repository for information on all aspects of NDT, maintains an up-to-date computerised reference store of more than 25,000 publicatons and publishes regular information bulletins and handbooks. It keeps contact with commercial NDT firms and research organisations and refers clients to existing instruments or services whenever this is possible.

When testing problems are beyond the present capacity of the industry the Centre may undertake the work itself and contract research and consultancy accounts for the bulk of its present activities. It maintains a capability in a wide range of inspection techniques, especially in ultrasonic and acoustic methods and in X-ray, gamma-ray and neutron radiography: it is especially concerned with the quantitative evaluation of defects, so that their significance can be judged and failure anticipated before it occurs.

Typical of applied research projects was a requirement by Rolls-Royce Ltd. for inspecting blade and seal clearances in an operating aero-engine. Thermal expansion and operating stresses make these small clearances quite different from those in a stationary engine. Working closely with the Company's engineers, the Harwell team devised a dynamic radiography technique capable of revealing and monitoring these small clearances. *Fig. 27* shows a test engine installed in the Company's test facilities. The application of this technique has produced significant savings in the design costs of the Company's aero-engines and earned, both for Rolls-Royce and the NDT Centre, the Queen's Award for technological achievement in 1978.

British Rail had the problem of inspecting their track for signs of metal failure and devised a mobile test vehicle which records on a photographic film the details of an ultrasonic inspection of the rails, carried out while the vehicle is moving at up to 20 miles per hour. The film indicates both the nature and location of flaws in the rails but visual analysis of it is slow and laborious. In collaboration with British Rail, the NDT Centre has developed an electronics system incorporating micro-processors and a mini-computer, to process the ultrasonic signals from the rail as they are received. Significant information is recorded on a magnetic tape for subsequent evaluation with a computer and

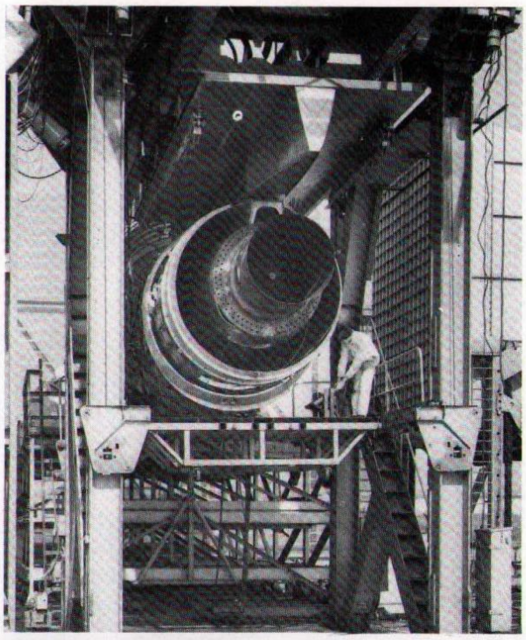


Figure 27

Dynamic radiography of RB211 aero engine

The picture shows a linear accelerator set up for dynamic radiography of the operating engine during a test programme at Rolls-Royce (1971) Ltd, Hucknall. The method was developed jointly by the Non-Destructive Testing Centre, Harwell and the Bristol Engine Division of Rolls-Royce (1971) Ltd.

By courtesy of Rolls-Royce (1971) Ltd.

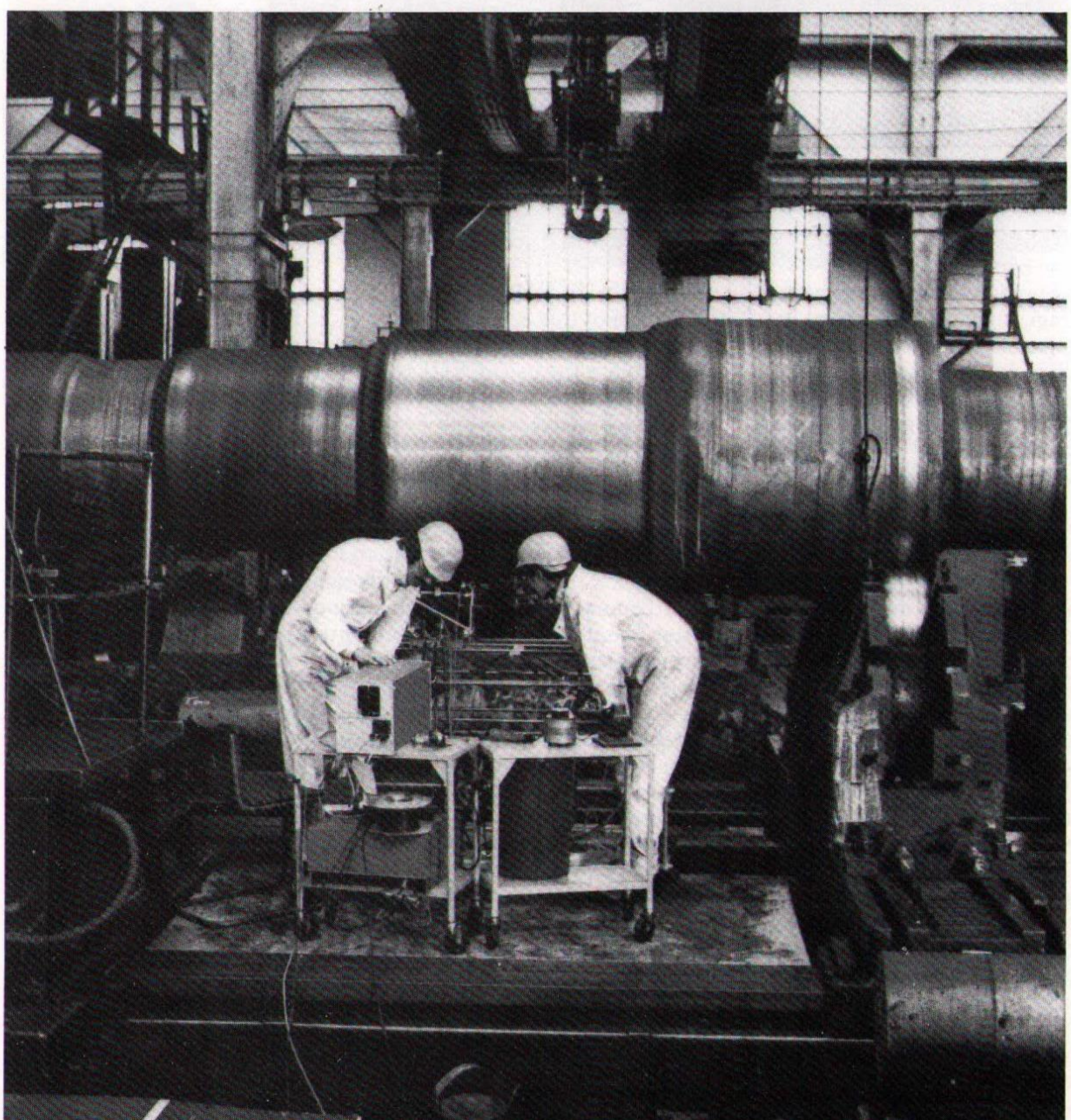


Figure 28

Ultrasonic holography of a turbine rotor casting

As carried out for the Central Electricity Generating Board.

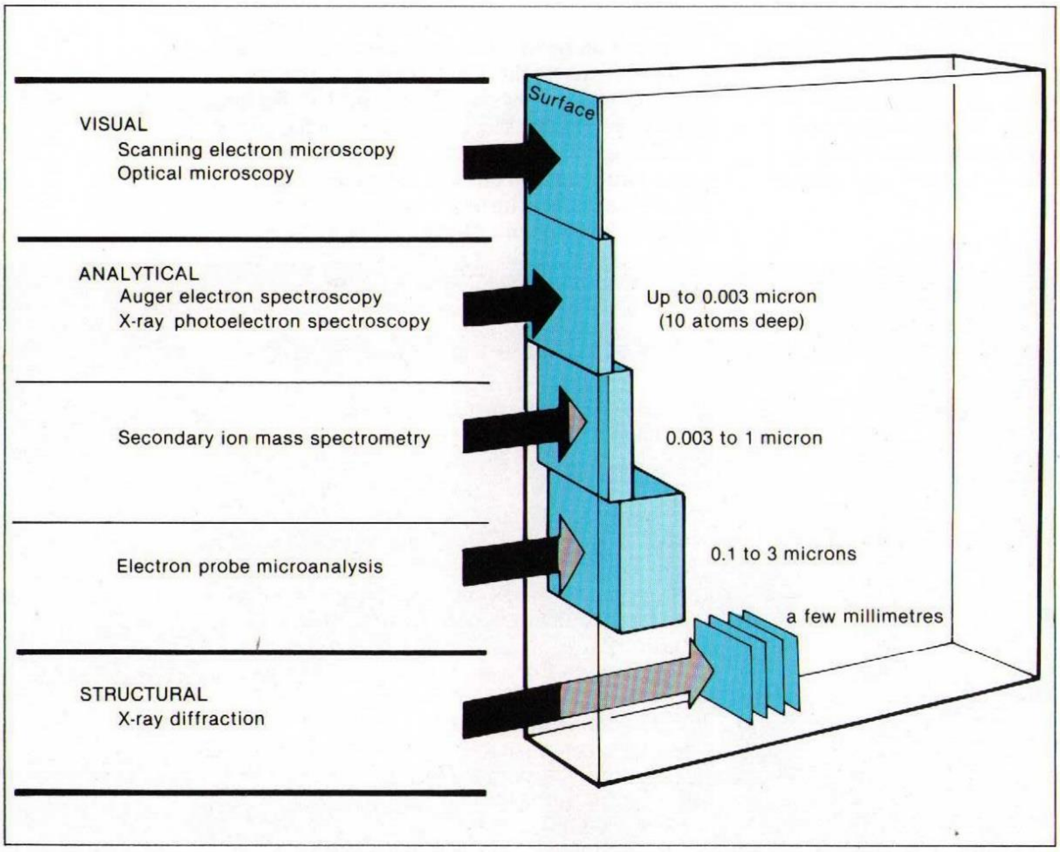


Figure 29

Surface and near-surface analytical techniques

The depth ranges indicated are those at which the various techniques are normally used. The micron unit is one thousandth of a millimetre. The smallest depths may be compared with the size of typical atoms and their spacing in metals (0.0003 micron in copper), so the first two analytical techniques are normally used for depths up to ten atomic layers from the surface.

visual display unit. Real-time information on certain critical rail conditions is also provided. The new system, now commissioned, avoids the need for human evaluation when the rails are faultless and by concentrating attention on any abnormalities, greatly speeds up the inspection process.

The MEMTRB funds a longer term programme to promote new NDT technology. This work includes the development of acoustic holography for visualising metal flaws in the depth of thick forgings, like the turbine rotor shown in *Fig. 28,* the analysis and interpretation of acoustic creaks emitted by distorting metal and the use of ultrasonic diffraction techniques to measure the size of localised defects.

Analytical services and instruments

The **Analytical Research and Development Unit (ARDU)** was set up in 1968 to undertake applied research on industrial analytical problems and to promote the use of modern instrumental methods in industrial analysis and process control. A strong capability in chemical analysis has always been essential to the nuclear programme and it is not surprising that a major part of the Unit's services are devoted to the nuclear power industry, especially the processing of nuclear fuels.

For non-nuclear industries, ARDU mainly develops instruments and techniques to meet specific requirements and uses existing resources and nuclear techniques to provide a broadly based analytical service, especially for trace elements. A recent specific task is a joint investigation, with the Metal Box Company, of the origins of lead contamination in canned foods and the development of instrumentation to detect its presence in can production. The Unit has devised techniques for monitoring atmospheric pollution by toxic and malodorous emissions from factory stacks, public waste disposal and car exhausts and has developed nuclear radiation instruments for a variety of inspection purposes.

The **Physico-Chemical Measurements Unit (PCMU)** is a separate analytical service supported by the Science Research Council to provide specialised measurements of organic chemicals for the Universities. In addition, materials for analysis are accepted from Industry and Government Establishments. The techniques available include infra-red spectroscopy, nuclear magnetic resonance and high resolution organic mass spectrometry.

Over its first ten years the PCMU analysed some 33,000 samples. Problems have ranged from the assessment of complex hydrocarbon mixtures derived from coal and oil, the quality control of polymers and the detection of fraudulent perfumes to matters of environmental concern such as the determination of toxic or carcinogenic residues in manufactured goods and in factory atmospheres.

A feature of Harwell's analytical programme is the wide range of facilities for examining solid surfaces. *Fig. 29* summarises the physical techniques deployed by the **Solid State Instruments Service** to analyse and characterise surface and near-surface layers of almost any metal, ceramic or plastic. Detailed analyses of composition and structure are made at depths from a few microns to within one atomic layer of the surface. Apart from making analyses in support of the nuclear power programme, the service has enabled some 250 industrial organisations to supplement their own research and development programmes and to resolve manufacturing and operational problems.

COMPUTER APPLICATIONS

Harwell computers

The increasing complexity of the demands for data and information in the nuclear programme alone has made the large computer an essential tool for carrying out mathematical tasks, manipulating information and modelling a wide range of natural and contrived phenomena. For more than 15 years, small computers have been an integral part of sophisticated experiments, controlling the equipment directly as well as collecting and processing the results.

The central computer, an IBM 3033, completes on average about 1900 batch jobs a day for over 1000 UKAEA and other registered users as well as providing an interactive computing service. It is supplemented by a number of smaller computers, most of which perform specialised local tasks but some of which are connected in a network to use the central facility when necessary. In addition some of the latter computers are part of a wider network and can interact with other computers throughout Europe and the USA to their mutual advantage. These wider interactions are being developed in a project funded by the Computer Systems and Electronics Requirements Board of the Department of Industry.

This overall computing capability, built up mainly to serve the nuclear power programme, has been diversified in a number of non-nuclear projects, of which the following are examples.

Modelling and optimisation

Computer progams are developed to model complex systems in commerce and industry. Optimisation techniques have been applied to such problems as the scheduling of fleets of ships or road vehicles and the design of district heating networks. The rapidly interactive fleet scheduling progam, reacting to up-to-the minute information on ship movements and conditions, saved the users millions of pounds by optimising the use of available tonnage.

The use of modelling techniques to visualise the behaviour of North Sea oil-fields is described in *Chapter 4*.

Information retrieval

World-wide growth in published information of all kinds during the last two decades has stimulated the growth of computer-based storage and retrieval systems. The STATUS system was originally developed to handle textual information for the UKAEA, but has proved to be adaptable to meet a variety of needs, from the management of technical information, through commercial applications and library management to the documentation of national and international codes of law.

Written in Fortran, the progam is currently available on ten different computer types. It is designed to combine ease of use with advanced retrieval techniques for the experienced user. It can also analyze and process the retrieved information through interfaces with other computer facilities.

On-line access, without the need for specialist computer experience provides rapid results from information searches. Privacy controls protect the security of confidential files and records.

The growing club of franchise holders licensed to market STATUS includes several software houses, computer bureaux and computer manufacturers. The system is in use in Government Departments and commercial organisations in Britain, Australia and the EEC.

The Energy Programme

4

Figure 30

Unmanned submersible, 'CONSUB 1'

An underwater rock-coring tool, built for the Institute of Geological Sciences by B.A.C. Ltd. (now part of British Aerospace), under MaTSU supervision. This submersible served as a prototype for the development of underwater engineering versions. Its design and construction were partly funded by the Ship and Marine Technology Requirements Board.

Quite apart from the nuclear energy programme, Harwell is deeply concerned with the total energy resources of the UK. A significant part of this work is in direct support of Government Departments in planning, assessing and organising balanced research and development programmes. Two Support Units provide these services in the areas of offshore oil and gas and of renewable energy sources and conservation.

GOVERNMENT SUPPORT UNITS

Marine technology

The **Marine Technology Support Unit (MaTSU)** was set up in 1968 by the Ministry of Technology to formulate a government sponsored programme of research and development in the technologies needed to exploit the UK continental shelf. The work itself was largely carried out by industrial contractors and government laboratories. It included such activities as the development of a hydrographic sonar system, the design and development of submersible vehicles for underwater working *Fig. 30* and the investigation of wave loading on marine structures.

By the early 1970's MaTSU was helping the Department of Trade and Industry by technically supervising much of the contract research programme and came to be regarded as an extension of the Department itself. Early in 1974 the Unit was invited by the Department to review the strategy of the newly-formed Ship and Marine Technology Requirements Board. It recommended that at least half the Board's resources should be committed to developing technology for offshore oil and gas.

In the following year the Department of Energy assumed responsibility for this part of the marine programme and made MaTSU its executive arm for technical and financial control of research and development contracts – a new and demanding role for the technical staff. MaTSU Project Officers now interact closely with the Offshore Supplies Office and the Petroleum Engineering Division of the Department of Energy in stimulating and controlling a research and development programme valued at some £10 million a year. Programmes initiated by MaTSU and now controlled by its Project Officers include the UK Offshore Steels Research Programme – a major investigation of fatigue and corrosion of structural steels in seawater – which combined the efforts of the National Engineering Laboratory, the Welding Institute, Harwell and several universities and industrial firms over six years and has had a strong influence on the design and planned maintenance of offshore platforms at the oilfields. Other examples of the programme include a similar investigation of concrete in the oceans jointly undertaken by industrial companies; the development of a variety of underwater welding techniques *Fig. 31* and the protection of divers from electrical hazards underwater.

Similar activities on a smaller scale serve the continuing Ship and Marine interests of the Department of Industry; in projects of mutual concern, like the marine environment programme *for example Fig. 32* MATSU serves both Departments as an intermediary. The Unit has about 30 technical staff, supported by administrators.

Energy technology

When the **Energy Technology Support Unit (ETSU)** was established in 1974 by the Department of Energy, its first task, like that of MaTSU, was technological assessment and planning. From a background of conventional fuel resources and possible future energy scenarios, ETSU set out to appraise the potential of renewable energy sources and a short list was selected on which further research and development was recommended. The proposals were adopted by the Department; they comprised wind and wave energy, tidal, solar and geothermal energy. Management of the resulting programmes in these areas is now one of ETSU's major tasks.

With a technical staff of about 50, plus administrators, ETSU also provides a focus for the overall strategic planning of energy R&D for the Department's Chief Scientist and for the Advisory Council on Research and Development of Fuel and Power (ACORD). Strategic studies are based on energy scenarios for the next 25 to 50 years. The aim is to provide future Governments with alternative options when supplies of the conventional fuels begin to fail and to lay a sound basis for commercialising any new sources of energy which can be shown to be cost effective.

RENEWABLE ENERGY SOURCES AND ENERGY CONSERVATION

The following account is a brief indication of the programmes administered by ETSU. Only a small part of the research and development itself is done at Harwell.

Wind and wave energy

Both horizontal and vertical-axis aerogenerators are examined in the current programme and one of the present aims is to gain practical experience of building and operating a large aerogenerator coupled to the electricity grid. Industrial contractors have completed the detailed design of a 3.7 megawatts horizontal-axis machine and construction is under consideration by the Department of Energy.

Sea waves draw their energy from the wind too. Wind energy over a very large area is conveniently concentrated in advancing wave-fronts, particularly in areas west of the Hebrides, with a two thousand mile 'fetch' for prevailing winds from the Atlantic Ocean. Several alternative methods of electricity generation from ocean waves have been proposed by universities and engineering establishments and small-scale models are being tested and examined for cost-effectiveness.

The interest in wave energy is international

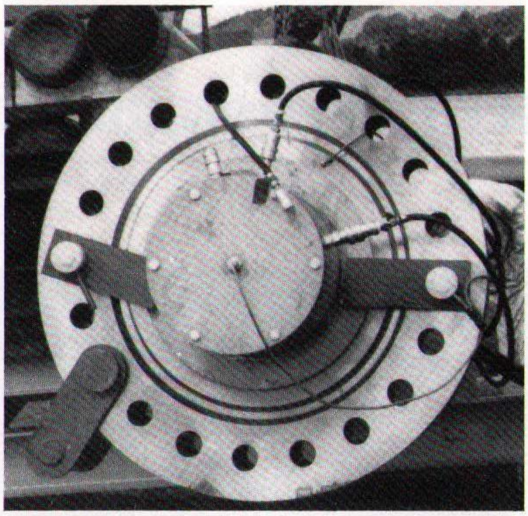


Figure 31

Explosive welding

Pipeline flange prepared for underwater welding. The welding charge assembly is seen projecting from the central bore of the pipeline. The method was developed by Vickers Offshore Developments Ltd, supported by the Department of Energy and supervised by MaTSU. It is now being applied by British Underwater Pipeline Engineering Ltd.

and ETSU is providing the UK lead in a joint programme of sea-going trials organised by the International Energy Agency. British firms have already built one of the trial installations, which is being tested in the Sea of Japan.

Tidal energy

Tidal power systems use the head of water raised at high tide over the level at low tide to drive generating machinery. Their efficiency thus depends on an adqequate tidal range where a large body of water can be dammed at high tide. Tidal power stations have been proven technically on a small scale at la Rance barrage near St Malo in France. The Severn estuary is the most favoured location in Britain, and the Department is advised by the Severn Barrage Committee, whose Working Party on Tidal Power analyses and progresses the necessary research and development. ETSU provides the secretariat for this Working Party and with the programme consultants, Binnie and Partners, has co-ordinated the strategic and engineering analyses and data collection.

Solar energy and biological fuels

The sun is the ultimate source of nearly all our conventional energy, including combustible fuels and water power, and sunshine is already used directly in warmer latitudes for heating water and for space heating in buildings. Even in Britain some commercial systems are already available and ETSU is co-ordinating field trials in a variety of houses, flats and institutional buildings to monitor and understand the performance of solar heating systems under real-life conditions. A particular aim of the present programme is to bring down the cost.

A further renewable source of solar energy is that stored in plant materials which can be recovered as fuel. ETSU is initiating trials on the combustion of refuse and organic wastes and is collaborating with the Waste Research Unit in an experimental study of methane gas production on a landfill site in Bedfordshire *Chapter 2*.

Geothermal energy

The Earth's crust is a very good heat insulator. Vast quantities of heat, generated in the crust

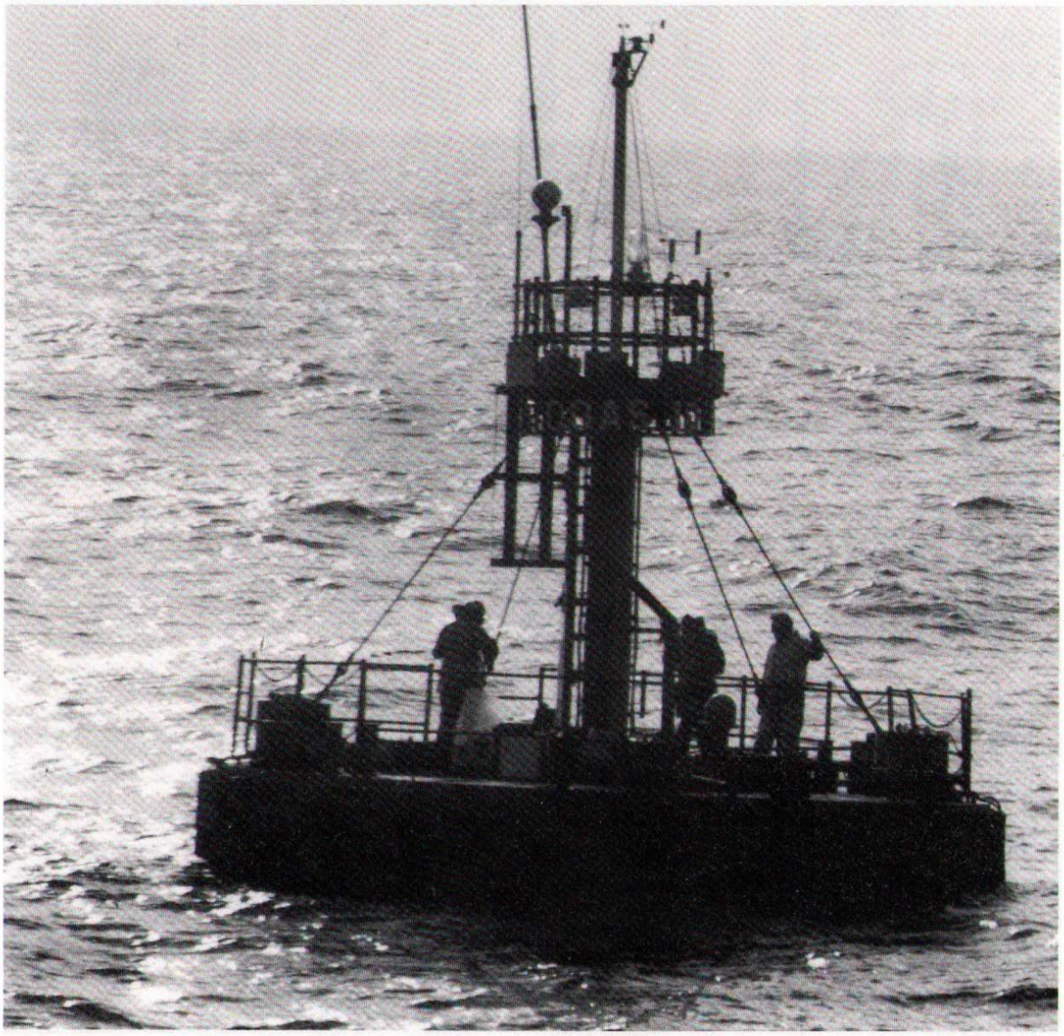


Figure 32

Britain's first national ocean data buoy

On station in the south-west approaches. The buoy is shown during a routine maintenance; normally it is unmanned and transmits atmospheric and oceanographic data by radio to a shore station.

and the interior by radioactive decay, seep out over a time-scale of a thousand million years. In some locations, notably in Iceland, natural water circulating through hot rocks emerges at the surface as geysers and hot springs which can be used for district heating and other practical purposes. Britain is not greatly endowed with hot springs, but the ETSU programme aims to identify the locations most favourable to the practical use of geothermal energy and to explore other possible ways of recovering it. The first exploratory borehole, drilled near Southampton, found water at 70°C in permeable rock at a depth of 1660 metres. Plans to demonstrate its practical use are in hand.

The prospects of extracting heat from deep-lying hot granite show considerable promise. A major project in Cornwall aims to do this by fracturing the rock and circulating water through it to the ground surface. The method is intended ultimately for generating electricity.

Energy conservation

A vital part of the Government's energy policy is energy conservation. With a few exceptions like solar energy, the supply of energy is centralised and controllable by Government and by public utilities. In contrast, the conservation of energy depends on millions of consumers for success, from the managers and workers in energy intensive industries and the designers of buildings to individual householders and drivers of cars and lorries. The full implementation of energy saving methods based on known technology could reduce current UK energy consumption by up to 30%, equivalent to 100 million tons of coal a year. Estimates of future demand presented by the Department of Energy allow for savings of over 23% by the end of the century through the introduction of conservation measures. Several Government Departments are actively concerned with promoting energy conservation, notably the Departments of Energy, Industry and Environment.

ETSU's part in these efforts is to assist the Department of Energy in planning and managing the necessary research, development and demonstration. The work includes assessment of ways to reduce fuel consumption in motor vehicles (in collaboration with the Department of Industry), to save energy in houses (in collaboration with the Department of Environment) and especially to improve energy utilisation in industry (in collaboration with the National Engineering Laboratory – NEL). These three sectors at present account for 20, 30 and 40 per cent respectively of the national fuel consumption. Previous experience of working

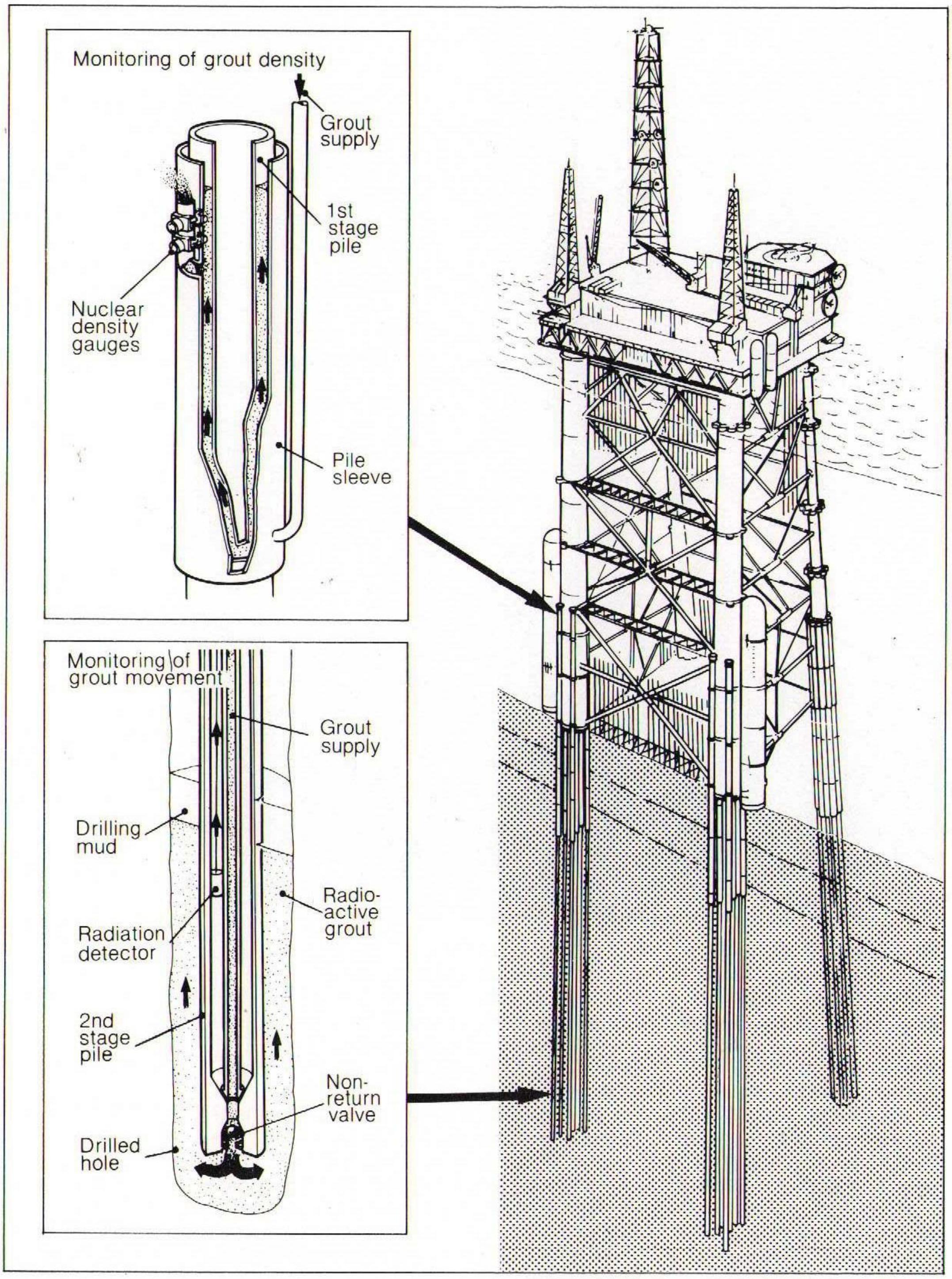


Figure 33

'THISTLE' oil production platform

The oilfield is located 130 miles north-east of the Shetland Islands. Insets show uses of nuclear techniques to monitor the grouting of piles.

with industry on commercial research and development has been valuable in these activities.

To use already existing technologies, like waste heat recovery for improving industrial energy efficiency, current emphasis is on the Government's Energy Conservation Demonstration Project for which £20 million was allocated. Working closely with the NEL team, ETSU staff prepare cases for demonstrations, organise independent monitoring, manage the implementation and promote the results in relevant markets to stimulate widespread investment. Some projects are already operational. For example an electrically heated forehearth in a glass furnace has more than halved the primary energy consumption. Of the 260 similar furnaces in the UK, it is hoped that about 80 may be changed as a result of the demonstration, thus saving 15,000 tons coal equivalent per annum. Most of the capital cost of demonstration projects is met by Industry itself. During the first year, the total investment was £8 million of which the Government contributed £2 million. The national energy saving target for these projects alone is one and a half million tons coal equivalent per year.

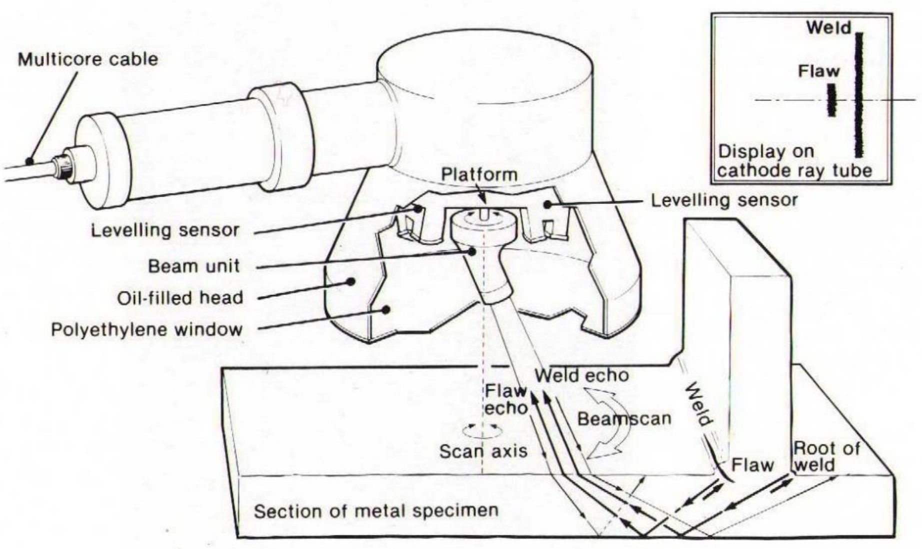


Figure 34

Ultrasonic torch

For underwater inspection of offshore structures. The instrument is shown here with a simple cracked, welded specimen. The beam unit operates from a self-righting platform mounted on gimbals and the scan axis is automatically kept perpendicular to the face of the specimen by the action of the levelling sensors. At the other end of the cable, a cathode ray tube display follows the beam as it scans around the axis and features of the specimen are distinguished by their echo delay times.

HARWELL MARINE AND ENERGY RESEARCH

Marine research and development

Harwell is about as far from the sea as one can be in the UK, but awareness of marine problems grew partly as a result of MaTSU activities and partly through direct industrial contracts. The NDT Centre, the Corrosion Service and others became involved in research for the growing offshore oil and gas industry and later in government programmes. To ensure that MaTSU's advice to government Departments remained unbiased by commercial interests, these activities grew up quite separately in the laboratories and are now co-ordinated in the Marine programme.

Although some of the work is related to shipping, a majority is concerned with offshore oil technology.

Offshore structures

Some of the work is in the harsh environment of the North Sea itself. The steel lattice supporting tower for the oil production platform of the 'Thistle' oilfield *Fig. 33*, cemented into the seabed under 160 metres of water, is typical of some of the offshore structures now being installed. The final grouting of the 'Thistle A' structure into position during Easter 1977 was monitored by a Harwell team who had worked on it throughout the winter. Radioisotope tracers were mixed with the cement slurry so that detectors, lowered inside a pile, could follow progress of the grout up the outside of the pile from its base 150 metres beneath the seabed. Gamma ray density gauges were also used to indicate the arrival time of the grout at the top of the pile sleeve and to measure its density there. These gauges were specially designed and built for the purpose and were installed during construction of the platform jacket on land; they had to withstand the rigours of a 500-mile sea journey and subsequent vibrations from the large hammer whilst the piles were being driven. Such was the success of the exercise that radioisotope methods of grout monitoring have been adopted by several oil companies in further installations. The technology has now been licensed to Wimpey Laboratories Ltd. for world-wide exploitation as a commercial service; the original team is likely to be involved in a consultative capacity for at least the next five years.

There are already 100 offshore steel structures in British waters. As their number and size increases, so does the problem of inspecting these huge and complex structures underwater. Methods suitable for underwater inspection are being developed to reduce the need for human intervention. One step in this direction was the development of an ultrasonic torch *Fig. 34* held by the diver, which presents a visual map of flaws in a structural node joint to inspectors above the sea surface, revealing cracks which would be invisible to the diver himself. The instrument, sponsored by the Department of Energy, is now being further developed for commercial exploitation by a licensee.

Oilfield appraisal

Seismic surveys of geological structures based on the measurement of sound pulse echo patterns have long been established for exploring and assessing potential oil and gas formations. The method has been greatly refined by the oil industry during the last decade, but the interpretation of results to recognise formations likely to contain oil and gas is a highly skilled job sometimes involving personal judgement. Harwell's contribution to this technology has been the development of computer techniques for analysing seismic data and for testing the validity of a model of the reservoir structure by comparing synthetic responses with those actually obtained in a seismic survey. These techniques have been used to improve the delineation of a number of oil and gas fields for the Department of Energy.

Mathematical modelling techniques have also been developed jointly with AEE Winfrith for simulating and predicting the behaviour of oil-fields, in support of the Department's oil depletion policies. Computerised models of North Sea reservoirs are constructed, incorporating all available data in order to predict their behaviour under alternative operating conditions. Colour graphics techniques are used to visualise the movements of oil, gas and water inside the reservoir. Harwell's programme, jointly sponsored by the Department, the British Gas Corporation and the British National Oil Corporation, specialises in the development of mathematical techniques for reservoir simulation. Winfrith concentrates mainly on developing individual models for specific fields and on their use for evaluating enhanced oil recovery techniques.

Energy research and development

Several parts of the Industrial Programme described in the last chapter are very relevant to the conservation of energy. Most of the activities of the Heat Transfer and Fluid Flow Service are directed to more efficient and economical uses of heat energy and this project is now administered as part of the Energy Programme. The Separation Processes Service too is largely concerned with energy economy and the development of improved catalysts can reduce energy consumption in industrial chemical processes. Heat insulating materials developed by the Ceramics Centre are aimed at fuel savings in houses and factories. The Internal Combustion Engine project will undoubtedly contribute to the design of more efficient vehicles. In the following two examples, energy storage and energy conservation are the main concern.

Electrochemistry and battery research

The Applied Electrochemistry project has developed from earlier work on electroplating and advanced batteries. While much of the project is still on batteries, its interests also include electrosythetic processes and the development and adaptation of electrochemical polishing and machining. Work for the chemical industry is aimed at developing a range of specific oxidation and reduction processes with improved energy economy and many provide the technical basis for a UK electrochemical plant manufacturing industry.

Work on the sodium/sulphur battery began in 1971 in collaboration with Chloride Silent Power Limited, British Rail and the Electricity Council. This major undertaking was highly successful and Chloride Silent Power is now largely responsible for its further development. At present Harwell's largest single battery project is for Lucas Research Centre on nickel/zinc batteries for electric vehicle traction. In this connection a development facility has been built at Harwell to produce nickel oxide electrodes.

A forward-looking Anglo/Danish programme on battery materials involves us with three UK universities and three Danish institutions. The programme is funded jointly by the EEC, the Department of Industry and the Science Research Council. A separate study of battery applications for electrical energy storage and traction within the EEC was published jointly with Odense University.

Aerial infra-red surveys

Infra-red imagery from the air can be used to locate and measure radiant heat emitted from the ground. *Fig. 35* has already been used as a guide to energy conservation at Harwell. It is one of several surveys organised in 1978 to establish the value of 'aerial thermography' for locating roof losses of heat from buildings. As a result of the work, Clyde Surveys Ltd. are now organising surveys on a commercial basis, especially over industrial areas, to show where savings could be made by better heat insulation.

With support from the Department of Energy, the method is now being refined, using digitised survey data, in an attempt to quantify heat losses from specific buildings. The aim is to enable energy managers to compare the cost of improving insulation with the savings likely to be achieved.

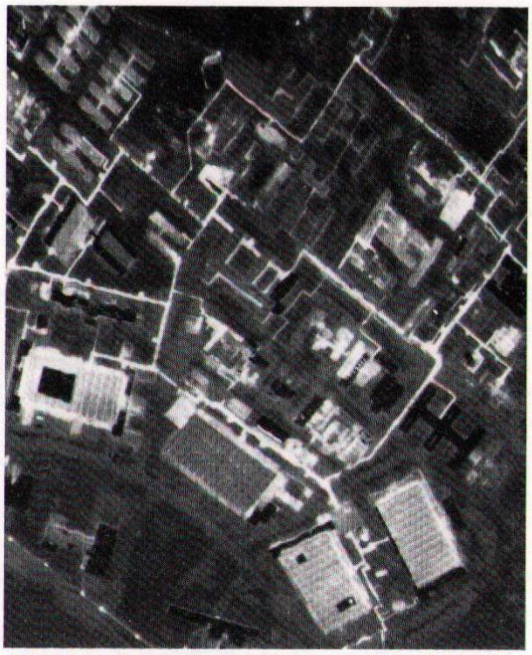


Figure 35

Aerial infra-red survey

Thermograph of part of the Harwell site taken from the air at night. Lighter areas indicate heat losses and can be examined in greater detail from the digitised record. In this picture, the losses from underground steam pipes, used for heating buildings, are especially noticeable.

Site Services

TECHNICAL SERVICES

Most of the Divisions at Harwell provide technical services to the Laboratory as a whole in parallel with the research and development projects they undertake. Examples have been quoted of the engineering design and development *Chapters 1, 3,* the instruments development *Chapters 1, 2, 3,* the physical and chemical analytical services *Chapters 2, 3* and the computer services *Chapters 3, 4* to the site. The matrix system of management *Appendix 2* facilitates this interaction between different disciplines in the Laboratory, often at short notice.

GENERAL SERVICES

Central services are listed with the central administration units in *Appendix 2.* Two of these are worth special reference:—

Library and information

The Library provides the main access for staff to world scientific literature and is supplemented by small Divisional Libraries of books and periodicals in frequent use. The Reading Room contains some 30,000 books and 40,000 volumes of periodicals, of which about 1500 current titles are taken. Over 250,000 reports are held, including those of most atomic energy projects throughout the world; subject to security classification, the staff has access to these and to over 300,000 microcards and microfiches. The library meets over 80% of requests for documents from its own stock and has ready access to the British Library Lending Division and other libraries.

The Information Office publishes a weekly Information Bulletin which lists selected articles from journals, conference proceedings and new books and pamphlets of immediate interest. Selected patents are listed in a supplement. Personal notifications on individual interests are also provided, including a computer based service from magnetic tapes supplied by the International Nuclear Information System (INIS) for which the Information Office provides the UK input.

Specific enquiries for scientific and technical information, including literature searches, are handled on request. Over 100 data-bases can be searched interactively on-line from a terminal in the Information Office. Appropriate enquiries are referred to specialised information systems, several of which are mentioned in *Chapter 3.*

A small Market Intelligence section (5 graduates) undertakes studies of markets and industries on behalf of commercial projects.

Education and training

The Education and Training Centre is responsible for organising most of the formal on-site training of staff and provides facilities for other UKAEA personnel to attend courses as required. Close contact is maintained with the Chemical and Allied Products Industry Training Board. Courses are also arranged for students from elsewhere to be trained for a realistic fee in subjects where the Authority has special expertise.

Course durations are from half a day to four weeks, averaging about three days. In a typical year about 200 courses of 100 different types are organised for some 4000 students, of whom 2700 are from Harwell, 500 from other UKAEA Establishments, 700 from elsewhere in Britain and 100 from overseas.

Most of the courses are on scientific and technical subjects, on various aspects of management or on health and safety. Many of them offer practical experience as well as lectures and discussion. About half the lectures are given by Harwell and other Authority staff and half by visiting lecturers.

Longer-term training is provided for school leavers in the Apprentice Training Scheme of four years duration and the Laboratory Trainee Scheme which lasts for two years. There is also special initial training for Assistant Scientific Officers, followed by short courses at intervals during their first two years. All of these longer-term training schemes are supplemented by part-time attendance at local colleges of further education.

The Education and Training Branch is well equipped to organise conferences and symposia for scientific interchanges between UKAEA staff and those from similar establishments in Britain and overseas. Fifteen to twenty such conferences are arranged every year, usually with international participation.

Management

Harwell Directorate

Director	Dr L E J Roberts CBE
Deputy Director	Mr F W Fenning
Research Directors:	
Energy	Dr F J P Clarke
Environment	Dr W M Lomer
Industry	Dr G G E Low
Nuclear Power and Underlying Projects	Dr J Williams
Chief Engineer	Mr J P Byrne
Commercial Director	Dr R G Sowden
General Secretary	Mr M A W Baker

The Harwell Board of Management consists of all members of the Directorate and in addition:—

Principal Officer Commercial Policy and External Relations, UKAEA London	Mr F Chadwick
Director Engineering, NPDE, Risley	Mr R F Jackson
Authority Fuel Processing Director, Harwell	Mr K D B Johnson

Its Chairman is the Director, AERE Harwell and its secretary the head of Scientific Administration Division, Mr R M Fishenden.

Line management

The use of resources is controlled by line management through Division Heads who report to the Director.

Divisions are established mainly on the basis of disciplines. The scientific and engineering divisions and their main technical groups are listed below, together with the administrative central units which provide services to the site as a whole.

Table 3. Central Departments

Finance and Accounts
Head: Mr D J Crabb
Contracts and Stores
Finance and Accounts

Marketing and Sales
Head: Dr R G Sowden
Central Sales
Commercial Office
Future Developments
Patents
Public Relations

Personnel and Administration
Head: Mr L L Martin
Education and Training
General Services
Housing and Accommodation
Personnel
Security and Emergency Services

Programmes and Planning

R and D Revenue Control
Head: Mr J T Wright
Agreements
Sales Secretariat

Scientific Administration
Head: Mr R M Fishenden
Information
Library
Market Intelligence
Overseas Relations
Photography
Publications
Safety Secretariat

Table 4. Research Divisions

Chemical Technology
Head: Dr R H Flowers
Gel Processes
Industrial Chemistry
Liquid Process Technology
Material Processing
Reactor Chemistry
Separation Processes (Nuclear)

Chemistry
Head: Dr C B Amphlett
Actinide Analysis
Actinide Chemistry
Actinide, high temperature and superconducting materials
Radiation and Surface Chemistry
Special Processing
Variable Energy Cyclotron

Computer Science and Systems
Head: Dr A E Taylor
Central Computer
Information Systems
Language Development
Mathematics

Networks
Operations Research
Real-time Systems
Systems Support

Energy Technology (ETSU)

Head: Dr J K Dawson

Energy Conservation
R&D Strategy and Strategic Studies
Solar, Geothermal and Synthetic Fuels
Wave Power
Wind and Tidal Energy

Engineering Design and Manufacture

Head: Mr D B Halliday

Design
Quality Engineering
Workshop
Work study

Engineering Projects

Head: Mr S L Nayler

Active Facilities
Direct Support to Divisions
Project and Development Engineering

Engineering Sciences

Head: Dr G F Hewitt

Biochemical Technology
Chemical Reaction Engineering
Design and Manufacturing
Heat Transfer and Cryogenics
Separation Processes
Thermodynamics and Fluid Dynamics
Transfer Processes

Environmental and Medical Sciences

Head: Mr N G Stewart, O.B.E.

Aerosols
Atmospheric Pollution
Environmental Safety
Inhalation Toxicology and Bioanalytical Chemistry
Materials Analysis
Medical Services
Nuclear Environment
Physico-Chemical Measurement
Radiation Physics and Radiobiology

Instrumentation & Applied Physics

Head: Mr E H Cooke-Yarborough

Advanced Electronics
Analogue Circuits & Signal Processing
CAMAC Instrumentation and Systems
Detection and Analysis
Environmental & Radiological Instruments
Lab. Instrumentation & Systems R&D
Microprocessor Technology
NDT Systems Development
Post Design Services
Ultrasonics and Sonar

Marine and Engineering Services

Head: Dr P Iredale

Engineering Services
New Works
Offshore Supplies and Engineering (MaTSU)
Petrolium Engineering (MaTSU)
Ship and Marine Technology (MaTSU)

Materials Development

Head: Dr D Pooley

Advanced Engineering Materials
Ceramic Development and Design
Chemical Metallurgy
Coatings
Composites
Defects in Solids
Electrical Materials
Electrochemistry (Basic & Applied)
High Temperature Technology
Interface Technology
Ion and Electron Beam Technology
Mass Transport and Diffusion
Solid State Instruments

Materials Physics

Head: Dr V S Crocker

Applied Optics and Acoustics
Computing and Reactor Physics
Image Analysis
Neutron Beam Applications
Neutron Beam Instrumentation
Neutron Diffraction
Neutron Physics
Neutron Scattering
Non Destructive Testing
Physical Engineering
Special Technology

Metallurgy

Head: Mr S F Pugh

Advanced Fuels and Graphite Physics
Composite Materials
Fabrication Technology
Fast Reactor Fuels
Fracture Studies
High Voltage Electron Microscope
Radiation Effects
Structural Materials

Nuclear Physics

Head: Dr J E Lynn

Electron Linear Accelerator
Geophysical Tracers
High Voltage Laboratories
Industrial Physics
Ion-Crystal Interaction
Mossbauer
Neutron and Fission Physics

Research Reactors

Head: Mr K J Henry

Design Services
Reactor Services
Work Study and Other Investigations

Theoretical Physics

Head: Dr A B Lidiard

Neutron and Liquid Physics
Nuclear, Atomic and Molecular Physics
Radiation Damage
Theory of Solid State Materials

Functional management: The matrix system

Several of the groups listed correspond with the names of projects reviewed in the body of this report; in these cases the project is mainly concentrated in a single Division. However, a large part of the work requires interdivisional and interdisciplinary co-operation, often in quite small jobs. To achieve this, a functional programme-management system crosses the line management structure as shown in *Fig. 36*. Each programme area, described in the separate chapters above, is under control of a Research Director, to whom Project Managers report.

The Project Managers are responsible for the technical and financial effectiveness of specific parts of the programme. In particular they:—

- plan the project and its objectives,
- obtain the necessary programme approvals,
- match these approvals to resources, as agreed with line management,
- monitor technical and financial progress and ensure that objectives are met.

Project Managers are often Group Leaders within the line management structure and in some cases Division Heads. In sponsored activities, the Project Manager is the immediate contact with the customer and must negotiate with line management to secure the necessary man-power. The co-operation of line management is assured by the need to maintain adequate financial resources through effective deployment of the staff on authorised projects.

Underlying Research is in a special position in that it is placed directly under the control of Division Heads. Besides providing some flexibility in staffing, this enables the Division Head to maintain capabilities at a high standard in each discipline and to arrange for relevant new ideas to be explored.

Staff Deployment and Funding

The total staff numbers about 4300, of whom some 1200 are professional grades – 850 scientists and 350 engineers. *Table 5* shows the allocation of professionals (Category A) between the programme areas of the foregoing chapters.

In the year 1979-80, the gross expenditure was £58.4 million (Sept 1979 values), of which £33.7 million (i.e. 57.6%) was earned in receipts, leaving £24.7 million as the net cost of the Establishment to the UKAEA. *Fig. 37* shows the earnings from research and development, which represent most of this revenue, in the five years from 1975 to 1980.

Programme Areas	Professional Staff
Nuclear power programme	385
Underlying research	215
Plasma and fusion	20
Nuclear research on repayment	160
Environmental programme	90
Industrial programme	180
Energy programme	150

Table 5. Staff Distribution (1980)

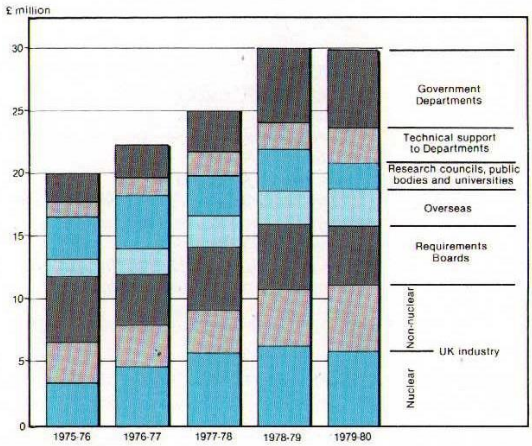


Figure 37

Research and Development Receipts 1975-80

Annual receipts are corrected for inflation to money values of September 1979.

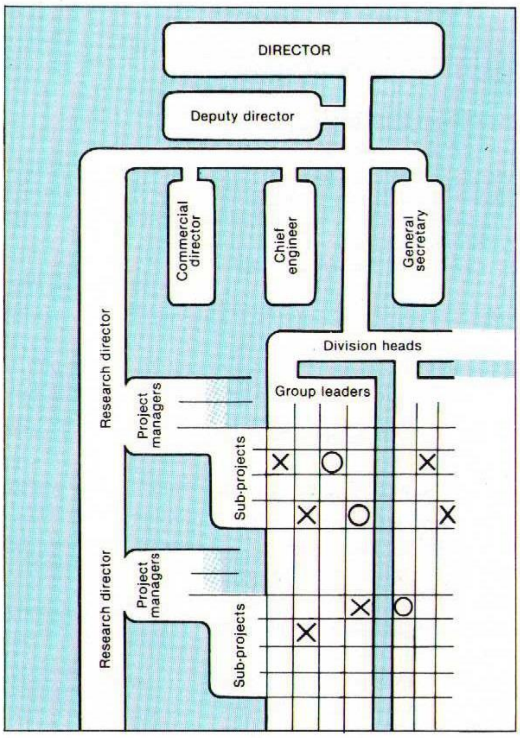


Figure 36

Harwell management system

Appendix 4

How Nuclear Reactors Work

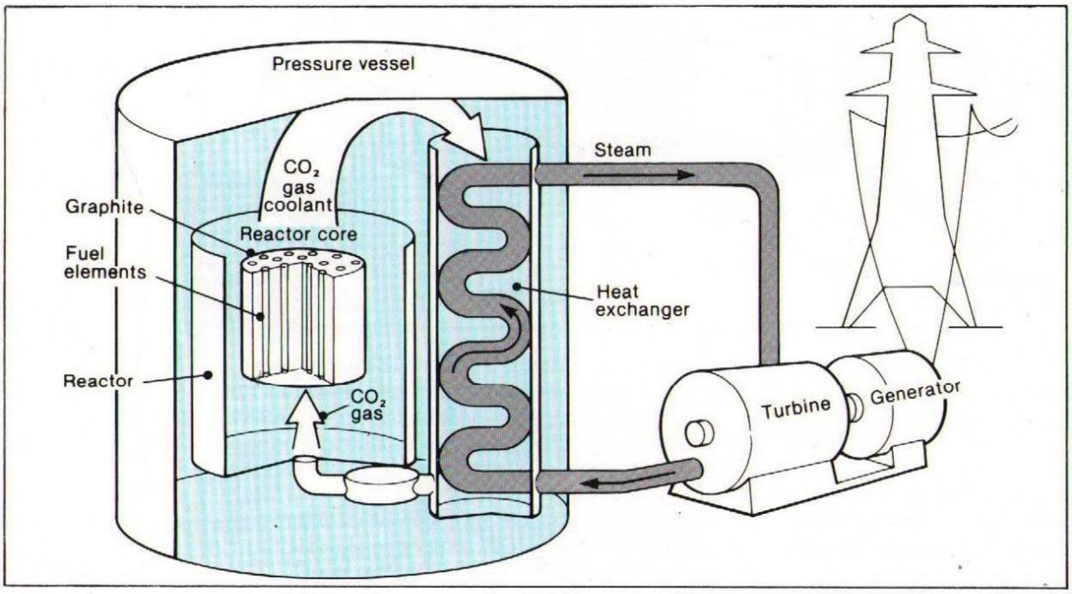


Figure 38
Advanced Gas-cooled Reactor: Layout

Nuclear reactors have been supplying electricity to the British Electricity grid since 1956. All the power stations now operated by the Central Electricity Generating Board (CEGB) and the South of Scotland Electricity Board use graphite-moderated thermal reactors in which heat energy is extracted from the reactor core by circulating gas. The UKAEA's Steam Generating Heavy Water Reactor (SGHWR) at Winfrith in Dorset is also supplying electricity to the grid and the American-designed Pressurised Water Reactor (PWR) is currently under consideration by the CEGB as an alternative system.

Fast Reactors are not yet in commercial operation, although the Authority's 250 Megawatt Prototype Fast Reactor (PFR) came on power in 1975 at Dounreay, Caithness and is also supplying electricity to the grid.

The following account reviews briefly the main features of thermal and fast reactors and their modes of operation.

Thermal reactors

The first thermal reactors to be used in UK power stations were of the 'Magnox' type, fuelled with uranium metal in cans of magnesium alloy. Although magnox power stations are still operating, the design has been superseded by the Advanced Gas-cooled reactor (AGR), whose essentials are shown in *Fig. 38.* Its basic fuel is uranium oxide, sealed in stainless steel cladding.

Heat is produced in the reactor core by the fission of some of the uranium nuclei into two smaller fragments when struck by slow-moving neutrons. At the same time, further (fast) neutrons are released and when these are slowed down by collisions in a moderator, the process becomes self-sustaining. Only the nuclei of the lighter isotope U-235 undergo fission in this way and these form about one part in 140 of natural uranium. The fuel can be made more effective if it is artifically enriched in U-235 and AGR fuel elements contain 2% of this isotope.

The moderator material is chosen to slow down neutrons by collision, but not to absorb them. Magnox reactors and AGR's use carbon in the form of graphite. Most structural materials absorb slow neutrons to a greater or lesser extent and a feature of reactor design is the selection of components to preserve the neutron economy or the compensation for losses by fuel enrichment.

Heat is removed from the reactor core by circulating high pressure carbon dioxide gas and transferred via heat exchangers to steam generating plant in the power station.

Fuel elements remain in the reactor for several years. When the burn-up of U-235 and the accumulation of fission products (which also absorb slow neutrons) has reduced the fuel efficiently to a given level, it is removed for reprocessing and replaced with fresh fuel.

Other designs of thermal reactors use water (H_2O) or the less neutron-absorbent heavy water (D_2O) as moderator material instead of carbon. Energy is entracted by circulating water through the reactor core as 'coolant'. The main types of concern in Britain are the SGHWR and the PWR: both use uranium oxide, enriched with U-235 as fuel, canned in zirconium alloy and in steel respectively.

In all these reactors the heavier isotope

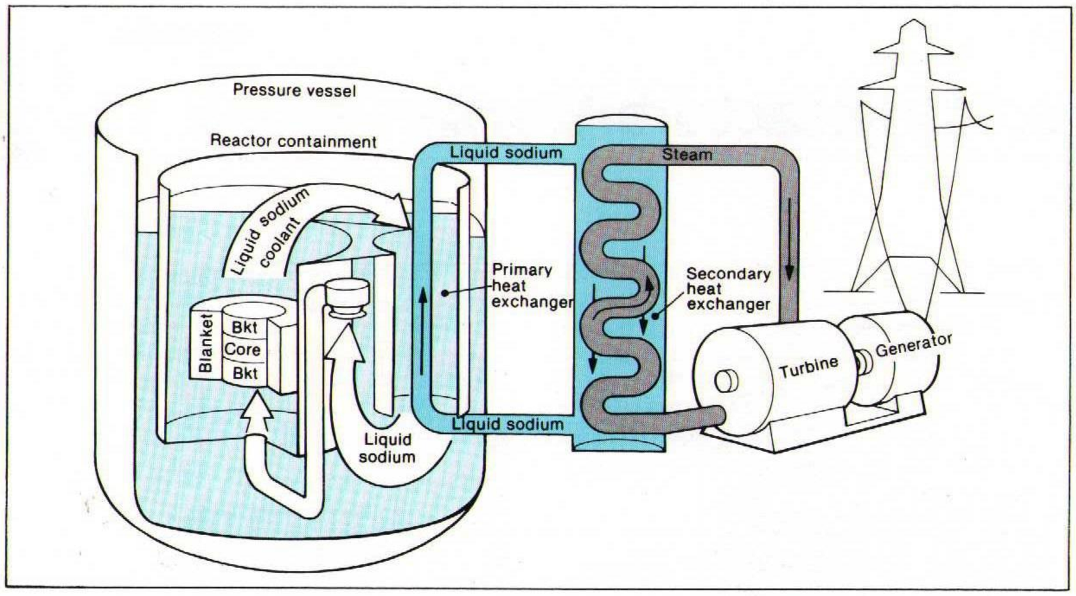


Figure 39
Fast Reactor: Layout

U-238, which makes up the bulk of the fuel, also absorbs slow neutrons and part of it is transformed thereby into a radioactive version which ultimately yields plutonium-239. The nucleus of Pu-239 can undergo fission and yield useful energy when struck by fast neutrons. In thermal reactors, plutonium builds up in the fuel and is separated during reprocessing for use in fast reactors.

Fast reactors

Fast reactors are designed to use higher concentrations of fissile material as fuel, with the fission process largely accomplished by fast neutrons. So in a fast reactor, as shown in *Fig. 39,* there is no need for a moderator, or for wide fuel spacing to accommodate it and the reactor core can be as little as 1½ metres across. The heat production is very intense and liquid sodium is circulated through the core as coolant to carry away the energy to primary heat exchangers and thence to the boilers in a power station.

In the fast reactors developed in the UK the fuel is a mixture of oxides of plutonium and uranium, canned in stainless steel tubes and grouped in closely spaced bundles, *Fig. 40.* The fast reactor can be used to 'breed' more fuel by surrounding the core with a 'blanket' of uranium-238. More plutonium is then produced by neutrons in the core and blanket together than the reactor consumes in the core; a fast reactor, operated as a 'breeder' can generate enough plutonium to fuel a second reactor in about twenty years. Thus much more of the natural uranium can be used eventually as fuel and fast reactors can produce 50 to 60 times as much energy from uranium as thermal ones (i.e. the equivalent of a million tons of coal from one ton of uranium).

The Prototype Fast Reactor at Dounreay besides producing power for the electricity grid, provides essential information for the development of fast reactors. The next logical step in the programme would be the construction of a commercial size demonstration fast reactor.

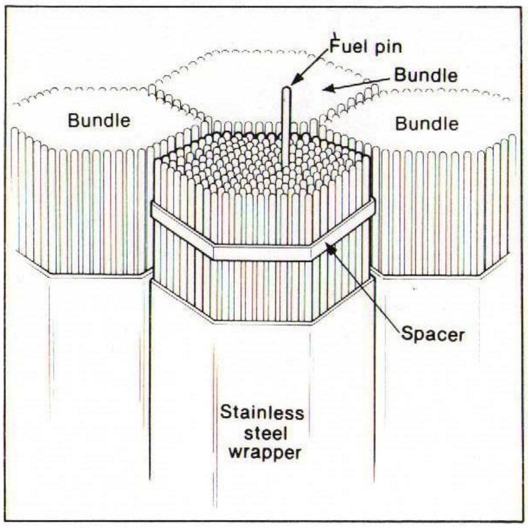
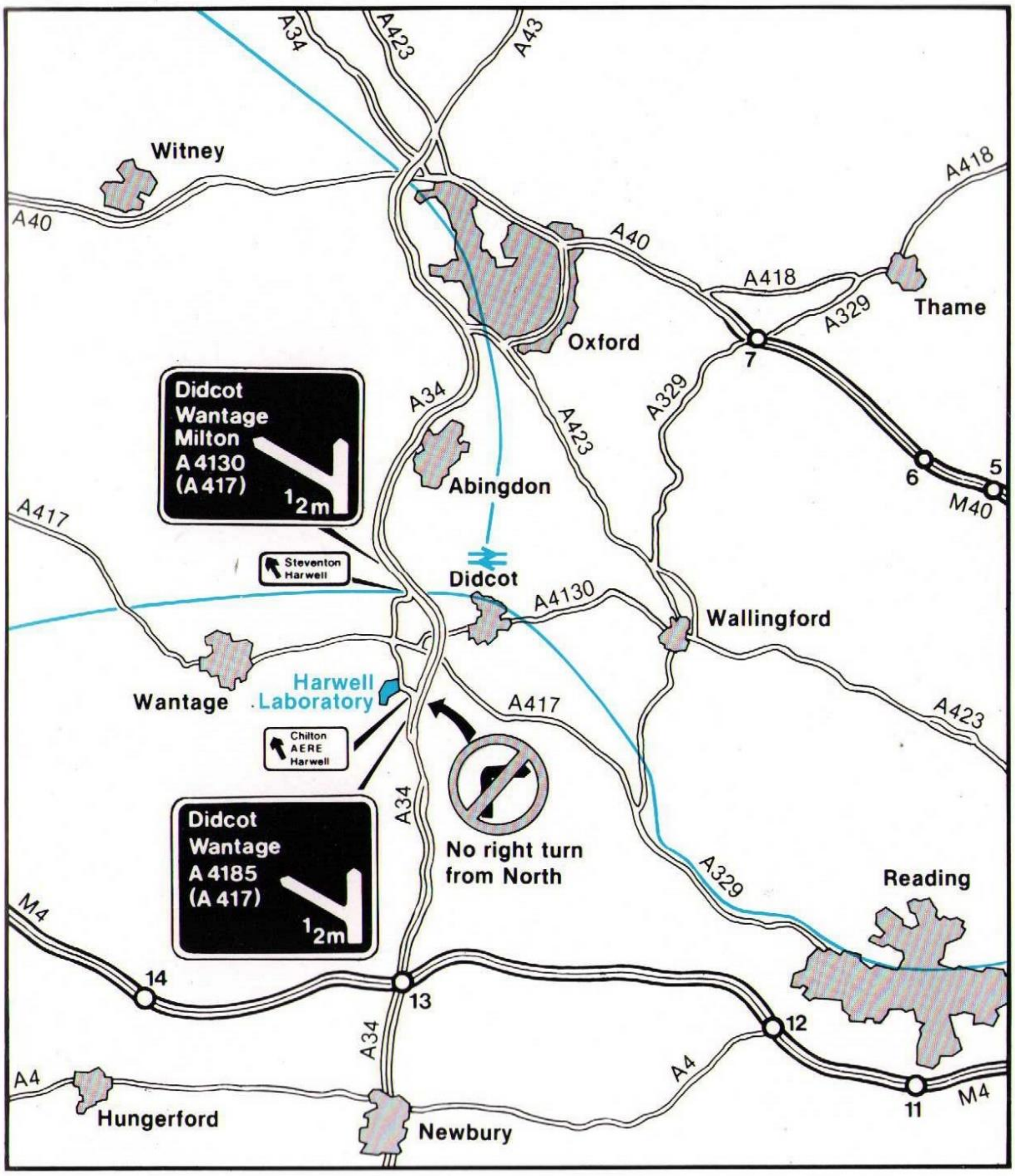


Figure 40
Arrangement of fuel pins in a Fast Reactor
Sodium coolant circulates between the fuel pins in the bundle and between separate wrappers.

HOW TO REACH HARWELL LABORATORY



By road: Harwell Laboratory is situated on the A4185 approximately midway between Newbury and Oxford. Approach from north and south is via the A34.

By rail: Harwell is 5 miles southwest of Didcot station, from and to which there are frequent connections with London (Paddington), Birmingham, West of England and South Wales. Rail passengers are met at Didcot by arrangement.

By air: Harwell is one hour from London (Heathrow) Airport. Plane passengers are met at Heathrow by arrangement.

FURTHER INFORMATION

The United Kingdom Atomic Energy Authority, of which AERE Harwell is the principal Research Establishment, publishes an Annual Report of its activities. For further information about other Establishments of the Authority and for copies of the Annual Report, the reader is referred to:

UKAEA Information Services Branch
11 Charles II Street, London SW1Y 4QP

For further information on Harwell and on the subjects described here, you are invited to contact:

Dr F J Stubbs, Head of Public Relations Group, AERE Harwell, Didcot, Oxfordshire, OX11 0RA

Telephone (0235) 24141. Extension 2424.

who will put you in touch with the appropriate experts.

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