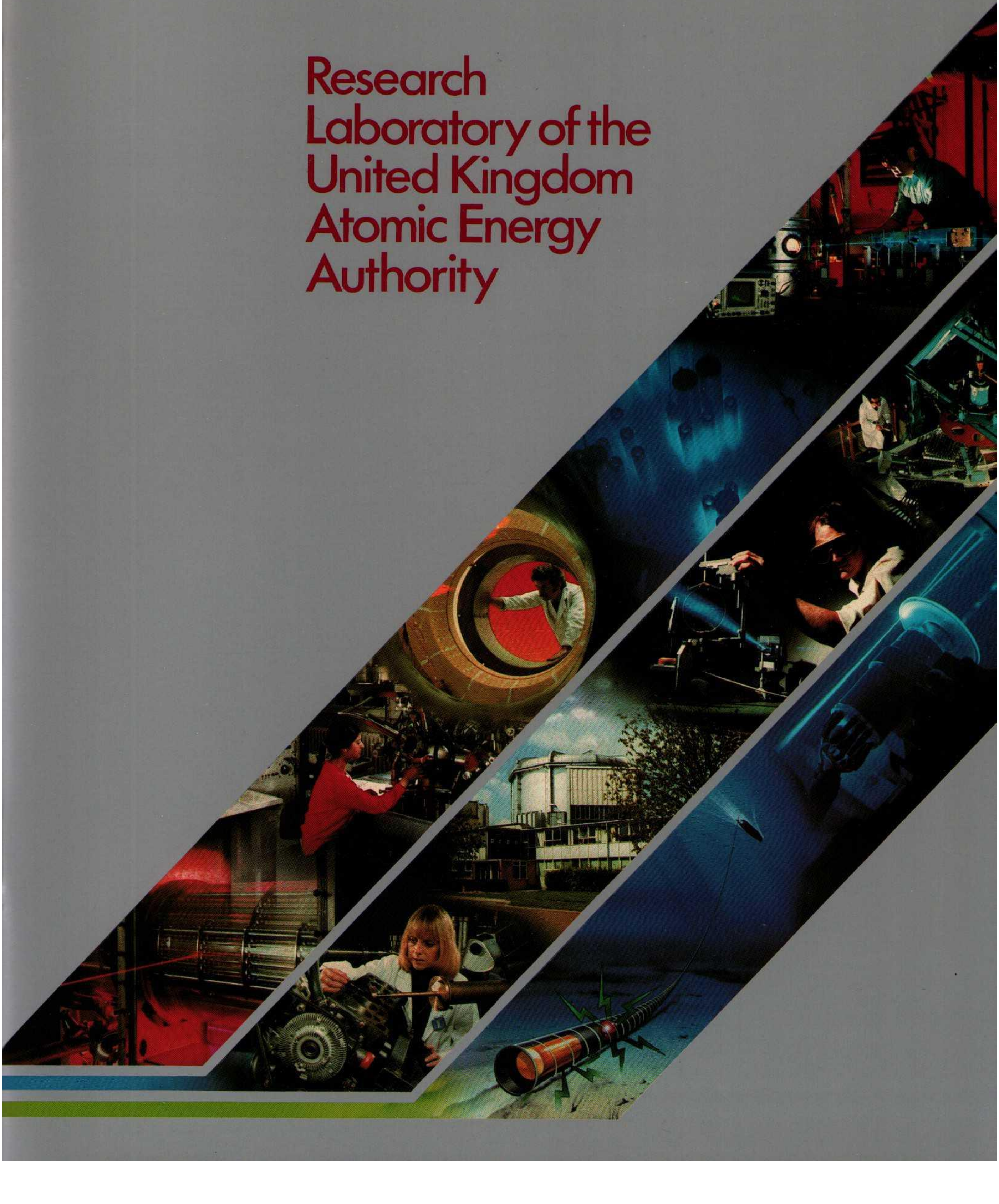
HARWELL

Research Laboratory of the United Kingdom Atomic Energy Authority



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INTRODUCTION

The Harwell laboratory was founded over 40 years ago, on 1st January 1946, on an RAF station that became redundant at the end of the war. Under the direction of the late Sir John Cockcroft, the laboratory rapidly pioneered much of the technology of the new nuclear power industry and acquired a high international reputation in nuclear science. Today Harwell is the largest research laboratory of the UKAEA and deeply involved in every major project of the Authority. In common with other AEA laboratories, an increasing proportion of our income in recent years has been earned from contracts placed by various customers rather than from the Atomic Energy Vote, and this transformation will be complete when the AEA operates on a Trading Fund basis from April 1986. Harwell is an applied research laboratory; it is multidisciplinary, market oriented and its fields of work are categorised under the following headings:

- **Nuclear science and technology**
- **Industrial sponsored research and development**
- **Government support services**

The principal objectives of the nuclear work are to provide the scientific base for the applied nuclear R&D programmes of the Authority and for the Nuclear Industry, and to undertake specific research to further the safe and economic use of nuclear power in the UK. The nuclear power programme has created a reservoir of advanced technology: the principal aim of the industrial work is to exploit this to yield significant economic benefits to industry and the country. In addition, Harwell's Energy Technology and Marine Technology Support Units, ETSU and MaTSU, provide technical and management services for the Department of Energy.

Harwell became part of the newly formed UKAEA in 1954; in time parts of the work originally carried out at Harwell were transferred to other sites or organisations. High energy nuclear physics and the necessary nuclear accelerator engineering moved to the Rutherford High Energy Laboratory on the adjoining site in 1958, the Reactor Physics Division went 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 research on nuclear fusion moved to the nearby site at Culham in 1961. Harwell remained a large laboratory well equipped to carry out research on all the materials needed in reactor development, on every aspect of the nuclear fuel cycle, and on health and safety, chemical, engineering, electronic and computing problems for the nuclear industry.

A great change in Harwell's character resulted from the Science and Technology Act (1965) which provided the framework for the UKAEA to diversify its research and development into non-nuclear fields with the vital support of the Department of Trade and Industry. The exacting demands of nuclear technology had led to Harwell building up a broad competence in the physical and engineering sciences, together with the smaller but important biological programmes. From the start, Harwell had sought to extend the applications in industry and medicine of the new sources of radiation and radioactive materials that were its characteristic product. The new challenge was to transfer relevant parts of the other technologies developed to support the nuclear power industry into other industrial applications.

In addition to nuclear science and technology and the Government support units, key subjects at Harwell include the following:

- **Environmental Sciences and Services**
- **Materials Science and Technology**
- **Inspection, Analysis and Characterisation of Materials**
- **Chemistry and Chemical Technology**
- **Engineering Science and Process Technology**
- **Computer Science and Services**
- **Marine Technology**

This booklet has been produced to illustrate by some up-to-date examples the success of this enterprise. Harwell has developed productive and close relationships with hundreds of customers for applied research, in industry, in government and overseas. We continue to experiment and to evolve new methods of bridging the gap between research and practical application. Our multidisciplinary applied projects depend on nurturing centres of expertise which continue to achieve a high output of first class science oriented to future needs. The transformation of the AEA from a Vote funded body to a Trading Fund in April 1986 marks a further step in our evolution, but one we face with confidence in a proven record for flexibility and for quality.

The material for this booklet has been provided by a large number of the staff at Harwell. Dr C M Nicholls undertook to structure the text and wrote much of it himself and the editing and production was the responsibility of Mr P A H Saunders; I should like to thank them both.

Louis Roberts

L E J Roberts, Director

ORGANISATION AND FUNDING

Harwell is an applied research laboratory and applied research, to be useful, must be translated into practice. Nearly half of the laboratory's programme has formed an integral part of the work of the AEA, itself closely coordinated with that in other parts of the nuclear industry in this country. In addition, Harwell has over 20 years experience in carrying out research and development under contract and the amount of this customer-funded work has grown rapidly in the past decade. Now, with the establishment of the UK Atomic Energy Authority as a trading fund in April 1986, the whole of Harwell's £100 million programme is funded through contracts with customers, drawn from both industry and government organisations, in the UK and overseas.

The major part of Harwell's business – roughly two-thirds – is in support of nuclear power and other nuclear technologies. Customers include the Central Electricity Generating Board (CEGB), South of Scotland Electricity Board (SSEB), British Nuclear Fuels plc (BNFL), the National Nuclear Corporation (NNC) and Amersham International, government departments concerned with nuclear power development and nuclear technology (Department of Energy, Department of the Environment, Ministry of Defence), and overseas organisations in Europe (particularly the Commission of the European Communities (CEC)), the United States, Canada, Japan and elsewhere.

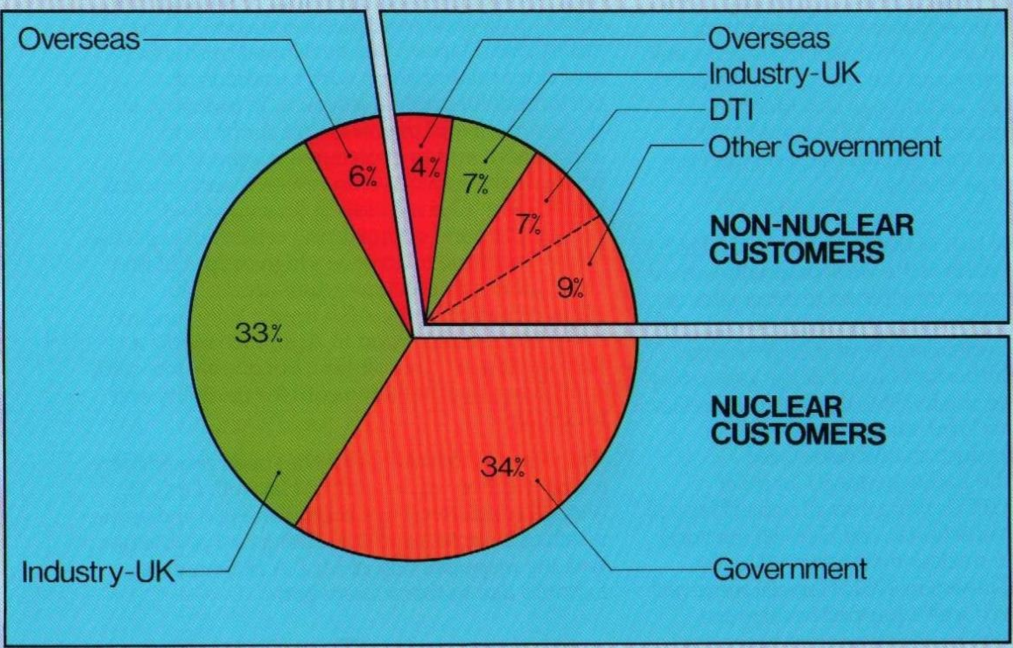
The remaining third of Harwell's research and development business is carried out for industrial and government customers outside the nuclear field. Here Harwell has used the same expert teams that have been built up for the nuclear power programmes, but applying their skills in a broader context. This work is widely spread, involving typically over 700 customers and in excess of 1000 contracts each year. Special importance is attached to work for industrial firms. Valuable support for this comes from R&D funding of new industrial technologies provided by certain government departments, particularly the Department of Trade and Industry through its Requirements Boards.

Harwell's applied research is carried out through more than 20 Business Centres each specialising in a particular market or field of technology. Each Centre is headed by a Manager reporting to a member of the Harwell Directorate, and operates as a small business within the Harwell umbrella; annual turnovers are generally in the range £1 million to £2 million, and derive from a portfolio of contracts with a variety of customers. Some of the main Business Centres are listed in Table 1, and their names provide a graphic demonstration of the wide range of technology which Harwell is able to offer.

To carry out their contracts, the Business Centres deploy scientists and engineers drawn from the fifteen Harwell Divisions listed in Table 2, which are organised around specific scientific and engineering disciplines. An important feature of Harwell's contract work is the proven ability of the Business Centres to bring together the multi-disciplinary teams needed for working in many advanced fields of technology: some programmes have involved inputs from as many as ten different disciplines.

Most of Harwell's R&D contracts are with individual customers; the work is carried out on a confidential basis with the results available only to the customer concerned. Contracts range in size from the very large – well in excess of £100,000 – down to a few tens or hundreds of pounds, eg. for relatively routine use of some of Harwell's extensive range of analytical equipment or for small consultancies on specific problems.

Harwell also operates a number of cooperative research programmes ('Clubs'), ie. R&D programmes where the cost of the research is divided between a number of sponsors, all of whom have access to the results. Since the results are



Sources of Harwell's Research Funding

CHAPTER 1

ORGANISATION AND FUNDING

shared, such programmes must necessarily be on technologies which are at a pre-competitive stage, and often involve a substantial amount of generic work.

The names of some of the Harwell R&D clubs are listed in Table 3 which shows the wide range of topics they cover. Some clubs involve only a few members and concern tightly focused programmes spanning perhaps one or two years. Others are longer term, broader in scope and have memberships of 100 or more. The key attraction of a club is that, for a relatively modest fee, its members can benefit from a large-scale research programme. In many cases a government department such as DTI, or the Commission of the European Communities (CEC) provides additional support to a club, often matching the industrial contributions, and this substantially increases the gearing of the club member's subscription.

Licensing of processes and products is another important route by which Harwell's new technology gets to the marketplace. In many cases, Harwell helps the licensee through the critical early stages of a venture by providing consultancy, training etc. in the new technology. Increasingly, finance from venture capital companies is helping to fund the later stages of developing new products or process, as well as their subsequent exploitation through a licensee.

As well as developing new technology on its own initiative, Harwell undertakes the development of new processes and products for customers against their specifications and to agreed budgets and timescales. An essential feature of this work is close and frequent contact between our technical staff and the customer to ensure that market needs are taken into account at every stage.

This large and diverse effort in applied research is supported by a programme of longer range strategic scientific research, carried out in the same Divisions and often by the same staff. This 'Underlying' programme, oriented to the future needs and interests of the nuclear power industry, has been funded until now from the Atomic Energy Vote and will be supported in future by a levy on most applied contracts; the range of the work is described in Chapter 2. Some support for longer-term research in selected non-nuclear topics is provided by the DTI Requirements Boards and from R&D club subscriptions.

TABLE 1

Some Harwell Business Centres

Non-nuclear

- Analytical R&D Unit
- Applied Electrochemistry Centre
- Atmospheric Pollution
- Biotechnology Centre
- Chemical Technology Centre
- Combustion Centre
- Computer Optimisation
- Energy Conservation Technology
- Hazardous Materials Service
- Heat Transfer and Fluid Flow Service
- Materials Engineering Centre
- Metals Technology Centre
- Microelectronic Materials Centre
- Nondestructive Testing Centre
- Nuclear Applications Centre
- Offshore Technology Centre
- Physico-Chemical Measurement Unit
- Reservoir Simulation
- Separation Processes Service
- Systems Design and Computer Applications

Harwell Nuclear Programme Areas

- Fast Reactors
- Thermal Reactors
- Water Reactor Safety
- General Reactor Safety
- Fuel Cycle
- Radioactive Waste Management
- Radiological Protection
- Fusion
- Nuclear Engineering
- Nuclear Instrumentation

TABLE 2

Harwell Divisions

- Chemical Engineering
- Chemistry
- Computer Science and Systems
- Energy Technology
- Engineering Design and Manufacture
- Engineering Projects
- Engineering Sciences
- Environmental and Medical Sciences
- Instrumentation and Applied Physics
- Materials Development
- Materials Physics and Metallurgy
- Nuclear Physics
- Research Reactors
- Theoretical Physics
- Thermal Hydraulics

TABLE 3

Some Harwell Clubs

Listed below are some of the multi-sponsored Clubs currently operated by Harwell

- Boetechnical Separations Service (BIOSEP)
- Biochemical Sensors
- Composite Metal Jointing Working Party
- Gas Sensor Materials Working Party
- Heat Transfer and Fluid Flow Service (HTFS)
- Petrol Engine Working Party
- Metal-Matrix Composites Working Party
- Mining Instrumentation Development Advisory Service (MIDAS)
- Offshore Inspection R&D Service
- Offshore Bolting Materials
- Separation Processes Service (SPS)

NUCLEAR SCIENCE AND TECHNOLOGY

- **Applied Nuclear Research and Development**
  – project oriented
- **Underlying Research**
  – long term, strategic

Current main objectives:

- to improve the performance of the Advanced Gas Cooled Reactor
- to increase confidence in Pressurised Water Reactor Safety
- to continue the development of the Fast Reactor
- to continue development of fuel cycle technology, fast and thermal reactor systems, particularly in the area of fuel reprocessing, fuel fabrication and waste management

The UKAEA has as a primary task the provision of research and development support for the United Kingdom nuclear power industry; for existing power stations and those planned for the future, and for the associated fuel fabrication and processing plants. This priority at Harwell is reflected in staff allocations.

The current nuclear power programme concentrates on work which will improve the economic performance of the established and planned nuclear power stations, including fast reactors. Other priority topics include reactor safety and reliability, fuel handling and reprocessing for both fast and thermal reactors, and waste management and disposal.

Harwell has worked on every reactor system which has ever been of interest to the UK. For the foreseeable future Harwell will be concerned with:

Gas-Cooled Reactors
The Advanced Gas Cooled Reactor (AGR)

This is well established with very high reliability and safety performance. Current work is concerned with the improvement of the performance and life of plant and of fuel and the provision of safety information to meet demands for even higher safety and efficiency standards.

Pressurised Water Reactors (PWR)

This commercially successful system has been adapted to the needs of a number of countries. The Central Electricity Generating Board (CEGB) is proposing to introduce the PWR to the UK generating system. The purpose of Harwell's work is to help clarify a number of generic safety issues raised by the Nuclear Installations Inspectorate and to provide R&D support for CEGB.

Fast Reactors

The long term development of the fast reactor (FR) for commercial use has always been a main role for the UKAEA. Harwell assists in a number of areas, including materials studies, fuel behaviour and safety work.

The R & D programmes at Harwell fall into two broad categories:

Applied Nuclear Research and Development

- The time horizon of this research is relatively short. It is closely geared to current design and operational requirements of the UKAEA, the CEGB and the wider nuclear industry. This work is strictly customer oriented.

Underlying Research

- This is broadly based work which aims to increase the scientific understanding in areas relevant to nuclear power in the medium to long term.

Both categories rely on a considerable infrastructure of specialised experimental plant, equipment, laboratories and services. Some of the facilities are described in the next section, and the remainder of this Chapter gives examples of recent and current research projects.

NUCLEAR PLANT AND EQUIPMENT

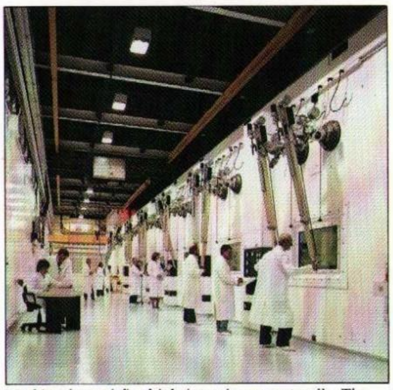
- **Research Reactors**
  (DIDO, PLUTO)
- **Accelerators**
- **Radiochemical Laboratories and Post Irradiation Examination Facilities**

The development of nuclear technology depends upon the availability of highly specialised plant and equipment. Controlled sources of high intensity neutrons and charged particles are required, together with hot cells and remote handling equipment sufficient to allow the examination of irradiated fuel and the development of pilot-scale fully active plant and processes.

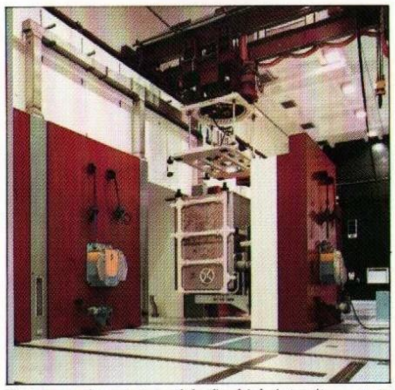
Harwell has two 25MW fully instrumented Materials Testing Reactors, DIDO and PLUTO, both excellent neutron and radiation sources. Fluxes of high energy (fast) neutrons at 1×10^{14} neutron/cm^2/sec are available for the irradiation of specimens within specially constructed hollow fuel elements, which can accommodate experimental rigs up to five centimetres in diameter. Lower energy (thermal) neutron fluxes at 10^{14} neutron/cm^2/sec, which is ten times that normally found in a civil power reactor such as an AGR, are available in a wide variety of experimental loops and rigs. Fluxes of these intensities enable accelerated tests of materials to be undertaken under measurable and observable conditions. The full temperature and pressure conditions of a PWR can also be simulated in specially constructed facilities in the DIDO reactor.

Other neutron beam sources have been developed over the past decade in close collaboration with the Science and Engineering Research Council, including the use of the high-flux reactor at the Institute Laue-Langevin, Grenoble.

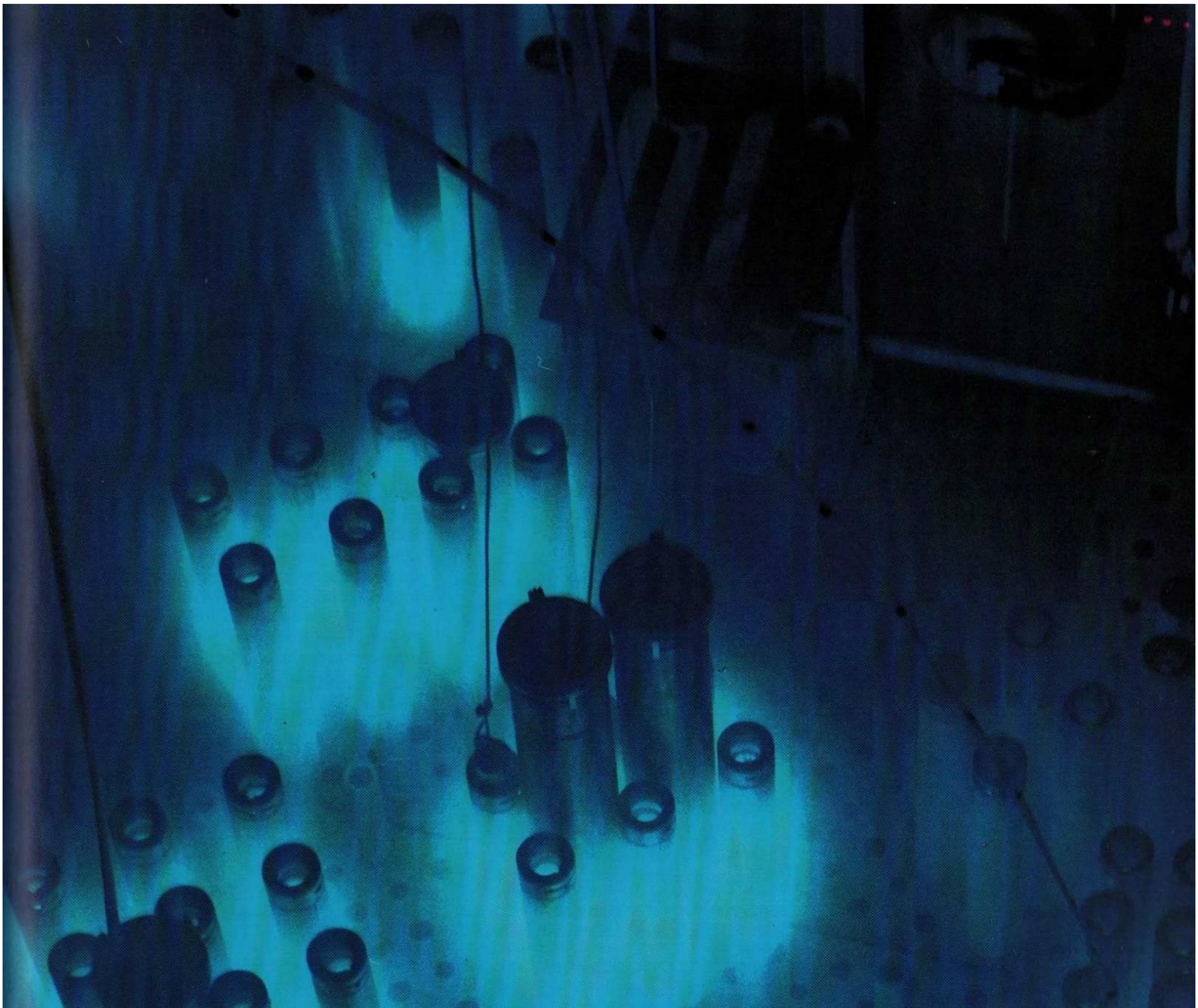
Harwell has a range of particle accelerators used for a variety of materials studies, commercial applications and data measurement. These include Van der Graaff machines, a variable energy cyclotron and a high energy electron linear accelerator used primarily as a pulsed source of neutrons for the precision measurement of reactor nuclear data.



Working faces of five high-integrity concrete cells. The manipulator station shown in the background is part of a large decontamination facility which is common to all cells.



Rear access doors to two of the five high-integrity concrete cells recently constructed at Harwell for radiochemistry experiments involving highly radioactive materials.



CHAPTER 2

NUCLEAR SCIENCE AND TECHNOLOGY

The radiochemical hot cells and post-irradiation examination (PIE) remote handling facilities are central to Harwell's work in the nuclear fuel cycle, work on radioactive waste management, fuel fabrication and reprocessing and safety studies. New and unique facilities for handling highly radioactive materials have now been constructed which enable fully active processes to be demonstrated at pilot plant scale. These are highly shielded and capable of handling 10^3 MeV curies of gamma ray emitters and alpha particle emitting materials, limited only by criticality considerations. The use of mobile containment boxes in those facilities, capable of easy decontamination, enables chemical investigation to be carried out inactively and then at full activity very rapidly, as well as enhancing the basic safety of operation.

Harwell's PIE facilities are used in fast reactor, AGR and PWR fuel studies as well as in a variety of reactor material developments and examinations. They are supported by a wide range of analytical and support services. These include non-destructive and destructive testing, fission product examinations and metallurgical studies of material changes under conditions of intense radiation, essential to advanced studies in nuclear science and technology.

APPLIED NUCLEAR RESEARCH AND DEVELOPMENT

- **Nuclear Fuels**
- **Coolant Chemistry and Circuit Activity**
- **Materials and Safety Studies**
- **Reprocessing Technology**
- **Radioactive Waste Management**

Applied nuclear R&D is the largest single programme area at Harwell. It covers aspects of the nuclear fuel cycle, ranging from advanced fuel studies and reprocessing technology to the study of management and disposal techniques for radioactive wastes. Safety considerations affect all parts of the fuel cycle and continue to be an important part of Harwell's work. Supporting technologies such as the development of instrumentation and remote handling techniques are also important components of the Harwell programme.

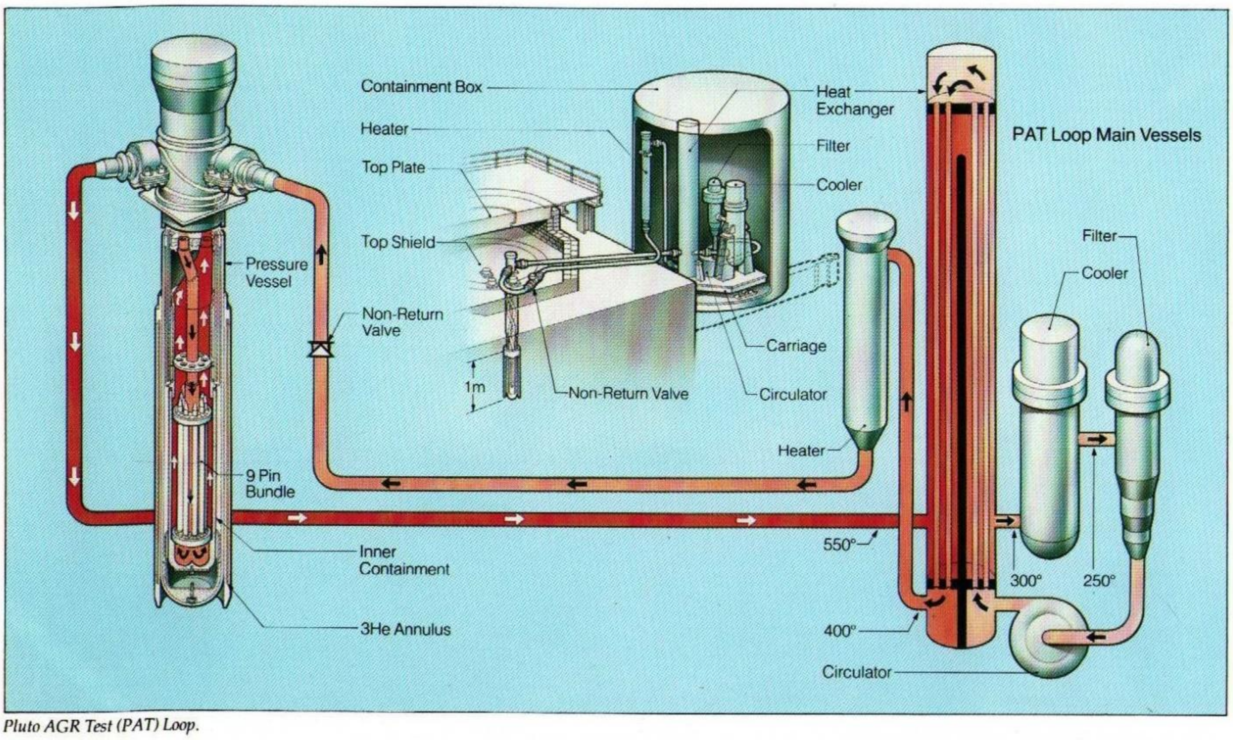
Many projects of direct application to the nuclear power programme are included in later Chapters on specific technical areas.

NUCLEAR FUELS/CLADDING

Extensive use is made of the Harwell Material Test Reactors (MTRs), DIDO and PLUTO, for the characterization and development of nuclear fuel and cladding materials in support of AGR, PWR, FR and commercial repayment programmes. The programme depends upon Harwell's suites of shielded cells and caves for post irradiation examination (PIE) and subsequent analysis of these materials. The facilities available for the examination of in-core and structural materials include metrology rigs, gamma scanning, gas sampling equipment, mechanical testing and optical microscopy. In addition a shielded electron microprobe, and scanning and transmission electron microscopes are available for the detailed microcompositional and microstructural characterization of irradiated materials.

Currently an irradiation experiment is being conducted in PLUTO to assess the performance of large grained UO_2 which is a candidate fuel for extended burn-up operation in both AGR and PWR systems. Tests will provide valuable information on release at high temperatures (over 1200°C) from fuel operating under both steady state and transient conditions.

A major experimental programme is planned to commence for the new irradiation facility known as the PLUTO AGR Test Loop (PAT Loop). With the



Pluto AGR Test (PAT) Loop.

closure of the Windscale AGR this new loop will be the only experimental facility available for testing AGR fuel under representative operating conditions. It is designed to accommodate a cluster of nine commercial AGR fuel pins, either unirradiated or irradiated. A wide range of fuel endurance experiments will establish the operating limits of existing and new fuel designs under normal and abnormal operating conditions. The loop has the capability of power cycling pins over a wide range or subjecting them to power or thermal transients.

Information on the oxidation of UO_2 is of primary importance in safety assessment studies relating to the handling of fuel after discharge, subsequent transportation and storage. Detailed studies are in progress to determine the kinetics of oxidation, oxide product, particulate size distribution and fission product release from irradiated UO_2 exposed to air at temperatures in the range 250° - 1000°C.

COOLANT CHEMISTRY AND CIRCUIT ACTIVITY

Pressurised Water Reactor

Much of the work in this area is concerned with the reduction of radiation exposure of PWR operating staff, which has significant economic and safety implications. Exposure during maintenance work results from the transport of radioactive material deposited on fuel pins by coolant water to other parts of the primary circuit.

A research contract, worth over £1.1M was recently completed for the Nuclear Fuel Division of Westinghouse Electric Corporation, USA and FRAGEMA of France. This is a typical example of the studies currently in demand, which required a multi-disciplinary team and complex in-reactor equipment.

The investigation was concerned with the deposition of corrosion products on the surface of PWR fuel rods. The programme involved fuel rod irradiations under a range of thermohydraulic and coolant chemistry conditions. These were carried out in the pressurised water loop facility in DIDO. The findings will help Westinghouse to specify the optimum operating conditions for its power reactors.

The pressurised loop used in the Westinghouse Project simulates conditions in the primary coolant circuit of PWRs. Its wide range of instrumentation makes it a versatile facility for the detailed investigation of the basic chemical reactions which occur in the water coolant and on metallic surfaces, in the presence of intense nuclear radiations and under different thermal and chemical conditions. A comprehensive programme supported by the CEGB and the Electric Power Research Institute (EPRI) in the United States has produced new data which is providing valuable insights into the transport of radioactive material out of the reactor core within the coolant circuit.

Coolant Chemistry
Advanced Gas Cooled Reactor

The long term mechanical stability, and hence useful life, of the AGR core depends on the strength of the graphite moderator blocks. This strength is reduced by corrosion by the carbon dioxide coolant which is controlled by two inhibitors, carbon monoxide and methane. However, these inhibitors, in excess, promote the production of carbon deposit on the fuel pin surfaces which impairs the heat transfer from the fuel to the coolant.

A major experimental programme to determine the dependence on the inhibitor concentration of both the moderator corrosion rate and the rate of deposit production has been undertaken in the Harwell Materials Test Reactors. The data obtained in this way have provided a key input to the formulation of the coolant control strategy adopted by the Electricity Generating Boards to maximise core life.

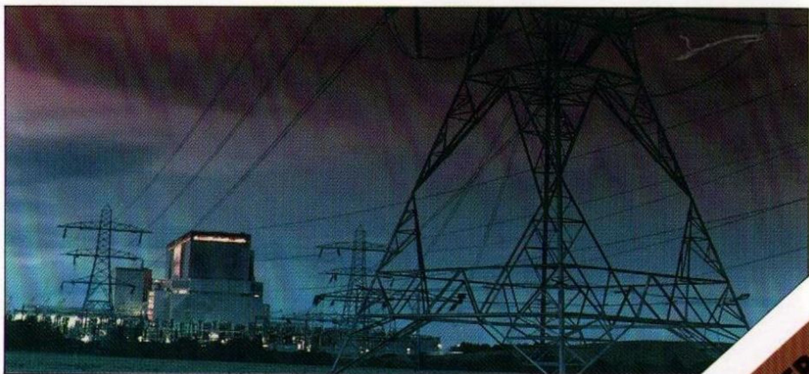
Dimensional changes in the graphite moderator induced by neutron irradiation will have an increasing effect on the stress patterns occurring across the moderator bricks as time progresses. This will have an important influence on the stability of the core. The effect is modified by corrosion and the interaction of the two processes is being studied in a MTR experiment in which full reactor life behaviour will be simulated in a few years. This accelerated test will provide information which is essential for making the case for extending the operating life of the reactors, which would be of major economic benefit.

Circuit Activity
Advanced Gas Cooled Reactor

A knowledge of the rate of release of fission products (primarily iodine and caesium) from fuel containing various defects is of prime importance in the preparation of safety cases for AGR operation and also in the assessment of circuit contamination. Such information lessens the possibility that output from the stations is impaired by adherence to operating rules based on pessimistic assumptions about fission product release.

Experiments are in progress in the PLUTO reactor in which small scale AGR fuel pins containing deliberately induced failures are irradiated. Fission product releases are monitored continuously and the failures may be induced either before or during the irradiation. Parallel experiments are also underway measuring the release of gaseous fission products from small samples of unclad reactor fuel. A wide range of conditions ranging from normal operation to severe power transients is being studied.

A large high-pressure high-temperature cell at Harwell for studying a range of PWR problems.



Hinkley-Point B, Somerset. Completed in 1976 for the CEGB, this 1250MW station was the first of Britain's second-generation nuclear power stations using the Advanced Gas Cooled Reactor (AGR). There are five nuclear power stations of the AGR type operating in Britain and two more are under construction.

NUCLEAR SCIENCE AND TECHNOLOGY

Thermal Hydraulic Behaviour of Coolants in Fast Reactors

The high volumetric heat generation in the fuel and the need to maintain the neutrons in their 'fast' state have led to the adoption of liquid sodium as the fast reactor coolant, for a number of reasons including a low absorption coefficient for neutrons. However, because of the excellent heat transport properties of sodium, problems related to thermally generated stresses in vital structural components are severe.

A pool type fast reactor has two large volumes of sodium at relatively hot and cold temperatures; these pools are separated by steel structures which must be capable of withstanding both normal steady-state conditions and rapid temperature changes which occur during transients. In association with the National Nuclear Corporation this problem is being studied using water and liquid metal scale models and various theoretical approaches. A water-filled, scaled model of the fast reactor has been built to study the intricate coupling of forced and natural convection during steady, full-load, part-load and transient conditions. The construction is used for studies of the thermal performance of both the hot sodium volume, and a relatively quiescent zone below it, known as the intermediate plenum. This work is important in giving new and accurate insights into coolant behaviour and bringing together the experimental and theoretical approaches to this central problem.

Analytical and numerical techniques are being developed to predict the thermal performance of the various components of the fast reactor. These are validated against experimental data and will then be used to analyse the thermal hydraulic performance of the appropriate fast reactor component.

MATERIALS AND SAFETY STUDIES

Pressurised Water Reactor

The development of non-destructive testing techniques for critical PWR components and studies into the embrittlement and corrosion fatigue of pressure vessel steels have been important Harwell contributions to the UKAEA nuclear power programme. A novel ultrasonic technique has shown considerable promise for the detection and sizing of intergranular attack in PWR steam generator tubing.

Ultrasonic techniques are also being applied to the inspection of defects in large castings such as used in primary circuit circulation pumps.

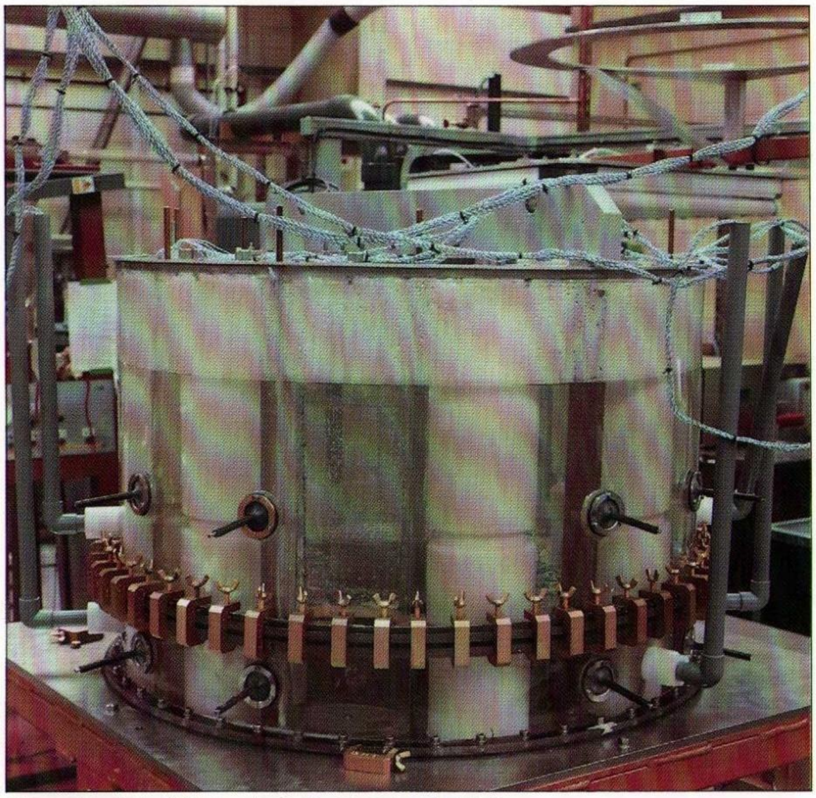
The integrity of a PWR pressure vessel depends on its resistance to crack propagation. Pressure vessel steels undergo a transition from high toughness at high temperatures to low toughness at low temperatures. Experiments have been conducted to determine the extent to which this ductile/brittle transition temperature and the high temperature toughness of the steel are changed by ageing and irradiation effects in the reactor. Results to date show that ageing at the normal PWR operating temperature of 290°C produces only small effects on the ductile to brittle transition temperature. Ageing and irradiation both result in an increase in this temperature, but the effects are not additive, which improves the safety margin.

Under conditions in which PWR water coolant chemistry is well controlled, it has been possible to show that fatigue crack growth in modern pressure vessel steels and associated weldments lies well within safety limits. A test rig has been designed and operated at the full temperature and pressure of a PWR, thus enabling a wide range of relevant tests in this area to be undertaken.

Fast Reactor

The fast neutron flux in the core region of fast reactors produces radiation damage – the displacement of atoms from their normal crystal lattice position due to collisions with fast neutrons – which is manifested by a volume increase (swelling), irradiation creep and embrittlement. A major effort is devoted to identifying steels which are resistant to these effects. The swelling of materials is of particular significance as it can distort components. A large computer code has been developed to calculate these distortions and their effect on fuel handling operations. Such calculations enable these effects to be taken into account in setting safe operating procedures for fast reactors.

Safety studies have always been an important part of fast reactor research. Two collaborations are being conducted with the USA and France and Germany to study the response of fast reactor fuel to hypothetical accident conditions simulated in experimented reactors. Harwell plays an important role in the planning and interpretation of these experiments. A computer code has been written to describe fast reactor fuel behaviour over a wide range of normal and accident conditions. This code has given increased confidence in the safety of existing designs and has provided safety guidelines for new designs.



Close-up view of water-filled test section used for fast reactor coolant studies.

REPROCESSING TECHNOLOGY

For over 25 years Harwell staff have been involved in the development of processes and plant for the recovery of fissile and fertile materials from reactor-discharged nuclear fuels. The processes now universally used are based on fuel dissolution followed by cycles of continuous solvent extraction, care being taken to minimise volumes of radioactive wastes. Special attention is paid to avoiding 'criticality' accidents by appropriate plant and process design and operating procedures. Present attention is directed towards the commercial reprocessing of fast reactor fuel, developments based on experience obtained on the present Dounreay plant. The Harwell contribution to this UKAEA programme involves:

- Flow sheet (process) development
- Dissolver development
- Solvent extraction research

Longer-term work is concerned with exploring the feasibility and potential for improving plant reliability, and reducing costs through innovative processing concepts.

The design of solvent extraction flowsheets for fuel reprocessing is dependent on the availability of comprehensive data on the distribution of solutes (uranium, plutonium, nitric acid) between the aqueous and organic phases under a wide range of equilibrium conditions. Harwell has adapted for use with fully active plutonium solutions an apparatus for the continuous collection of such data. The operation of the analytical equipment for measuring the concentrations has been extensively automated and is controlled by a microcomputer. This facility enables the collection of reliable distribution data considerably more rapidly and economically than is possible using conventional batch methods.

This experimental rig was constructed at Harwell in collaboration with the Nuclear Plant Design Office at the UKAEA's Risley Nuclear Power Development Establishment. The rig is a full-scale inactive prototype of a batch dissolver under development for the reprocessing of fuel from a Commercial Demonstration Fast Reactor.

Solvent extraction research is concerned with the development of equipment required for this phase of the fuel cycle. A Solvent Extraction Pilot Plant (SEPP) is operated to establish scale-up relationships for the throughput and efficiency required in the commercial plant. The results are also relevant to plant cost studies. Solvent extraction equipment studied has included pulsed columns and extractors using centrifugal force to assist phase-separation.

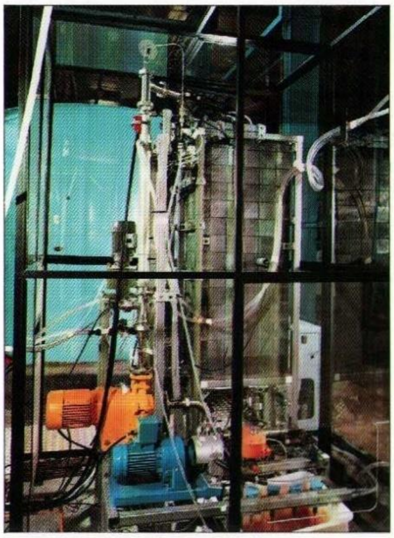
RADIOACTIVE WASTE MANAGEMENT

A wide range of projects concerned with radioactive waste management is underway at Harwell. Most of these are funded by BNFL, the Department of Environment, the Commission of the European Communities and the UK Nuclear Industry Radioactive Waste Executive (UK NIREX). The aim throughout is to reduce discharges to the environment to a minimum and ensure that the wastes can be stored and disposed of safely. The Government's strategy is to store high-level waste for at least 50 years to allow the heat it generates to decay to ease the disposal problem, and to develop disposal routes for low and intermediate level waste where there is no benefit in delaying disposal. Emphasis is therefore being placed on low and intermediate level wastes, although some work on advanced immobilisation techniques for high level waste is continuing.

Pretreatment

Pretreatment is concerned with developing processes for treating raw waste streams (gas, liquid, solid) to give a form of concentrated waste suitable for disposal and, where appropriate, a stream containing only very low levels of radioactivity for direct discharge to the environment. A particularly important area is the treatment of liquid effluents. Pilot scale development was carried out on SIXEP (Site Ion Exchange Plant) for BNFL Sellafield and an improved flocculation process is currently under development for the Enhanced Actinide Removal Plant (EARP) which will reduce discharges to sea. More advanced treatment methods such as ultrafiltration, electro-osmosis and electrochemical ion exchange are under development. These advanced processes offer the prospect of achieving high decontamination factors and the minimum of secondary wastes arising.

Decontamination of solid wastes forms an important part of the programme. Electropolishing has been shown to be capable of reducing levels of surface contamination to negligible levels. Other techniques are being developed to remove the bulk of the plutonium from a wide range of combustible and non combustible wastes.



General view of Ultrafiltration Pilot Plant for treatment of Harwell's medium active liquid waste.

Immobilisation

Immobilisation of intermediate level wastes (eg plutonium contaminated material, fuel cladding, sludges from effluent treatment) for safe interim storage and eventual disposal to an underground repository is receiving a high priority. Processes for the immobilisation of wastes in concrete, polymer modified concrete and organic polymers are currently being developed. Extensive work is underway in the testing of the immobilised product covering factors such as:

- matrix/waste material interaction
- mechanical strength
- leach resistance
- gas evolution
- fire resistance
- radiation stability

CHAPTER 2

NUCLEAR SCIENCE AND TECHNOLOGY

Concrete is emerging as the most suitable matrix for a wide range of wastes.

In conjunction with work on the immobilisation of wastes, measurement techniques are being developed for non-destructive analysis of the various wastes before and after immobilisation. The techniques include gamma spectrometry and active and passive neutron counting.

Section of solidified intermediate level solid waste – Magnox swarf in concrete.

Disposal

Research programmes in this area are establishing the basis of safety for radioactive waste repositories and justifying the selection of immobilisation. The studies cover both the engineered barriers (waste form, backfill, structure of repository) and the geological barriers, which together will ensure isolation of the wastes until they have decayed to negligible levels.

Extensive corrosion studies have shown that waste containers should remain intact for at least some hundreds of years, thus retaining the relatively short lived nuclides, including important isotopes of strontium and caesium, within the waste package. Measurements and calculations have revealed the importance of ensuring the right chemical condition in the repository to reduce the solubilities of key long lived radionuclides to very low levels indeed. These conditions are achieved when concrete is used as the immobilisation material and backfill in the repository. Harwells work with real fully active materials has shown that the long lived radioactive materials are likely to be retained for a sufficiently long period that water coming out of the repository will be at concentrations approaching drinking water levels.

Laboratory and field experiments are being carried out to establish the chemical and physical processes which control possible movement of material away from the repository. Mathematical models to describe the movement of radionuclides are under development. These studies suggest that the radiological impact of disposal under a number of different scenarios is very small indeed.

UNDERLYING PROGRAMME

- **Nuclear Studies**
- **Radiation Effects**
- **Fracture**
- **Chemical aspects of Surface and Corrosion Science**
- **Solid State Processes and Instrumentation**
- **Neutron Beam Studies**
- **Heat Transfer and Fluid Flow**
- **Theoretical Studies**

A strong scientific base is an essential part of any large-scale innovatory scientific or technological R&D programme. The main aim of the underlying programme is to provide that base for the Authority's applied nuclear research and for the UK nuclear industry. The programme at Harwell is organised in the above technical areas. Some topics are also dealt with elsewhere in this document, in Chapters dealing with the particular scientific or technical subject.

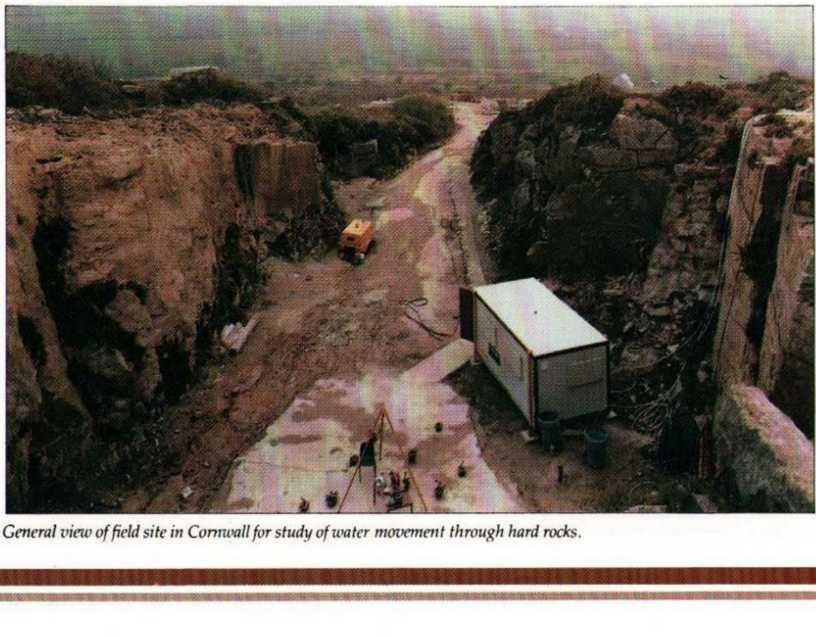
NUCLEAR STUDIES

This work is concerned with the nuclear physics of neutron reactions, the study of charged particle reactions and the study of radioactive species and their decay processes. Particular areas of note are:

- More accurate nuclear data is still needed for both thermal and fast reactor design. Significant progress is being made in refining existing data and in producing new data on fission yields and neutron capture for fast reactor materials. Such information is important to the better analysis of operating reactors and in the evaluation of new reactor designs leading ultimately to improved performance.
- Charged particle beams are being increasingly used to give valuable information about the properties of materials of importance in the nuclear industry (see Chapter 5 – Inspection, Analysis and Characterisation of Materials). Many of these techniques were originally developed as part of the Nuclear Studies underlying programme.
- Radioactive decay studies include the development of dating methods for samples of radioactive materials. These are applied to diverse studies such as safeguards of nuclear materials and the measurement of the ages and characteristics of rocks and groundwater, important for waste disposal.

RADIATION EFFECTS

The requirements in nuclear installations, both reactors and process plant, for reliability and safety are such that materials and structures must perform under conditions of high radiation levels in totally predictable ways. Important areas of work include – void swelling in fast reactor fuel element materials; the interactions of temperature, radiation damage, alloying elements and impurities; radiation effects in ceramics (eg uranium oxide) and in glasses and other possible host materials for radioactive wastes.



General view of field site in Cornwall for study of water movement through hard rocks.

FRACTURE

Fracture is a subject of importance to all reactor systems. In particular it has formed an important part of the PWR Safety Programme which includes studies of fracture mechanisms and techniques for its detection in plant components. Work in this area is also of wide industrial relevance (see Chapter 4 – Materials Science and Technology).

CHEMICAL ASPECTS OF SURFACE AND CORROSION SCIENCE

These are topics important to most process plants. In nuclear plants they are especially important because intense radiation and high heat fluxes enhance chemical activity, reaction products can help to spread unwanted radioactivity and because corrosion can severely affect plant reliability and maintenance and the radiological exposure of operators.

Work underway covers studies of the detailed chemistry of corrosion processes, the properties of colloids and particulate materials, mechanisms of surface contamination and decontamination and the effects of radiation on chemical interactions.

SOLID STATE PROCESSES AND INSTRUMENTATION

Predictable materials behaviour is vital for the safe and reliable operation of nuclear plant. This area of the underlying programme is concerned with understanding the atomic processes in solids that govern such behaviour and with the development of some of the advanced measurement techniques used by the nuclear industry (see Chapter 5 – Inspection, Analysis and Characterisation of Materials). The technique of ion implantation, a process in which surfaces are bombarded with energetic charged particles, was pioneered in the underlying programme and is now of growing general industrial importance (see Chapter 4 – Materials Science and Technology).

NEUTRON BEAM STUDIES

Neutron beams are unique and powerful probes for studying the properties of matter in bulk. Being uncharged, they do not interact with the electronic structure of matter, can therefore penetrate massive structures and can be used to measure materials properties in hostile environments.

The neutron beam programme is centred on a range of techniques relevant to most areas of underlying research as well as to many applied programmes. Work in these underlying areas is concerned with:

- the development of experimental equipment for the study of materials by neutron diffraction, inelastic scattering and radiography.
- the application of these techniques to nuclear materials.
- the demonstration of new applications of neutron beam techniques.

The use of neutron beams is included in Chapter 4 – Materials Science and Technology.

HEAT TRANSFER AND FLUID FLOW

The underlying programme in this area develops the detailed understanding of the complex heat transfer and fluid flow phenomena that occur in nuclear reactors and plant. The work, also of direct relevance to many industrial problems (see Chapter 7 – Engineering Science and Process Technology), includes:

- development of techniques to measure the flow patterns and parameters in complicated turbulent flows;
- modelling of heat transfer from hot surfaces to fluids and through fluids, both for single phase coolants and for two phase coolants where, for example, both water and steam are present;
- investigation of the effects of surface conditions (such as roughness, chemical state, fouling) on the heat transfer;
- study of the processes that may occur during reactor fault conditions and during the operation of emergency cooling systems which they might actuate.

THEORETICAL STUDIES

The above programmes are supported by a programme of theoretical, basic studies to improve the understanding of physical systems of importance to the nuclear industry. This work, mainly mathematical and computational, is applied to theoretical metallurgy, solid state theory, ultrasonics, fluid dynamics and statistical mechanics, atomic and molecular theory, nuclear theory, neutron transport and highly reliable computing systems.

COMMERCIAL USES OF NUCLEAR REACTORS

In addition to materials testing and research for the nuclear power programmes, Harwell's two nuclear reactors, DIDO and PLUTO, are used for the neutron irradiation of large silicon crystals for the microelectronics industry. Neutrons transmute silicon atoms into phosphorus, thus producing a uniform phosphorus 'doping' throughout the crystal. Nearly half the world market for silicon doping by neutrons is handled by these reactors, and current production is over 20 tonnes per annum. Recent modifications have increased the capacity of the two reactors to over 30 tonnes per annum.

Harwell also produces about two thirds of the radioisotopes sold by Amersham International plc. Many radioisotopes are short lived, and to maintain the optimum stock against possible demand requires careful planning and control of production.

Oxford AERO Charter Ltd and CES Aviation Ltd

Consignments of Iodine-123 are regularly flown from Oxfordshire to Zürich for use in Swiss, German and Austrian hospitals.

One particular isotope, Iodine 123, is a special case. The short half-life and nuclear properties make it ideal for medical purposes and many hospitals in the UK now use it regularly. However, because of its short useful lifetime, a quick and reliable delivery service to hospital is essential. Following the development of a successful service in the UK, Harwell is now supplying a number of European hospitals. Consignments of I-123 are flown direct from Oxfordshire to Zurich and then transported by road to Würenlingen for further processing and rapid delivery to hospitals and research institutes throughout Switzerland, Germany and Austria. Harwell also serves customers in Holland, Sweden and Finland.

ENVIRONMENTAL SCIENCES AND SERVICES

- **Radiological Protection**
- **Atmospheric Chemistry and Physics**
- **Environmental and Industrial Toxicology**
- **Hazardous Materials Research and Services**
- **Hydrology**

As with all operators of nuclear plant, the Atomic Energy Authority is legally obliged to comply fully with radiological protection regulations made and enforced independently.

These requirements demand staff expert in radiological protection and its instrumentation. Responsibility for safety is an operational requirement and falls on the line management; expert back-up is provided by a team of health physicists which serves the regular needs of the site for surveillance of radiation areas and personal monitoring.

The Authority's research and development programme in radiological protection and the nuclear environment is centred at Harwell. Many of the techniques and skills can also be applied to the study of a wide range of environmental problems, such as pollution by lead or dieldrin. Some examples are given below.

RADIOLOGICAL PROTECTION RESEARCH

- **Radiation Effects**
- **Radiation Dosimetry**
- **Environmental Radioactivity**
- **Accidental Dispersion of Radioactivity**
- **Instrumentation**

Radiation Effects

The Authority needs to be kept informed about the effects of very low doses of radiation such as are encountered in routine nuclear operations. Where there is uncertainty, decisions about radiological protection have to be based upon deliberately pessimistic assumptions and unnecessarily elborate and expensive protection measures are probably being taken in some areas as a result. The purpose of this part of the programme, which is carried out in close collaboration with medical research groups, is to maintain an experimental contribution to the basic understanding of the shape at low dose of the dose-effect curves and hence of the risk coefficients.

The effect of inhaled actinides in the rodent lung has been studied to measure the occurrence of long-term damage in collaboration with St Bartholemew's Hospital Medical College. Information from studies on rodents is also used to check the validity of urine analysis for the routine surveillance of workers.

Microdosimetric modelling is based on experiments with mammalian cells in order to test the predictions of various models of radiation damage such as cell killing and chromosome aberration when exposed to nuclear radiations.

Radiation Dosimetry

Research and development in dosimetry covers photon and neutron dosimetry and the determination of radioactivity in air, in environmental and biological samples and in the human body. Constant regulatory pressure leads to increasing stringency in setting protection standards. For this reason techniques of measurement available to the health physicist must be regularly reviewed and more adequate methods must be developed. Of particular current concern is the measurement of neutron dose to the person, and the assessment of internal dose, especially that due to plutonium in the lung.

Continuing efforts are made to improve the estimation of neutron dose to the person. Currently under investigation is a new plastic material in which the direct registration of proton recoils is made possible by electrochemical etching of the latent tracks.

For the measurement of radioactivity in the body improvements are sought by devising new forms of body counter or by carrying out tracer experiments with volunteers to investigate the relationship between lung burden and urinary excretion.

Environmental Radioactivity

The aim here is to discover and understand the environmental distribution of radioactivity after regulated releases from a nuclear installation (such as a reprocessing plant), the transfer between the various environmental media and hence the pathways to man. Because the amounts of radioactivity are so low, the sensitivity of measurement of the radionuclides, against baselines set by nuclear weapon fallout, has to be much greater than that required for monitoring according to the normal radiological limits.

Environmental radioactivity has been investigated in a number of regions including Cumbria and Caithness. The radioactive content is measured in samples from the atmosphere, the soil, the sea, lakes and growing plants. The results of these measurements are incorporated in models that are used to make radiological assessments at the present time and into the future. For example, it has been possible in Cumbria to estimate and predict the radiation dose to coastal residents, arising from the minute amounts of radioactivity transferred from sea to land.

Accidental Dispersion of Radioactivity

This research is concerned with the accidental release of radioactivity from nuclear installations – the initial containment, transmission through the atmosphere and finally deposition to ground and possible resuspension.

Initial containment has been investigated by studying the behaviour of aerosols in the coolant circuit of a commercial AGR and of the ventilation of the building. Measurements are made of the deposition of particles onto surfaces in rural (soil and growing plants) and urban areas.

Instrumentation

Harwell has developed a comprehensive range of instrumentation for radiological protection. This includes a range of air monitoring equipment for tasks such as detecting alpha/beta particulates in air, specific elements such as iodine, and sophisticated stack/duct monitors. This range of instruments incorporates new techniques which place them at the forefront of this technology. Other developments include tritium detection equipment and a range of gamma, neutron, alpha and beta monitors suitable for permanent installation or for portable instruments.

Examples of recent contract research in this area include the development of microprocessor-based high sensitivity neutron and gamma doorway monitors, personal dosimetry based on a radiophotoluminescent phosphorous glass and a neutron sensitive silicon diode.

CHAPTER 3

ENVIRONMENTAL SCIENCES AND SERVICES

ATMOSPHERIC CHEMISTRY AND PHYSICS
Non-Nuclear

- **Acid Rain and Acid Deposition**
  Sulphur dioxide, nitrogen oxides, chemical transformations, wet and dry deposition
- **Vehicle and Photo-chemical Pollution**
  Hydrocarbons, nitrogen oxides, photo-chemical reactions, ozone and peroxyacetyl nitrate (PAN)
- **Stratospheric Ozone**
  Halocarbons, nitrous oxide, photolytic and free radical reactions, ozone depletion
- **Atmospheric Chemistry and Atmospheric Modelling**
  Regional, global, tropospheric, stratospheric
- **Local Pollution**
  Dioxins, incineration for chemical and municipal waste

Non-nuclear Atmospheric Research

Research interest worldwide in this area has expanded considerably in recent years; many sophisticated techniques have been applied by Harwell to studying the physical and chemical behaviour of various air pollutants and their life cycles in the atmosphere. Much of this work is publicly funded and has become instrumental in the development of national pollution control policies.

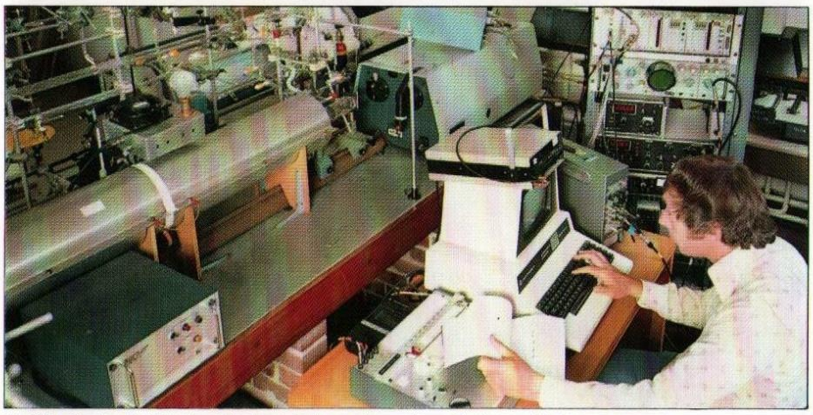
The various mechanisms by which sulphur and nitrogen oxides are converted to sulphuric and nitric acids and by which they are removed from the atmosphere are a particular area of study. Investigations of acid-forming processes in clouds are currently underway in a major field-experiment at Great Dun Fell, Cumbria in conjunction with the University of Manchester Institute of Science and Technology and the Institute of Terrestrial Ecology.

Other work is related to the presence of oxidants in the atmopshere formed by the action of sunlight on the unburnt hydrocarbons and the nitrogen oxides emitted by motor vehicles and other sources. Like the work on acid formation, this involves measurements of the species concerned, determining relevant reaction rates in the laboratory and using the results to formulate computer models for predicting the effects of various emission control strategies. There are close links with the atmospheric chemistry of acid formation and some ecological effects formerly attributed to acid deposition are now suspected of being caused by oxidants.

Harwell takes part in international investigations of the effects of man-made pollutants on the stratospheric ozone which protects the earth's surface from potentially damaging ultraviolet radiation. It is suspected that some contaminants, notably chlorofluorocarbons, may seriously deplete the ozone layer while others could offset this effect. Ozone depletion would lead to a higher ultraviolet intensity at the earth's surface and a possible increase in the incidence of skin cancer. Harwell's contribution to this programme involves determining atmospheric concentrations of the chemical species concerned, measuring the rate constants of important chemical reactions, and using computer models to calculate the likely effects on stratospheric ozone in future decades.

Harwell is also involved in the measurement, in atmospheric and other samples, of highly toxic dioxins and dibenzo furans which may be formed if PCBs and other chloro-carbons are burnt under insufficiently rigorous conditions in chemical waste and municipal incinerators. Comprehensive environmental surveys round these and other types of industrial plant are also undertaken.

Measuring the vertical profile of ammonia vapour over a wheat field to determine the rates of emission and deposition.



Studying the chemical kinetics of the atmospheric reactions using molecular modulation spectroscopy.

ENVIRONMENTAL AND INDUSTRIAL TOXICOLOGY

- **Characterisation of Environmental and Industrial Aerosols**
- **Generation of Aerosols for Research Purposes**
- **Studies of Deposition and Clearance of Inhaled Particulate Material**
- **Radiotracer Studies of Toxic and Trace Metals**
- **Short-term Toxicity Testing of Novel Materials**

The behaviour of many environmental toxins can be followed in the atmosphere, and, after inhalation and ingestions, in the human body.

A survey of the distribution of airborne lead, principally from motor-vehicle exhausts, involved field determination of atmospheric concentrations, chemical forms and particle sizes near motorways and busy streets. In addition the uptake and retention of both natural and radioactive lead in the lungs of human volunteers was measured 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.

Radioactive tracer measurements of lung retention are also used in studies of toxicity of asbestos and man-made mineral fibres. As one of the principal causes of adverse health effects associated with asbestos exposure is the durability of amphibole (eg. blue) fibres in the lung, there is considerable interest in the durability in the lung of alternatives such as man-made mineral fibres. Tests on glass fibres in the lung showed that they dissolve relatively rapidly but that fibres of rockwool dissolved much more slowly.

A radioactive tracer, suitable for use in volunteer experiments, has been developed for the tar in cigarette smoke. Measurements have been made of the changes in tar retention on switching from middle-to low-tar cigarettes, together with the location of the tar deposit within the respiratory tract.

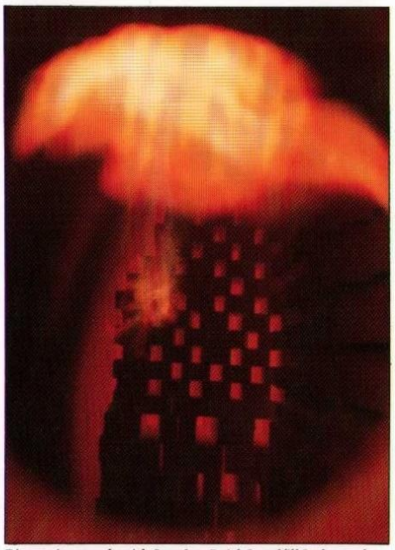
HAZARDOUS MATERIALS RESEARCH AND SERVICES

- **Waste Research**
- **Landfill Gas Exploitation**
- **Contaminated Land Reclamation**
- **Hazard Assessment**
- **Waste Management Modelling/Planning**
- **National Chemical Emergency Centre**
- **Waste Management Information**

WASTE RESEARCH

This research aims to facilitate the safe and economic disposal of domestic and industrial waste; it is carried out for the Department of the Environment and for industry.

The Landfill research programme is aimed at understanding refuse decomposition processes. The main emphasis is centred on the characterisation of landfill sites. Among the parameters studied are organic content, leachate analysis, moisture content, temperature, and gas production rates and yields: the programme seeks to relate these parameters to site operating conditions.



Pioneering work with London Brick Landfill Ltd, partly supported by the Department of Energy, helped London Brick become the first UK company to exploit landfill gas. To date, over 30 million bricks have been fired using landfill gas.

Landfill Gas Exploitation

Inflammable gas containing methane from landfill sites can be used as fuel. The potential of a large number of sites has been assessed and, where appropriate, recommendations made for a full-scale installation.

A research programme evaluates various techniques for abstracting gas from landfill sites and for stimulating more rapid gas generation rates.

The Waste Research Unit (WRU) carries out research on specific industrial waste problems. Its current programme includes examining trace gases and odours from landfill sites; solidification techniques; safe co-disposal of asbestos fibre wastes; neutralisation of acid wastes and co-disposal of copper chrome arsenate treated wood.

Contaminated Land Reclamation

Numerous sites (former gas works, chemical works and sites used for the dumping of chemical wastes) have been investigated for clients, prior to their redevelopment for housing, commerce or road improvements.

One site had been used for the manufacture of hydrofluoric acid by the reaction of calcium fluoride with sulphuric acid. Calcium sulphate waste had been deposited outside the factory buildings where it formed a hard mass several metres thick. The presence of this material could cause problems during redevelopment; remedial measures were proposed.

A site in Lancashire, previously occupied by a tannery, contained material in which significant concentrations of arsenic were present. Regular monitoring for arsine was carried out during trench excavation and strict standards of hygiene were introduced to prevent the ingestion or inhalation of contaminated material on site or in the neighbourhood.

Hazard Assessment

The Electricity Council was advised on the safety and environmental aspects of a programme to develop a totally non-flammable dielectric and cooling fluid for use in transformers. A Harwell group was responsible for overall co-ordination of the project as well as carrying out a comprehensive hazard assessment and testing programme. The new transformer fluid is not only totally non-flammable and satisfactory on other safety and environmental criteria, but also possesses exceptional heat transfer properties, thus

ENVIRONMENTAL SCIENCES AND SERVICES

enabling distribution transformers to be designed with technical and commercial advantages over all currently available models.

Waste Management Modelling/Planning

A waste management model was developed during 1983 for the Hong Kong government. It is now in routine use in Hong Kong aiding the preparation of a comprehensive waste disposal strategy to cover the next twenty years. The model comprises a suite of computer programs used interactively to construct and evaluate alternative waste management plans taking account of the variety of available technologies, the unpredictable nature of future waste quantities, uncertainty as to future costs, etc. The model is now under further development for other markets.

The National Chemical Emergency Centre

The Centre provides a 24-hour emergency response to public authorities, as an essential part of the Chemical Industry Scheme for Assistance in Freight Emergencies (CHEMSAFE).

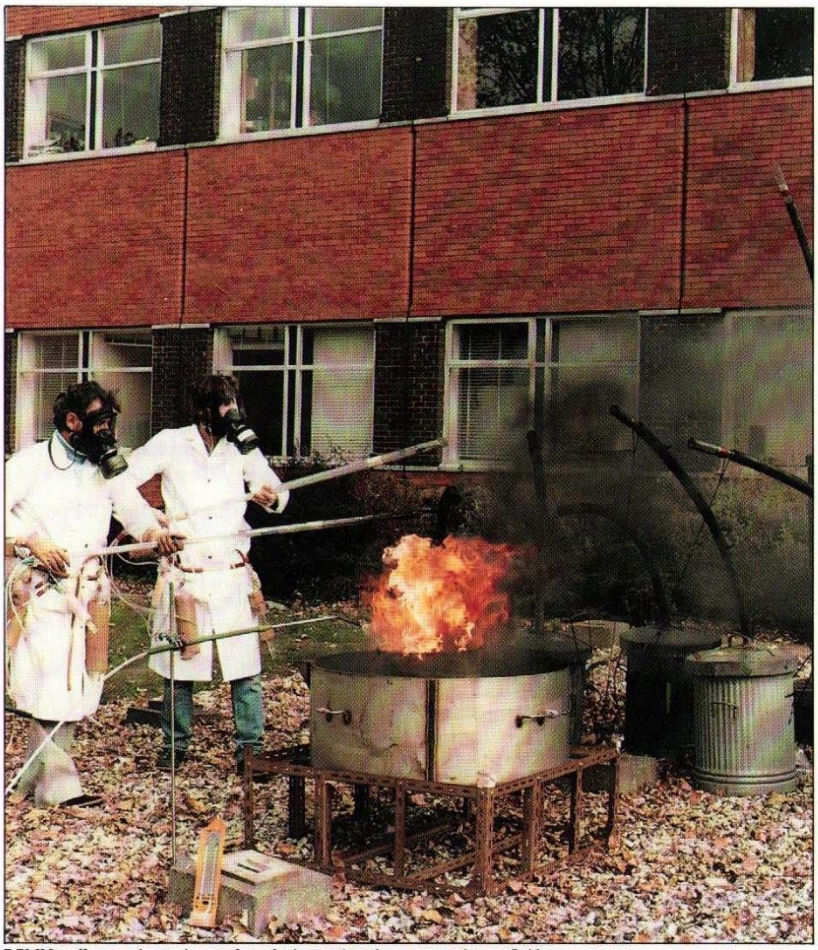
A computerised, continuously up-dated chemical databank (CHEMDATA) is now being used in the UK, Australia, Italy, South Africa and Hong Kong.

Operations include:

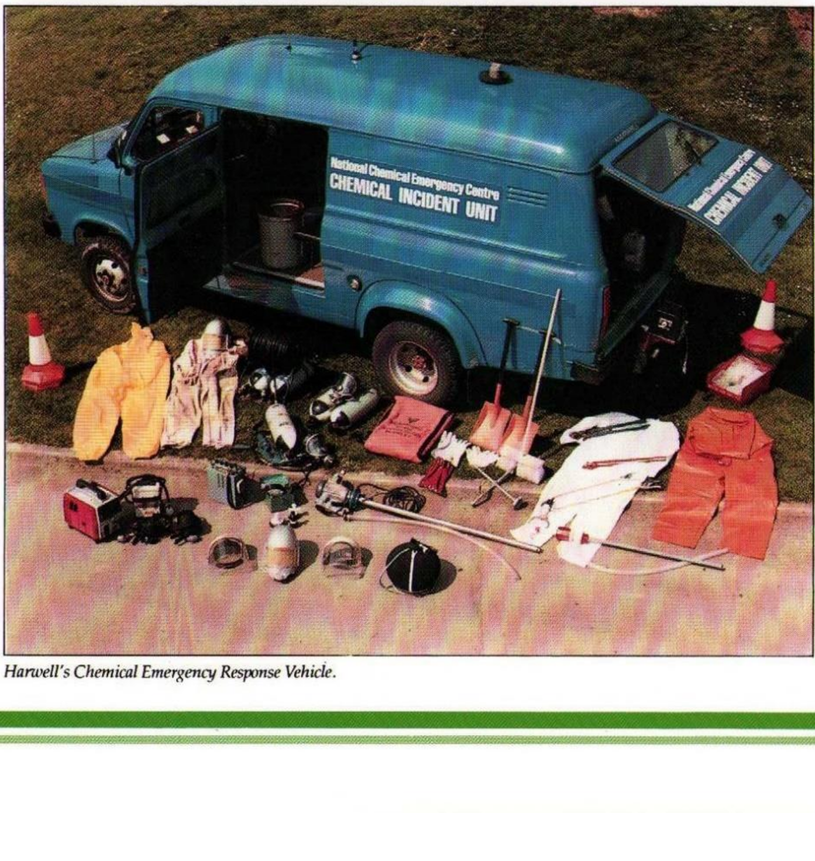
- The disposal of potentially explosive chemical or corroded industrial cylinders. A typical operation involved the disposal of aged ozonised ether discovered in hospitals.
- The decontamination of structures, apparatus or buildings. The hazards encountered are usually toxic, inflammable or explosive.

The Waste Management Information Bureau

This Bureau provides advice on non-nuclear waste management. Acting in its capacity as the national advisory centre it provides information from a comprehensive library and a computerised bibliographic database and publishes a current awareness bulletin, which is available on subscription.



PCMU staff measuring toxic gas release during testing of a new transformer fluid.



Harwell's Chemical Emergency Response Vehicle.

HYDROLOGY

- **Water Movement**
- **Water Supplies**
- **Effluent Dispersal and Recycling**

Conservation of public water supplies requires a knowledge of the movements of water through rainfall to the soil, through risers to the sea, its storage in porous rock strata and its transpiration through living plants. Radioactive tracers have been useful but the present tendency is to use natural radioactivity to indicate patterns of groundwater movement. Tritium is one of the most valuable of the radioactive 'labels' for time-scales up to about 30 years and Harwell's Low-Level Measurements Laboratory is involved in studies to relate nitrate concentrations in soils to the age and movement of groundwaters.

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 is provided by the balance of dissolved uranium isotopes where these occur in water; they can indicate movements over a million years.

The hydrology team carries out such measurements for Water Authorities and other users and interprets them as required. The behaviour of groundwater is also 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.

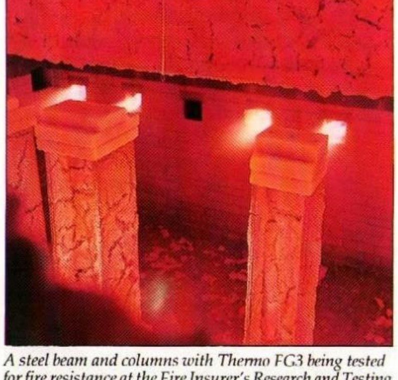
MATERIALS SCIENCE AND TECHNOLOGY

MATERIALS ENGINEERING CENTRE
- **Engineering Ceramics**
- **Ceramic Powders by Sol-Gel Processing**
- **Coating Technologies**
- **Polymer and Ceramic Based Composites**

METALS TECHNOLOGY CENTRE
- **Special Processing of Metals**
- **Interface Technology**
  - welding
  - brazing
  - joining
- **Fracture and Corrosion**
- **Ion Implantation and other Surface Treatments**
- **Metal Matrix Composites**

MICROELECTRONICS MATERIALS CENTRE
- **Special Materials Processes for the Microelectronics Industry**

Advances in materials lie at the heart of many new developments in engineering fields such as power generation, electronics, space and transport: nuclear engineering is a notable example. Nuclear power programmes continue to require detailed study of the behaviour of materials under extreme conditions of temperature, stress and in corrosive environments. New materials continue to be developed and manufactured to meet new engineering requirements. While some aspects of Harwell's materials development work are geared to specific nuclear needs, the resulting technology is of wide industrial relevance, and many of the special materials developed have found important applications outside the nuclear industry.



A steel beam and columns with Thermo FG3 being tested for fire resistance at the Fire Insurer's Research and Testing Station.

CERAMICS, COATINGS AND COMPOSITES

The Materials Engineering Centre is providing a focus for a wide range of materials developments at Harwell. An important aspect of this Centre's work concerns the development of manufacturing routes and applications for 'engineering' ceramics, such as 'REFEL' silicon carbide, reaction-bonded silicon nitride, various refractory oxides and fibre-reinforced ceramic based composites. Typically R&D in this area leads to the design, development and pilot plant production of specialised ceramic components. A recent example has been the development of a new lightweight material for use as thermal insulation and fire proofing applications. This product, called 'Cenolite,' is made by bonding together the microscopic, hollow glass 'cenospheres' which form part of the pulverised fuel-ash from coal-burning power stations. The resulting product can be moulded into a variety of shapes and panels, can be drilled, sawn and nailed and withstands temperatures up to 1000°C. This material has been developed jointly with the Central Electricity Generation Board.

The Centre is also deeply involved in the materials development and prototype fabrication of ceramic heat exchangers, gas turbine accessories and automotive engine components, and is helped in this by a wide range of supporting Harwell services, such as chemical analysis, data processing, performance simulation and computer modelling expertise.

SOL-GEL PROCESSING OF CERAMIC POWDERS

This is a group of chemical processing procedures for the production of powders of inorganic oxides, achieving close control of physical properties and forms. 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.

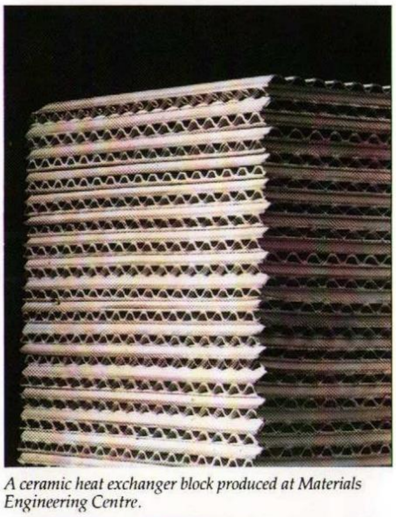
Originally developed for the preparation of nuclear fuels, sol-gel uses have expanded considerably.

Absorbent silica and alumina particles have been developed as chromatographic support materials and are now marketed world-wide by Phase Separations Limited under the trade name of 'Spherisorb.' In one example of the use of these materials for the controlled release of pharmaceuticals from gels, experiments were done with simulated gastric fluids. These 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 of the powder particles.

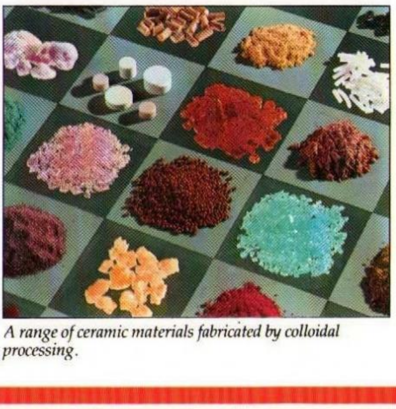
In the field of catalysis, special oxide-based catalytic materials have been developed, using sol-gel processing technology for both industrial and vehicle exhaust control applications. Some of these developments are now being manufactured world-wide by Johnson-Matthey Limited.

Other possibilities being explored and developed include:

- free flowing spherical powders;
- powders for pigments, glazes, cements and bonding agents;
- dense solid particles for ceramic and electro-ceramic production, abrasives, polishing, plasma spraying and fibre insulation;
- radioactive particles for selective radiotracer studies.



A ceramic heat exchanger block produced at Materials Engineering Centre.



A range of ceramic materials fabricated by colloidal processing.

CHAPTER 4

MATERIALS SCIENCE AND TECHNOLOGY

SURFACE COATING TECHNOLOGY

Harwell is developing advanced methods of surface treatment using thermal spraying, sol-gel washcoat methods, vapour deposition and ion beam techniques. These are important in many aspects of engineering: in thermal barrier and wear/corrosion resistant coatings, in jointing technology, in catalytic systems, and in the manufacture of sensor and other surface-dependent devices.

Thermal spraying developments are based mainly on flame, plasma, wire and hypersonic spraying of ceramics, and hard or oxidation resistant metals. Thermal barriers of yttria-stabilised zirconia have been applied to gas turbine and diesel components and a **Plasma Spraying Service** is operated as a contract coating service for industry.

Novel sputter ion plating and plasma activated vapour deposition methods have been developed which enable refractory carbides and nitrides to be synthesised on metallic or ceramic surfaces. Applications include wear resistant surfaces for turbine blades, critical bearing surfaces and nuclear reactor components.

COMPOSITE MATERIALS

Development and application of resin-based, fibre reinforced composite materials form an important part of the Materials Engineering Centre's R&D programme.

The properties of fibre reinforced composites depend on the direction and disposition of the fibres. A main theme in the Centre's composites work concerns the development of techniques for the design and fabrication of components for specific engineering requirements with the reinforcing fibres placed in appropriate directions to match the principal stresses. Important industrial applications for these materials exist especially in aerospace and in the car industry, where lightness and strength are needed for fuel economy.

Drills being coated with titanium nitride using Harwell's Sputter Ion Plating process.

Development, evaluation and component design of reinforced resin materials has now been expanded to include carbon, glass, boron and low-cost natural fibres such as sisal. Fatigue, fracture properties, toughness and impact strength are studied using extensive mechanical testing facilities, and computerised modelling and computer aided techniques are used in the design of specific engineering components. Special non-destructive methods are also being developed to evaluate composite materials during their manufacture and service operation.

Studies at Harwell on resins and their chemistry have made it possible to predict fatigue lifetimes of composite materials. These fatigue predictions have enabled longer-life designs to be made, notable applications being in automobile suspension linkages, leaf springs and other load-carrying members. Torsional fatigue effects and mechanical and thermal stresses in composite/metal joints have been studied for other automotive components including propeller shafts and coil springs.

A range of engineering components either ceramic coated or fabricated directly by plasma spraying processes.

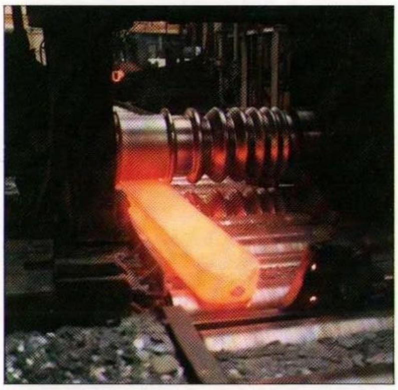
HIGH TEMPERATURE METALS, INTERFACE TECHNOLOGY AND FRACTURE

These are some of the R&D programme areas that are now being marketed to industry through the Metals Technology Centre. One of these programmes resulted in the development and exploitation of **Fecralloy Steels** which are suitable for many high temperature applications.

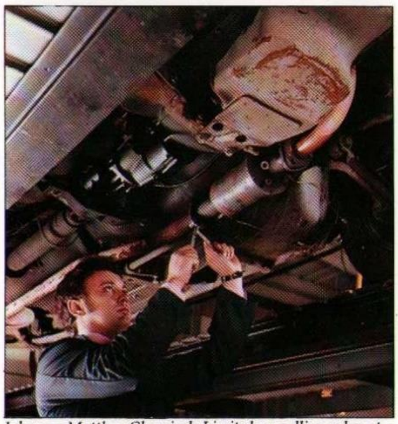
Fecralloy steel is the trade-name of a family of high-temperature, oxidation resistant steels, originally developed in laboratory scale quantities as a potential fuel cladding material for gas-cooled nuclear reactors. These ferritic steels contain chromium, aluminium and yttrium in a range of compositions tailored to the application required. They have exceptionally good oxidation resistance at temperatures up to 1200°C. Their development as a new material for industrial use was funded by the Department of Trade and Industry, and was undertaken by Harwell in partnership with specialist steel firms.*

Current applications include electric furnace windings where Fecralloy steels show marked improvement in service life over conventional nickel-chromium materials. These steels are also very resistant to sulphur attack and are being applied in the coal, gas and electricity generation industries. In the automotive field they are used as supports for exhaust clean-up catalysts and other applications being evaluated include their use as exhaust-port liners and other high temperature engine components. Potential applications in the process industries include high temperature materials of plant construction and as catalysts supports. (See Chapter 6 – Chemistry and Chemical Technology).

**Licencees: Firth Brown Limited and Resistalloy Limited, both of Sheffield.*



A Fecralloy steel billet during the early stages of fabrication into thin sheet.

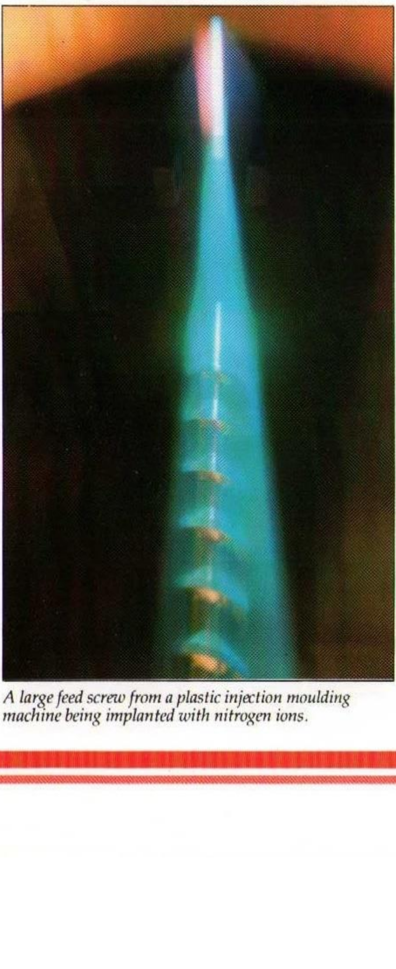


Johnson-Matthey Chemicals Limited are selling exhaust emission control catalysts based on Fecralloy steel developed at Harwell.

INTERFACE TECHNOLOGY AND SURFACE TREATMENT

R&D programmes studying the wetting behaviour of liquid metals with ceramics have led to important applications in the brazing of alloys to unmetallised ceramic surfaces and in extending knowledge of the behaviour of foundry moulds in the metal casting industry. In one commercial programme concerning the casting of nickel-based alloys for turbine blades, studies showed how surface preparation of the ceramic crucibles could reduce the blade reject rate five-fold.

Ion implantation and related ion beam surface treatments are being developed or applied for improving the surface durability of metals and cemented carbides. Research on ion implantation for increasing the wear and corrosion resistance of machine tools and critical engineering components was pioneered by Harwell. Particular applications include plastics injection moulding dies, screws and other tools, where implantation with nitrogen ions produces dramatic (up to 10 times) increases in tool lifetime through enhanced resistance to abrasive wear. This work has reached the stage where pre-production components are being evaluated by industry and Harwell-designed ion implanter machines are being marketed by licensees.



A large feed screw from a plastic injection moulding machine being implanted with nitrogen ions.

FRACTURE

Serious damage and loss of life can follow the sudden fracture of bridges, ships, aircraft, storage tanks, pressure vessels and buildings. In the nuclear field, the integrity of structures used to contain radioactive materials, such as PWR pressure vessels and piping, is clearly central to the safe operation of nuclear plant. Accordingly, the nuclear demand for research and development on fracture is of high priority.

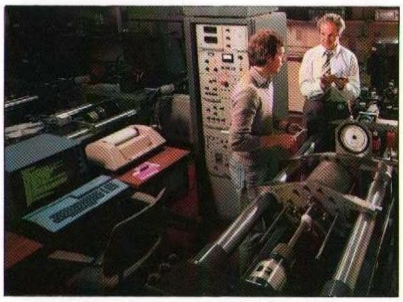
Early studies of fracture at Harwell concentrated on the problems of materials in regions of high irradiation, such as the embrittlement of AGR stainless steel cladding and the rise in the ductile-brittle transition temperature of pressure vessel steels exposed to fast neutrons. Attention was also given to components less subject to irradiation effects, e.g. primary containment circuits of thermal reactors, including the main pressure vessel, the pipework and the heat exchangers.

Until the demands of the nuclear industry had led to new ways of studying fracture, the accepted methods for predicting failure conditions in engineering structures were usually based on comparatively simple models, such as linear elastic fracture mechanics, and simple rules for damage summation. Generally these were not based on an adequate understanding of the fracture mechanisms likely to occur in service. With the growing interest in building PWRs in this country, a better understanding of failure and its prediction was essential. This led to a major research and development programme, the aims of which are:

- to develop techniques to identify and investigate the relevant microscopic properties of structural steels and the influence of steel composition and fabrication methods on those properties;
- to study the fracture behaviour of these steels under the conditions of stress, temperature, irradiation and corrosion expected;
- to develop models that allow predictions of the behaviour of full-sized structures to be made from observations on small samples;
- to develop methods of assessing and monitoring the size, distribution and development of cracks in key structures.

This programme is closely geared to other materials research at Harwell and relies on techniques described in Chapter 5 – Inspection, Analysis and Characterisation of Materials.

Investigations on ferritic steels, of practical interest in boiler and pressure vessel construction, have included studies of a wide range of embrittlement processes. A good understanding of fracture processes has been built up and studies are continuing on the effects of severe temperature transients on large components. Another important area is the study of the solidification of large steel ingots used in the manufacture of PWR pressure vessels.



Fatigue testing machine in the Harwell fracture laboratory.

MICRO-ELECTRONIC MATERIALS

A special business centre has been established at Harwell to develop ion beam and other processing techniques for the manufacture of microelectronic devices. This also provides a focus for other Harwell activities such as trace analysis and radiation damage effects on semiconductors, applicable in this fast growing, highly specialised area.

A feature of this work has been the necessity for clean working areas (also a characteristic of nuclear work). These have been established for ion implantation and processing of semiconductor wafer materials in pilot research quantities.

Fission particle tracks showing a region of natural uranium contamination covering several memory cells (about 20 microns square) of a 64K dynamic RAM.

Special ion implanters have been developed for industrial use, e.g. silicon-on-insulator technology work is based on the development of an industrial scale oxygen-ion implanter – a joint programme involving Harwell, the Culham Laboratory and VG Semicon Limited.

INSPECTION, ANALYSIS AND CHARACTERISATION OF MATERIALS

- **Nondestructive Testing**
  - Nuclear Power Inspection R & D
  - National NDT Centre
- **Materials Evaluation**
  - Neutron Beam Services
  - Accelerator Technology Centre
  - Nuclear Applications Centre
  - Solid State Instrument Service

Up-to-date, reliable techniques for the inspection, analysis and characterisation of materials are essential for advanced scientific and technological development such as nuclear power. Accordingly, Harwell is particularly well equipped for the nondestructive testing of plant and products, the evaluation of chemical reactions and process streams, and the analysis and characterisation of materials of all kinds. These techniques, and Harwell's capability for new developments, are increasingly being used under contract by industry. This chapter gives an overview of the Harwell services in this fast developing field, with examples of recent applications. Techniques for the inspection of offshore structures are described in Chapter 9 – Marine Technology.

NONDESTRUCTIVE TESTING

This is a major field of activity at Harwell and has become a substantial source of contract income.

Nuclear Power Inspection R & D

Nondestructive testing is clearly an essential part of nuclear power developments, both during manufacture and service use. Harwell has set up a special management unit, **Nuclear Power Inspection R & D**, to develop the particular capabilities needed in this field. These include development of special robots and ultrasonic probe manipulators for inspection of PWR nozzle weld regions, and evaluation of Harwell's own Time-of-Flight Diffraction method for the location and accurate sizing of defects in thick steel section.

The National NDT Centre

This Centre at Harwell provides industry with a broadly-based source of research and development expertise in nondestructive testing, backed by information and consultancy services. Launched in 1967, the Centre has a long experience of carrying out R & D for industries such as aerospace, vehicles, chemical plant, general engineering and defence.

Many industrial inspection requirements cannot be met directly by commercially available technology. In such cases, an R & D contract with the National NDT Centre can provide a cost-effective solution, for example, by clarifying the inspection requirements, by evaluating possible alternative solutions, or through the design and development of special-purpose inspection equipment. Contracts completed by the Centre have ranged from low-cost feasibility studies to large-scale developments of fully-engineered inspection systems for field use. This ability to handle a wide range of industrial work has been greatly helped by a major supporting R & D programme funded by the Department of Trade and Industry (DTI) through its Metrology and Standards Requirements Board.

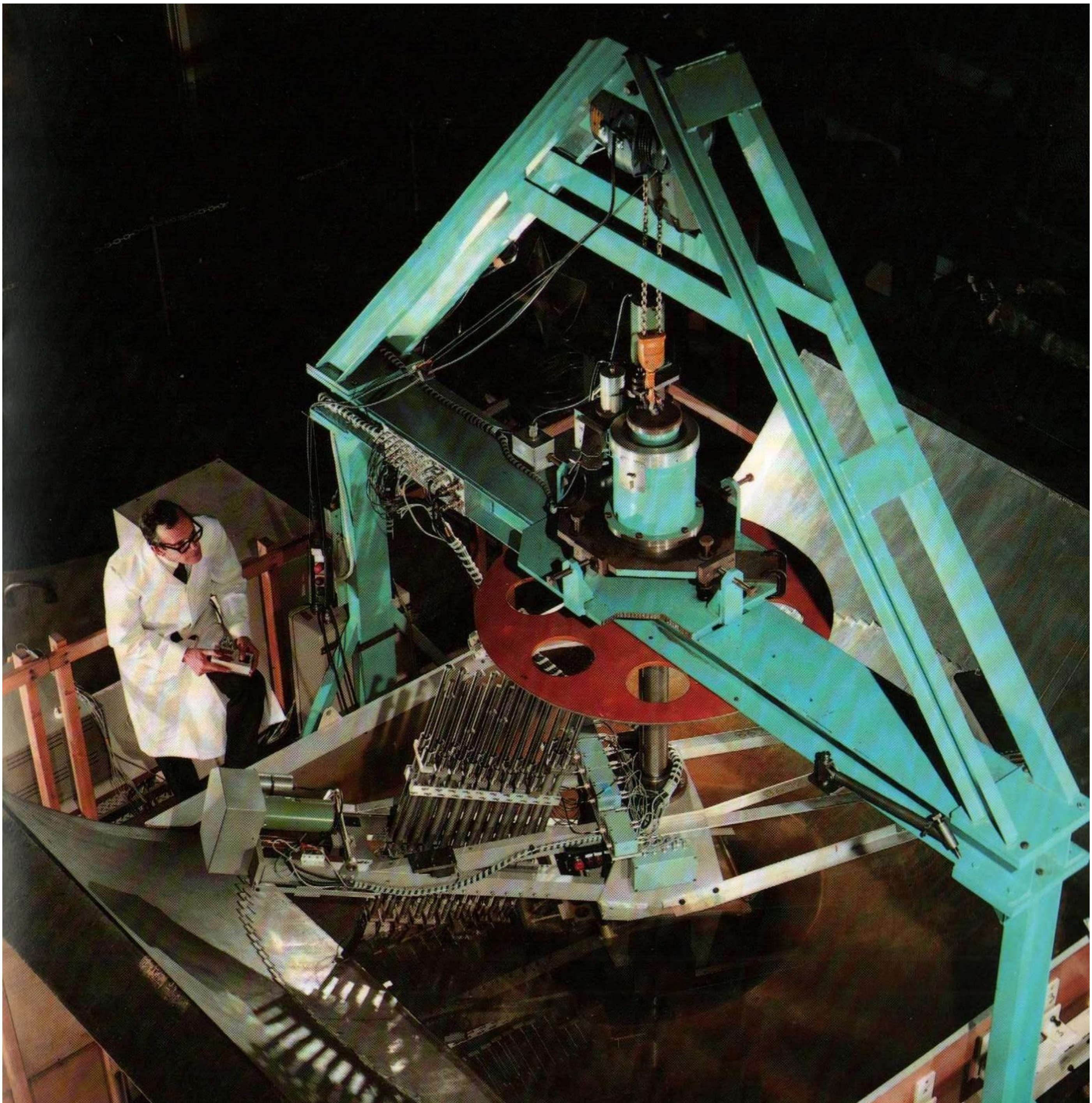
Main NDT Centre capabilities are in ultrasonics, radiography, eddy currents, thermography and data processing.

One of the Centre's largest industrial projects has been the development for the British Gas Corporation of some of the instrumentation for a special type of 'intelligent pig' which complements their existing range and which is intended to inspect high pressure gas pipelines for early indications of certain defects. This project involved a dedicated team of Harwell physicists, engineers and micro-electronics specialists. The resulting prototype inspection vehicles are now undergoing field trials conducted by the British Gas Corporation's On-Line Inspection Centre at Cramlington, Northumberland.

British Gas Corporation

A prototype gas pipeline inspection vehicle on trial.

Automated ultrasonic rig for inspection of PWR nozzle test sections.



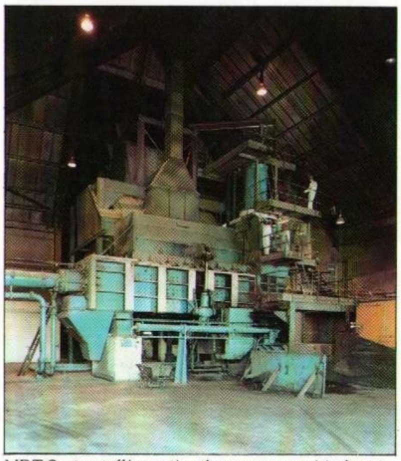
CHAPTER 5

INSPECTION, ANALYSIS AND CHARACTERISATION OF MATERIALS

A significant advance has been made in the ultrasonics field with the development of the ZIPSCAN data processing system. This greatly simplifies the collection and presentation of complex ultrasonic inspection data, and enables cracks and other defects to be located and sized accurately. ZIPSCAN is now being marketed widely under licence by SGS Sonomatic Limited for the inspection of pressure vessels, chemical reactors, etc.

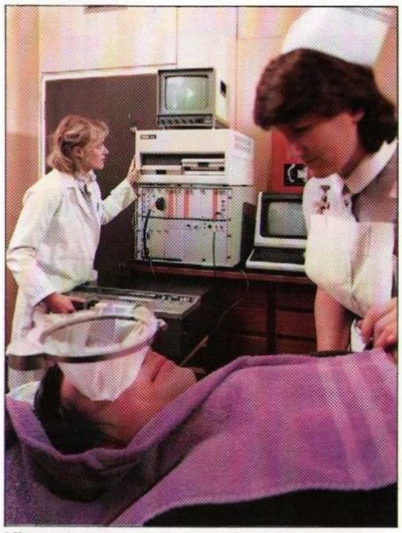
ZIPSCAN technology has been incorporated into a new ultrasonic eye scanner, now used at the Moorfields Eye Hospital to give surgeons vital pre-operation information.

Another new NDT Centre development is Pulsed Video Thermography, which uses an advanced TV-compatible infra-red camera to provide a fast technique for evaluating fibre reinforced composites and other materials on a manufacturing scale. A special 'club' of eight industrial firms has been assessing this technique, with a view to using it on their own production processes.



NDT Centre staff inspecting the ram on a municipal waste incinerator plant.

The National NDT Centre's **Advanced Applications Unit** carries out NDT services and consultancy, either at customer sites or at Harwell as required. It provides a 'rapid response' contract service, taking on those inspection tasks that NDT service companies are unable to handle. The Unit serves as a practical way of getting the Centre's new NDT developments into industrial use. Every year it handles many hundreds of enquiries from a wide range of industrial and commercial organisations on matters relating to NDT, in many cases at no charge to the enquirer. Examples of the Unit's activities include routine inspection of Rolls Royce RB211 gas turbine blades by neutron radiography to ensure the non-blockage of cooling passages, and the development of micro-focus X-radiography equipment and techniques, capable of detecting minute defects that may have caused failure in highly-stressed components.



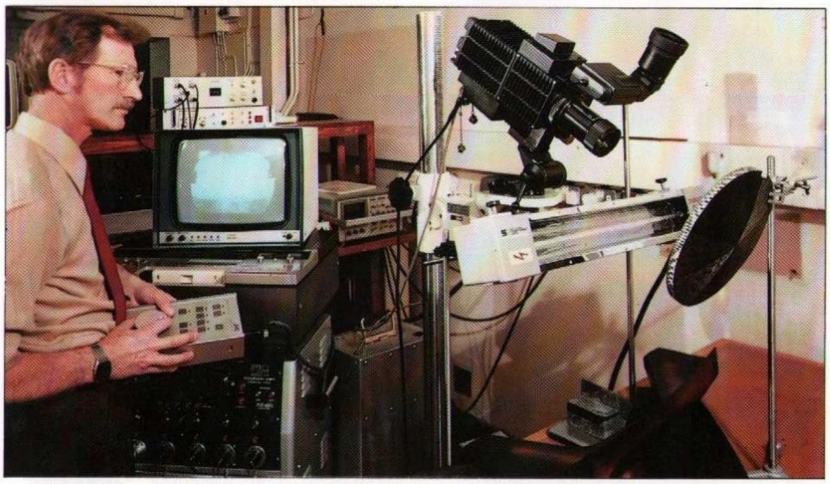
Ultrasonic eye scanner in use at Moorfield's Hospital.

MATERIALS EVALUATION

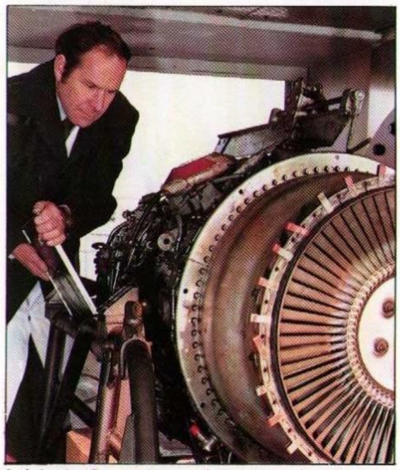
Neutron Beam Services

Most of Harwell's major facilities, such as reactors and particle accelerators, are widely used for materials evaluation and characterisation. The DIDO and PLUTO research reactors provide high quality beams of neutrons which have many applications. For example, residual stresses in fabricated metal structures can be of vital significance when fracture mechanics calculations are being made concerning the critical size of defects in stressed structures. They are very difficult to measure by conventional means and neutron diffraction measurements using reactor neutron beams provide a reliable method of measuring these stresses at any given point within a structure. Harwell's **Neutron Beam Service** is carrying out an increasing number of such measurements for industrial customers. Another technique, Small Angle Neutron Scattering (SANS), is used for nondestructive evaluation of the precipitates and microstructures that influence the properties of metal alloys.

Both of the techniques have to be carried out inside the 'shell' of the reactor, and this limits to some extent the size and nature of components that can be examined. However, for some other neutron evaluation studies it is possible to work well outside the reactor shell, allowing experiments on targeted components or working machines, gas turbines, etc. For example, a helicopter engine was examined by 'real-time' neutron radiography during rotation in order to solve a lubrication problem. Oils, being hydrogenous, are relatively opaque to neutrons, so that their flow patterns can easily be seen inside metal casings.



Pulsed video thermography being used to inspect a composite component for manufacturing flaws.



Lubrication flow studies on a helicopter engine using dynamic neutron radiography.

Accelerator Technology Centre

This Centre provides a focus for a number of Harwell's accelerators such as the Variable Energy Cyclotron, the Tandem Generator and two Van der Graaff accelerators. These are used widely for materials and process evaluation as well as for more fundamental nuclear research. The Tandem Generator is the source of 14 MeV protons used for the Thin Layer Activation (TLA) technique, a unique method of monitoring wear and corrosion processes over a long period. In the TLA technique, a thin sub-surface layer of radioactive atoms is embedded in the material or component in question by bombarding it with a beam of protons. If material is subsequently worn away from the surface by corrosion or wear, the total activity decreases. The activity level can be accurately monitored and, since the activity to depth relationship is easily determined, the amount of material worn away can be measured. The depth of the active layer can be varied, but is usually between 0.025-0.30mm.

For corrosion monitoring, Thin Layer Activation (TLA), has been developed into one of the most sensitive methods yet devised for continuous on-line monitoring of material loss by corrosion, without the need to stop processes or to dismantle equipment. Development of an industrial corrosion monitoring system, based on TLA coupon probes, is being part funded by the DTI's Mechanical and Electrical Engineering Requirements Board. Its aim is to develop rugged equipment for cost effective, on-line operation in heavy industrial or offshore environments.

Another accelerator, the 3MV Van der Graaff, is the basis of the **Nuclear Microprobe** system for surface and depth microanalysis. It is used for measuring trace-level concentrations of elements in samples, with sensitivities down to one part per million. Applications range from studies of catalyst poisoning mechanisms to forensic investigations, e.g. of trace elements present in a human hair.

TLA of a Rover 2.6 litre engine at Harwell.

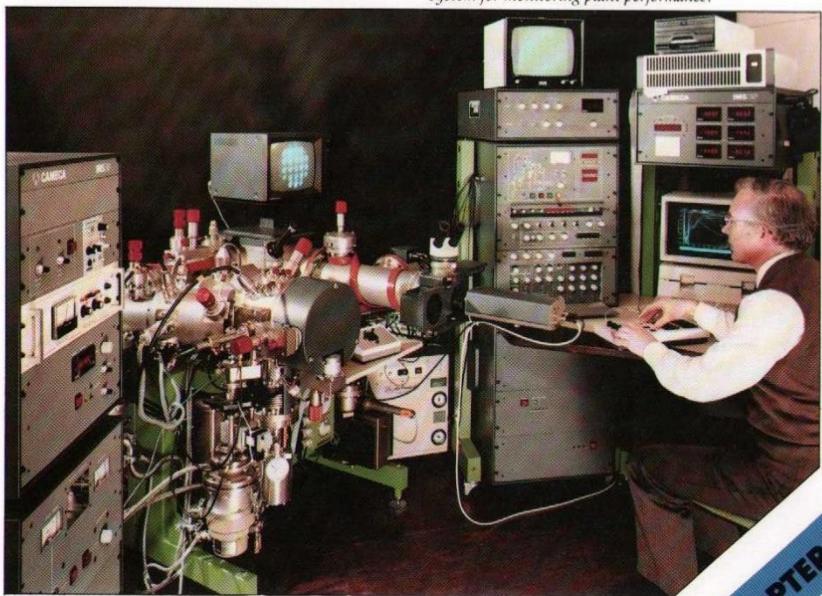
The Nuclear Applications Centre

Measurement techniques based on the use of nuclear radiation are extremely versatile. Because of the penetrating power of neutrons and gamma-rays, significant information can be obtained on the chemical composition and physical properties of bulk materials. Such measurements can usually be made through thick-walled containers, such as pipelines or chemical reactor vessels, without disturbing the system.

The Nuclear Applications Centre develops and applies nuclear analytical techniques and instrumentation especially for use in the exploration for metalliferous minerals, coal, oil and gas – and in subsequent extraction and processing operations.

Two recent examples of successful projects are:

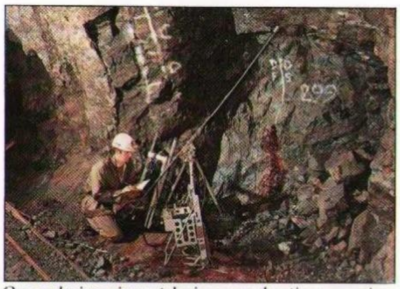
- the development of a multi-element analysis system for bulk coal, based on neutron interrogation and gamma-spectrometry. Operational parameters of interest (calorific value, ash content, sulphur content) can then be computed from values for elemental composition. This work has been supported by a Venture Capital company, Cogent Limited.
- the design, installation and commissioning of a process monitoring system for Amberger Kaolinwerke GmbH at their plant in Hirschau, West Germany. This system monitors potash composition at crucial points around the plant, based upon measurements of the naturally occurring ^{40}K isotope.



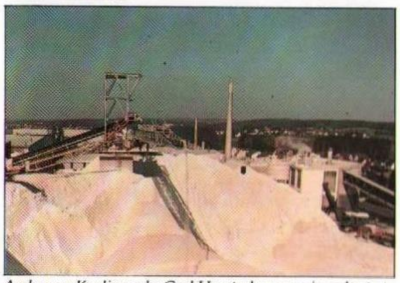
Cameca 3F secondary ion microscope used by Solid State Instruments Service for analysis and depth profiling.

The Solid State Instrument Service

A broad range of sophisticated instruments based on electron and ion beam techniques is used to examine and characterise the surface of materials, generally on a microscopic scale. Together, these instruments form an overall analytical facility that is unsurpassed by any other in the UK. Applications include fracture studies, corrosion and wear diagnosis, coating composition evaluation. Equipment charges are on a per day basis and many instruments are automated to increase their cost effectiveness.



Ore analysis equipment during an exploration survey in a Cornish tin mine.



Amberger Kaolinwerke GmbH potash processing plant at Hirschau, site of a Nuclear Applications Centre analytical system for monitoring plant performance.

CHAPTER 5

CHEMISTRY AND CHEMICAL TECHNOLOGY

- **Catalysis**
- **Process Monitoring and Control**
- **Analytical Chemistry**
- **Applied Electrochemistry**
- **Colloid Technology**
- **Radiocarbon Dating**

This chapter describes a number of technologies and services, mostly originally developed under the nuclear programmes, that are being exploited under contract research and club agreements with a wide range of industries and other organisations.

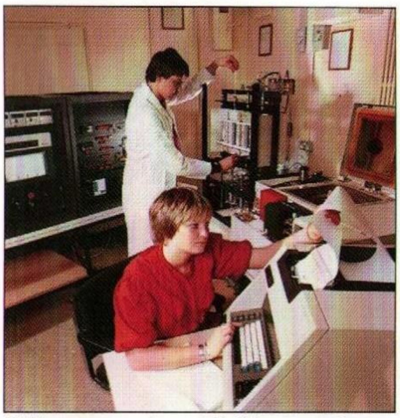
CATALYSIS

Better catalysts are needed to improve the profitability of many modern chemical processes. Harwell's unique combination of powerful surface analytical techniques with advanced materials science has provided a stimulus to catalysis research which is already benefiting British industry.

The work is backed by comprehensive catalyst testing facilities, including:

- a range of computer controlled laboratory scale reactors
- physical analytical techniques for the surface and bulk analysis of catalysts
- the use of laser anemometry and other optical techniques (see Chapter 7 – Engineering Sciences and Process Technology) for the non-invasive measurement of gas flow rate, temperature and composition in working reactors.

A pilot rig is used for realistic scale trials.



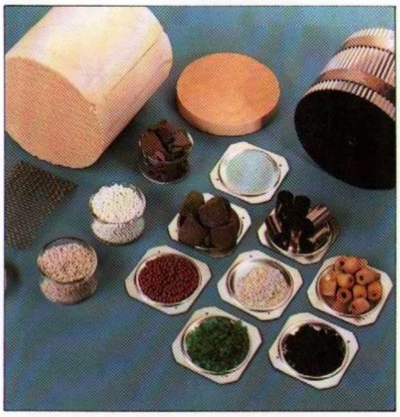
Multi purpose computer controlled laboratory reactors permit the detailed evaluation of experimental catalysts.

The work, carried out in close collaboration with industry and with partial DTI funding, has already resulted in a number of inventions, for example:

- catalyst supports made from Harwell's high temperature resistant Fecralloy steel
- an advanced nickel catalyst for steam reforming
- a lead resistant catalyst to control motor vehicle exhaust emissions
- a high temperature catalyst for a hydrogen cyanide reactor
- low pressure drop carbon monoxide (CO) oxidation catalysts with wide application, including the removal of CO from cigarette smoke.

In another programme the Catalyst Unit's low pressure drop catalyst supports and Harwell's cryogenics expertise are being combined to develop ortho to para hydrogen convertors for an earth orbiting infra-red observatory.

Commercial exhaust pollution control unit based on Fecralloy steel.



Catalysts can be fabricated into a variety of shapes.

PROCESS MONITORING AND CONTROL

Instrumentation

The growing use of computers to control process plants and the associated trend towards automation have given rise to needs for reliable monitoring methods, preferably non-invasive, and for sensors specific to particular process conditions.

Instruments have been developed at Harwell for the following:

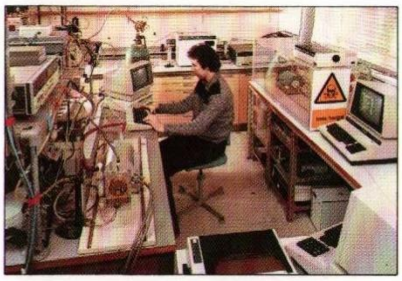
- depth and level gauging
- phase boundary monitors, e.g. interfaces between:
  - foam and liquids
  - liquid and solid sludges
  - liquids and gases
  - different solids, such as debris, fouling or crystals on metal surfaces
- flow monitoring in pipes, rivers etc.
- density, temperature and concentration monitoring
- process control by acoustic emission
- corrosion measurement by **Thin Layer Activation** (see Chapter 5 – Inspection, Analysis and Characterisation of Materials)

Many of the instruments are ultrasonic-based, non-invasive and hence suitable for hostile environments.

Chemical Sensors and Bio-Sensors

New types of sensor are required to enable improved monitoring and control systems to be developed. Harwell activities include:

- Optical and electrical sensors for chemical detection and analysis
- Enzyme-based sensors and immunosensors for detecting hormones, chemicals and metabolites in biological fluids
- FET (Field Effect Transistor) devices for detection of trace gases, e.g. CO_2, H_2, NO_2.



Sensors for detecting flammable gases under test.

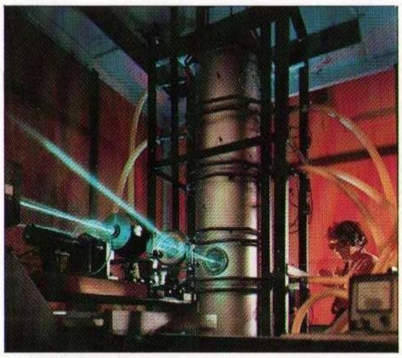
CHAPTER 6

CHEMISTRY AND CHEMICAL TECHNOLOGY

Evaluation of Chemical Reactions, Processes and Materials

Special techniques are available to give a better scientific understanding of reactions, processes and materials such as paints, detergents and fuel additives. Examples include:

- Non-invasive measurement of droplet and particle velocities in gas streams by **laser doppler anemometry**
- In-situ molecular and temperature analysis of reacting gas components using **spectroscopic methods**
- Particle sizing and counting in transparent fluids by **photon correlation spectroscopy**
- Particle sizing in opaque media by **proton straggling**
- Evaluation of microstructure in organic materials (e.g. detergents) by **neutron scattering**
- Measurement of **electrical charge** on colloid particles
- Remote or non-invasive chemical analysis of process streams by optical fibre techniques



Optical techniques measure the properties of flowing gas streams.

UK NIREX's geological studies of sites will include sampling and analysing local soils and rock formations.

ANALYTICAL CHEMISTRY

A strong capability in chemical analysis has been essential to the nuclear programme. There is a major commitment to the maintenance of the most up-to-date analytical equipment, and to the development of new analytical methods and instruments. Techniques available include mass and optical emission spectrometry, IR and atomic absorption, gas and ion exchange chromatography, X-ray and optical fluorescence, activation analysis and conventional chemical procedures. In addition to providing specialised support to specific customers, e.g. high resolution organic mass spectrometry for Universities, Harwell is increasingly involved with the solution of analytical problems generated by industry and government departments. Recent examples include:

- Instruments to detect lead contamination in food, arising during the canning process.
- Monitoring pollution from factory stacks, public waste disposal and car exhausts.
- New methods for detecting explosive devices and drugs.
- Techniques for measuring sensitivity to radiation of nuclear and satellite instruments, and analytical devices for use in satellites.
- Measurement of a wide range of trace elements in geologically derived materials including coal, fly ash and soils.
- Collection and measurement of potentially toxic organic and inorganic species of interest in occupational hygiene.

APPLIED ELECTROCHEMISTRY

The Applied Electrochemistry Centre carries out R&D in a number of fields, including:

- Batteries and fuel cells
- Electrochemical processes
- Separation processes in electric fields
- Colloid electrochemistry
- Electromachining of metals
- Electroplating, polishing and coatings
- Bioelectrochemistry

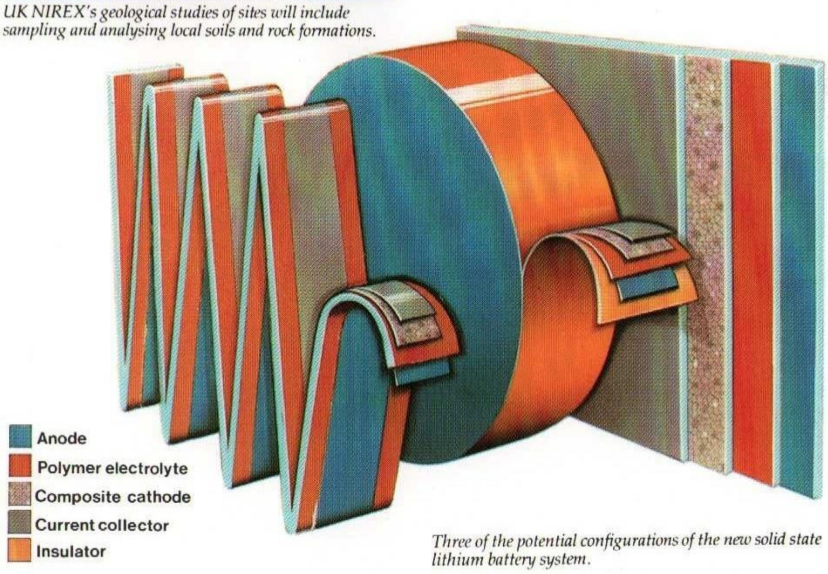
Some examples of recent work for the wide sector of industry served by the Centre are given below.

Advanced Satellite Batteries

These must be as light as possible, very reliable and have a long life. An improved, second generation nickel oxide/hydrogen cell has been developed; five 20 ampere-hour cells have exceeded 3000 charge/discharge cycles under geo-stationary orbit conditions, only 1200 cycles being required to give a satellite a 10-year life.

Solid State Batteries

A solid state rechargeable lithium battery has been investigated for vehicular traction applications, as a collaborative Anglo-Danish project with EEC and DTI funding.



Three of the potential configurations of the new solid state lithium battery system.

The research is now carried out under the Solid State Battery Working Party, with DTI and industrial funding. The solid state gives many advantages including high energy density and flexible construction. Widespread application is envisaged ranging from portable consumer products to electrically powered vehicles.

Metal Recovery and Refining

Electrochemical technology offers benefits in two areas; improved separation of metals from dilute solutions and a wider range of metal separations than is currently possible. Examples of Harwell developments include:

Electrochemical ion-exchange

A process has been developed for concentrating non-ferrous metals from parts per million to levels high enough for recovery by conventional plating methods. The process can be automated and integrated with existing electrochemical methods for metal recovery. It can also be applied to the treatment of radioactive waste streams.

Electrochemical Extraction

Solvent extraction is widely used in secondary mining operations for copper recovery from leach solutions. There is also an increasing interest in solvent extraction methods for metal recovery from mixed wastes. Harwell has developed techniques which combine the selectivity of solvent extraction with the advantages of high throughput, using new electrochemical cell design.

Organic Electrosynthesis

In recent years projects have been undertaken on (1) the electro-synthesis of bulk organic compounds in two-phase (organic and aqueous) media, and (2) enzymatic electrosynthesis of fine organic chemicals. The latter process depends on the specificity of enzymes to catalyse particular chemical oxidation or reduction reactions. Products which may be produced enzymatically, but are more difficult chemically, include key intermediates in the perfumery and flavour industry.

COLLOID TECHNOLOGY

Harwell and Bristol University operate a **Colloid Technology Consortium** the aim of which is to assist industry, particularly smaller companies, to make the most effective use of existing and currently developing knowledge and expertise in surface and colloid technology.

A wide range of techniques for the characterisation of materials and surfaces is being applied, including electron microscopy, analytical surface microscopy, light scattering, and small angle neutron and X-ray scattering. Industrial areas of interest include:

- Manufacture of colloidal dispersions: paints, inks, dyes, pharmaceutical and cosmetic products, agricultural chemicals, foodstuffs, lubricants.
- Use of colloidal dispersions in manufacturing processes; papermaking and coating, printing, textiles, ceramics, bricks and catalyst supports.
- Use of colloid technology to improve process efficiency; detergency, mineral extraction, oil recovery, metal working, wetting of powders, adsorption of impurities.
- Removal of unwanted colloids: water purification, fining of wines and beers, sewage disposal, breaking of oil emulsions and foams, dewatering of sludges.

RADIOCARBON DATING

Radiocarbon dating can be used to determine the age of archaeological, geological and hydrological specimens up to about fifty thousands years. Harwell is one of some 150 laboratories in the world which measure carbon-14 at the very low levels required.

A speciality of the laboratory is the ability to make radiocarbon dating measurements with extremely small sample sizes, even down to as little as ten milligrams of carbon. Harwell was the first laboratory in the world to set up a commercial service for such small samples (1981) and remains one of under ten laboratories currently able to do so. The techniques allow measurements to be made virtually nondestructive and are therefore of importance in the dating of ancient objects from which only a tiny fragment can be made available for the tests.

A recent example of its application is the dating of the first British 'bog-man' (Lindow Man) discovered in a peat bog in Cheshire. A date was obtained from measurements on a few tiny wrist bone fragments.

Harwell's Isotope Measurements Laboratory used the Carbon-14 counting facility to date the 'bogman' discovered recently at Wilmslow.
Photo: Courtesy of British Museum.

ENGINEERING SCIENCE AND PROCESS TECHNOLOGY

- **Heat Transfer and Fluid Flow**
- **Fouling**
- **Combustion and Internal Combustion Engines**
- **Energy Conservation Technology**
- **Separation Processes**
- **Biotechnology**

Nearly all the activities described in this chapter arose from the unique technical demands of the nuclear power programmes. For example, the need to remove the heat generated in a nuclear reactor under all anticipated operating conditions, including fault conditions, calls for a detailed understanding of heat transfer and fluid flow phenomena in complex plant. This, in turn, has required the development of completely new experimental and theoretical techniques. These allow the complex processes involved to be measured and analysed in detail and enable basic reactor concepts to be translated into safe, reliable and economic nuclear plant. The knowledge, skills and extensive test equipment developed have found application in a wide range of non-nuclear industries, through the activities of the Heat Transfer and Fluid Flow Service (HTFS). The Separations Processes Service (SPS), Combustion Centre and Fouling Forum have grown in a similar way to exploit and further develop skills and techniques originally developed in the nuclear programmes.

HEAT TRANSFER AND FLUID FLOW SERVICE

This is an international multi-client 'club' or organisation with over 160 members which provides design and research information in applied heat transfer and related fluid flow fields. It was established in 1967 and is now jointly operated by Harwell, the National Engineering Laboratory at East Kilbride and the Chalk River Nuclear Laboratories in Canada. The headquarters of HTFS are at Harwell.

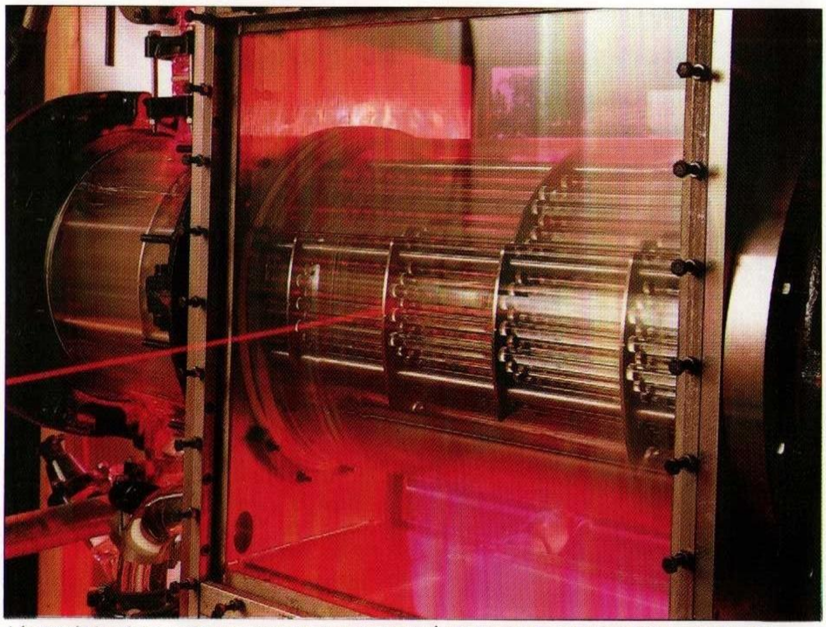
The activities of HTFS may be split into three parts:

The HTFS Research Programme

Work is conducted in seven main areas defined and developed in close co-operation with industry:

- Condensers
- Boilers and pipeline systems
- Refrigeration, air conditioning and proprietary heat exchanging equipment
- Cryogenic heat transfer
- Furnaces
- Air cooled heat exchangers
- Single phase heat transfer equipment

The results of this research are transferred to industry via the Subscription Information Service.



A laser technique being used to investigate the flow distribution on the shell-side of a shell and tube heat exchanger.

The Subscription Information Service

In return for an annual fee, member companies receive a design handbook, design reports, computer programs for equipment design, consultancy and access to the HTFS Information Office.

The information and guidance provided by HTFS are accepted as setting new standards in the design of industrial heat transfer plant.

HTFS Contract Research

The staff and facilities of HTFS are made available to member and non-member companies and other organisations on a confidential contract basis.

All members of HTFS automatically become members of the Fouling Forum (see next section).

FOULING

This programme, operated in collaboration with the National Engineering Laboratory, is providing improved understanding of fouling, particularly in heat exchangers and recently, in offshore installations. Recent developments include:

- Establishment of key parameters which cause scaling in heat exchangers, leading to the design of non-scaling equipment.
- Qualitative understanding of the growth and removal of biological fouling layers on surfaces.
- Studies of fouling in offshore operations such as fouling in oil wells, pipe scaling in the North Sea and formation of scales on offshore structures.

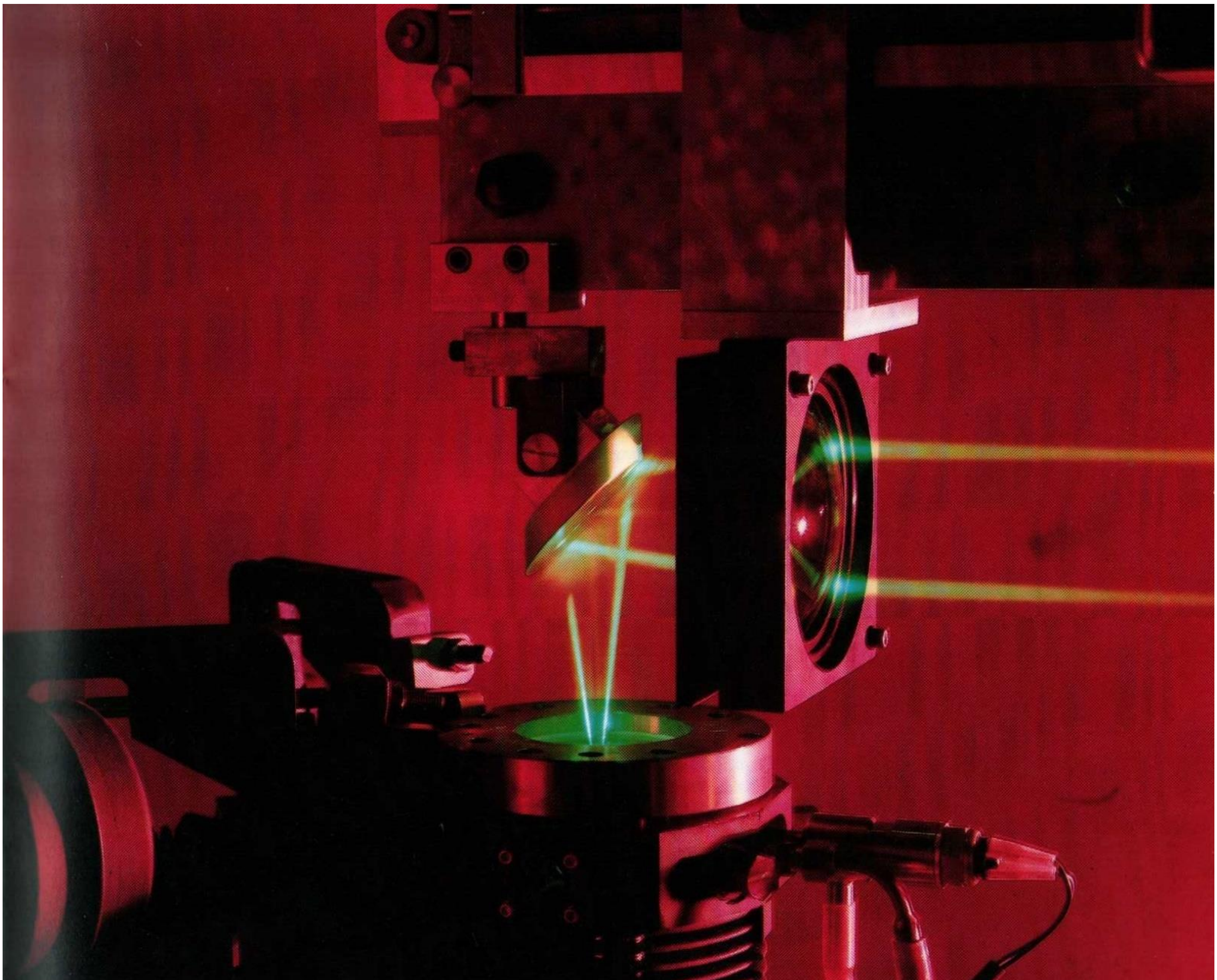
The results of the research are made available to members of the **Fouling Forum** through a computer-based information service.

ENERGY CONSERVATION TECHNOLOGY

A major programme to help industry develop new energy conservation technologies has been launched by the Energy Efficiency Office of the Department of Energy and Harwell has programmes in the following areas:

Energy and Process Integration Services (EPI)

This is a consultancy service aimed at UK process plant operators in a variety of



CHAPTER 7

market sectors including chemicals, petrochemicals, food and drink and oil. It was started in November 1983 in collaboration with Imperial Chemical Industries, based on "Energy and Process Integration," a technology pioneered by ICI. It involves first establishing the minimum practical energy requirement for a given process using advanced computer software. Systematic computational procedures are then used for integrating individual processes into an energy efficient system, optimising design and balancing capital costs against energy savings. Dramatic energy savings (10-60%) with short payback times (three months to two years) can be achieved.

EPI, which operates from Harwell, has conducted work for, amongst others, Procter and Gamble, Courtaulds and Gulf Oil.

Low Temperature Heat Utilisation

Sources of low temperature heat, such as industrial process and effluent streams, could form a valuable energy resource, equivalent to around 12 million tons of coal per year. The Harwell programme is designed to help industry to develop new equipment and techniques to enable this energy saving potential to be realised. It involves technical and economic assessments of suitable technologies, including heat pumps, heat exchangers and heat storage systems and is being carried out in close consultation with energy users and equipment suppliers. It is planned to extend the work into high temperature heat recovery and control and monitoring systems for energy management.

COMBUSTION AND INTERNAL COMBUSTION ENGINES

During the mid-1970s, automotive engine designers were faced with growing but conflicting demands for higher efficiency, lower pollution, less noise and increased fuel tolerance, all combined with a need for shorter development time in order to meet growing commercial competition.

Harwell has applied its expertise in hydrodynamics, chemistry, electrical and mechanical engineering, instrumentation and data handling, largely originating in the nuclear programmes, to the study of combustion processes inside running engines in a programme funded by the Department of Trade and Industry and guided by an Advisory Committee drawn from major UK engine and component manufacturers and fuel companies.

In particular laser techniques were developed to measure air flow and turbulence, fuel droplet size and velocity distributions, both at chosen positions in the cylinder, and at chosen points during the engine cycle.

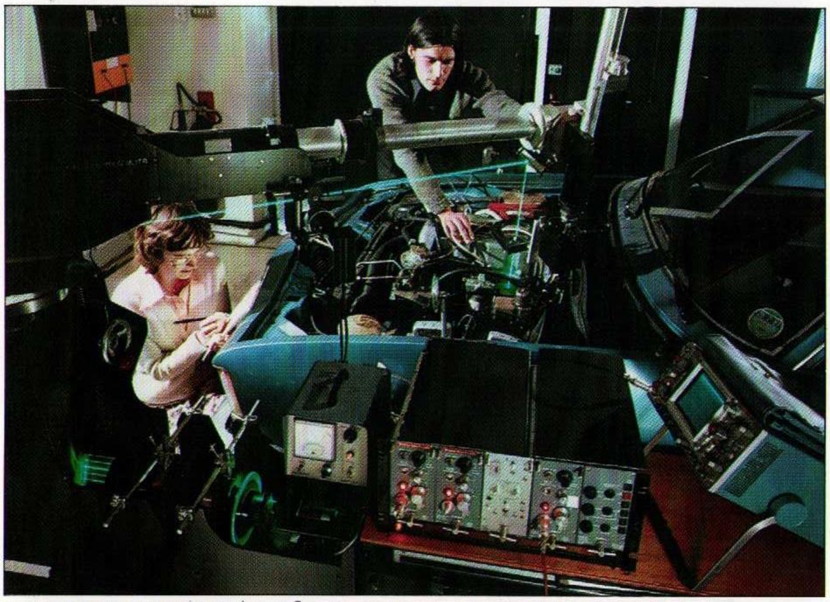
Another optical technique, Coherent Anti-Stokes Raman Spectroscopy (CARS) was also developed to give more detailed information on the combustion process. The instrument designs and techniques developed in this programme have been licensed commercially.

More recently the **Harwell Combustion Centre** has developed and evaluated mathematical models for the flow and combustion processes in internal combustion engines in collaboration with Imperial College, London, for BL Technology, Fiat, Peugeot/Citroen, Renault, Volkswagen and Volvo.

Other areas of activity include:

- The International Energy Agency Combustion Programme which has led to an improved model of the chemical kinetics of "knock" in gasolene engines; an important issue when lead is barred from petrol.
- Work for a consortium of UK and Continental medium-speed diesel engine and component manufacturers and fuel companies on the ignition and combustion behaviour of residual fuel oil. This programme is also supported by EEC funds.
- The further development of CARS to enable temperatures to be measured with good accuracy in combusting systems, even at high pressure. A new British company EPSILON has been formed to supply CARS software and instruments developed at Harwell.
- A survey of combustion research in the European community. This is providing the base for the next phase of the EEC Combustion Programme.

The initial programme on engines has therefore led to major business development in a wider combustion field. It has also provided important techniques for the study of chemical reactions and surface catalysis which are playing an important role in several other Harwell industrial research programmes.



Contract Research for Lucas CAV measuring engine aerodynamics to improve fuel injector design using the Harwell laser anemometer equipment.

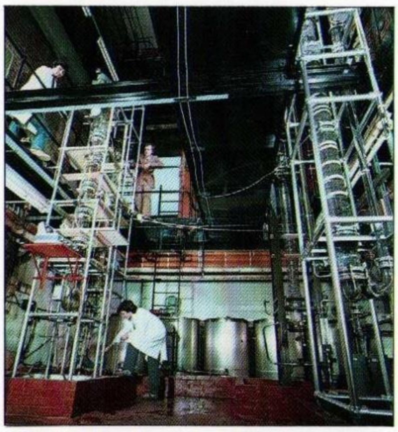
SEPARATION PROCESSES SERVICE (SPS)

This, also a multi-client 'club', is a joint service operated by the Harwell and Warren Spring Laboratories. It provides design information, consultancy and research on selected separation processes, making full use of the resources of Harwell, Warren Spring and, when appropriate, other centres of expertise in the UK. Programme subscribers receive design information, consultancy and research results on selected separation processes, including:

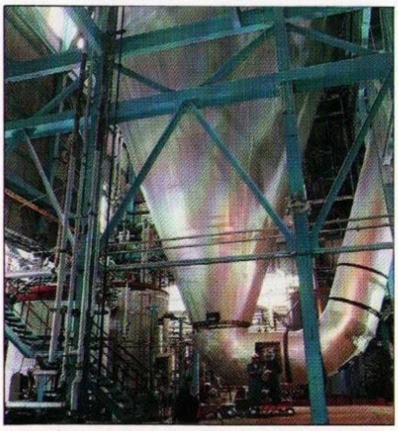
- solids drying
- gas cleaning
- solid-liquid separation
- liquid-liquid separation
- crystallization

Members take an active part in the selection of the work undertaken in the

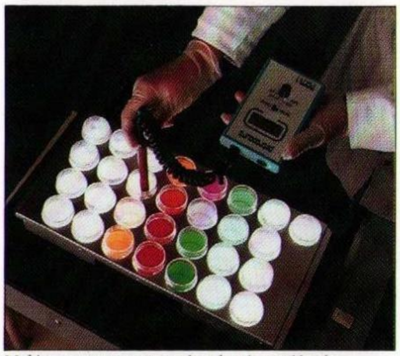
R&D programme, which embraces all the above topics, and in the Information Service. Design Reports give recommended procedures for equipment selection, reagent selection and equipment design; where appropriate, computer programs are provided for their implementation. Contract R&D is undertaken for individual member firms. SPS has a number of American members with British subsidiaries and an SPS symposium was held in St. Louis in 1984.



An SPS liquid-liquid extraction laboratory.



A team from SPS Harwell working on a spray dryer used in the manufacture of detergent. The dryer is operated by the British company Albright & Wilson Limited and is the largest of its kind in Western Europe.



Making measurements on dyes fractionated by the BIOSTREAM continuous electrophorectic separator.

BIOTECHNOLOGY

- **Enzyme Technology**
- **Cell Technology**
- **Biochemical Separations**
- **BIOSEP**

Harwell's expertise in chemical engineering and the biosciences has provided the opportunity for a multidisciplinary approach to a number of industrially oriented biotechnology programmes.

The main programme areas are:

Immobilised Enzyme Technology

A major technological advance in enzyme technology has been the development of the hetereogeneous catalysis, i.e. the use of enzymes bound to insoluble particles rather than fully soluble enzymes. This has resulted in increased productivity, improved process control and more compact production plant. The Harwell contribution has been the development to pilot plant scale of a range of porous ceramic spheroids (e.g. titania and kieselguhr) into which enzymes are incorporated. Porous titania and fabricated kieselguhr beads suitable for use as enzyme supports are currently manufactured under licence from Harwell by Sterling Organics Limited under the trade name "Macrosorb."

Immobilised Cell Technology

Some high value industrially important chemicals can only be obtained economically from living cells. Tissue culture has recently offered a new route for the biosynthesis of plant and animal cell products but these cells grow and divide very slowly and require complex growth media. Harwell has developed immobilisation techniques to permit more efficient use of these cells over prolonged periods in compact reaction systems.

The industrial applications could be numerous: steroid and alkaloid drugs, natural biocides, colouring and flavouring from plant cells and antibodies from animal cells.

Harwell has succeeded in developing methods of immobilising plant cells and continuously recovering secondary metabolites from the process fluid. These techniques are currently being adapted for the immobilisation of animal cells, particularly hybridomas, for the large scale production of monoclonal antibodies.

Biochemical Separations

A major development has been a large electrophoresis system. This provides continuous separation in a dilute buffer solution which flows through an annulus between two concentric cylinders, the inner stationary, the outer rotating. The solution to be fractionated is introduced at the base of the column; at the top the stream is separated into 30 separate fractions. Excellent recoveries of valuable biologically active materials have been obtained. The system is capable of handling cells without rupture, separating small ions and charged molecules. One important application has been for the fractionation of human blood plasma. The potential of this device is being exploited by CJB Developments Limited who sell the BIOSTREAM* separator worldwide.

**Trade mark CJB Development Limited.*

Harwell's electrophoretic separator, now licensed to CJB Developments Ltd. Its main application is the separation of macromolecules such as the anti-haemophilia Factor VIII from blood plasma.

BIOSEP

This Club is jointly operated by Harwell and the Warren Spring Laboratory with financial support from DTI. It provides design information, consultancy and research on the new downstream processes which will be needed to exploit new biotechnological production methods. The club has a membrship of about 50 and provides (like HTFS and SPS) a computer-based information service, design reports on new plant concepts, and a research programme on topics which are selected by the subscribers. These currently include adsorption, chromatography, membrane processes and protein recovery.

COMPUTER SCIENCE AND SERVICES

- Information Systems
- Scheduling and Planning
- Control (production, contract, project)
- Mathematical Modelling
- Knowledge Based Systems
- Decision Support Systems
- Software Engineering
- Computer Services

It has been essential to the development of nuclear power, as with other advanced technologies, to take full advantage of the latest available computer technology, both hardware and software. Harwell has accordingly one of the most powerful computing facilities in Europe. The provision of computing services at Harwell is the responsibility of the Computer Sciences and Systems Division which has four major roles:

- to provide computing support to all programmes and projects
- to carry out contract R&D for external customers
- to develop special purpose software
- to provide advanced computer facilities

Examples of this work are given below.

INFORMATION SYSTEMS

As the volume of useful information increases, many businesses and organisations are turning to the computer for help. However, computer information systems often deal only in figures and coded data, with the result that information becomes constrained to fit the computer program.

Harwell is one of the pioneers of text information storage and retrieval systems. Its STATUS package is marketed worldwide and used by a variety of organisations for a wide range of applications. The package can also be used in conjunction with other software products to provide such facilities as graphical and statistical analysis, and with knowledge-based systems to enhance the effectiveness of the search for information.

Information Management

The flexibility of the STATUS free text system has resulted in it being used for a wide range of very different applications. These can be classified into two major groups:

Full Text Systems

- legal statute, cases and related documentation
- documents in support of litigation
- technical reports, patents etc
- market intelligence
- accident or incident information systems
- office systems

Bibliographic Record Systems

- catalogues for special libraries
- catalogues of reports and document collections
- personnel records
- maintenance records

A prototype system for compact disc based information retrieval using STATUS.

Many applications involve an integrated Information Technology system with word processors, electronic mail, information storage and retrieval, and report or bulletin production. A major feature of STATUS is its ability to link readily with other parts of a total system without the need for further software development.

SCHEDULING AND PLANNING

Harwell has developed new and effective techniques for the traditionally difficult areas of planning, scheduling and production control. Major areas of expertise include:

Scheduling and Planning

Production scheduling, road vehicle scheduling, bulk carrier, oil tanker and cargo liner scheduling.

Control

Production control, contract management, project management.

Optimisation

Optimised layout for waste minimisation, blending and mixing, resource allocation, optimised packing.

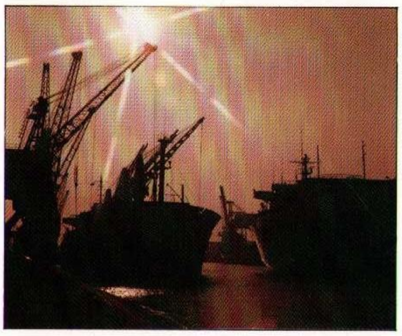
Examples of major projects in this area are given below:

Fleet Scheduling and Planning (FS&P)

FS&P is a management system designed in collaboration with major UK and Scandinavian fleet operators. The primary functions of the system are:

- long term scheduling of the fleet
- budget prediction
- evaluation of business opportunities
- assessment of alternative programmes of fleet renewal and expansion

Similar techniques have been developed for scheduling the movement of goods by road.



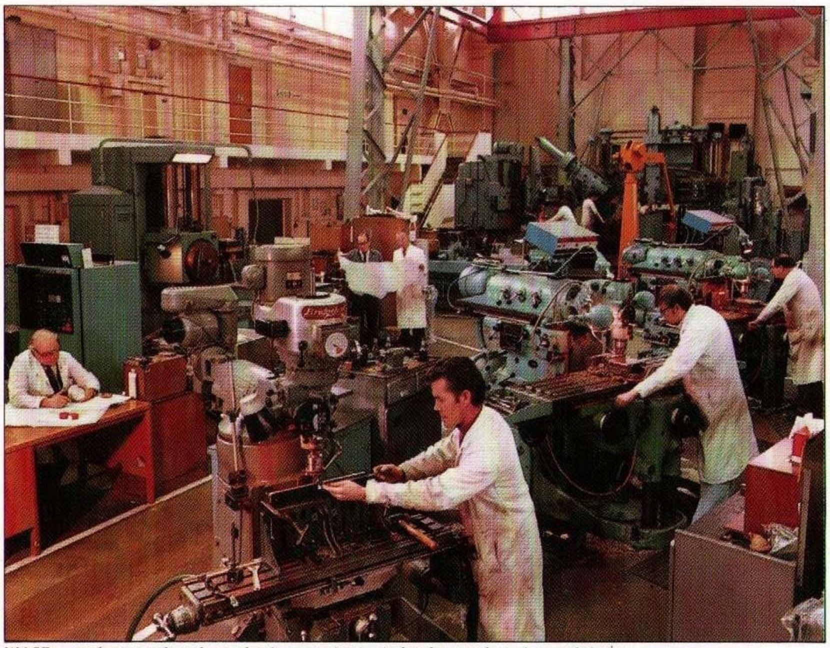
CHAPTER 8

COMPUTER SCIENCE AND SERVICES

Workshop Analysis and Scheduling (WASP)

Designed for use by small batch manufacturing workshops and job shops, the WASP software analyses and schedules variable workloads according to the availability of operators and machines. Better scheduling improves productivity, reduces costs and ensures that target dates are met. WASP displays all shop floor loads and future schedules and produces progress reports and planned completion dates for every job in hand. WASP can be used on personal computers and many mini and mainframe computers with a FORTRAN compiler.

WASP users include Philips Electronics, the National Coal Board, Davy McKee, the Ford Motor Company, the General Electric Company, and the National Engineering Laboratory.



WASP — a software package for production organisation in batch manufacturing workshops.

MATHEMATICAL MODELLING

Complex problems arise in many industrial or chemical processes and the best solution is not always immediately apparent. Trial and error approaches are time-consuming and expensive, and produce uncertain results. By the construction of computer models, the physical situations can be represented in a mathematical form, and a range of options can be simulated to determine the optimum conditions under which a system should be operated to achieve its objectives.

Several software packages which apply mathematical methods to solve complicated real life problems have been developed at Harwell. Areas in which these modelling techniques have been used include:

- fluid (liquid and gas) flow in systems
- chemical reaction kinetics
- oil reservoir extraction regimes
- general reservoir modelling
- nuclear reactor incident models

HARWELL SUBROUTINE LIBRARY

The Harwell subroutine library is a collection of over 300 subroutines, mostly written in FORTRAN, for assisting with numerical mathematical tasks. Topics addressed include differential equations, mathematical functions, linear algebra, numerical integration, approximation and data fitting, sorting, optimisation and solution of non-linear equations, and there is an extensive range of utility routines for IBM installations. This library is now used by over 600 organisations around the world.

ADVANCED PROGRAMMING AND KNOWLEDGE BASED SYSTEMS

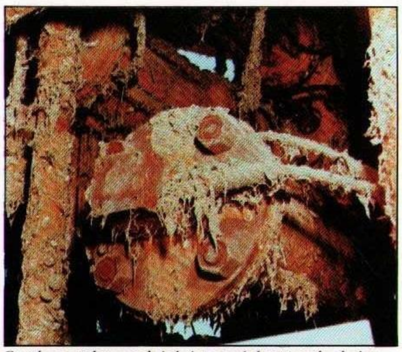
The applications of techniques derived from research in the field of artificial intelligence are providing many new approaches to the development of computer based systems. Harwell has considerable experience in constructing and using expert systems and is active in the following areas:

- the use of high level, logic based programming languages
- the development of consultative knowledge-based ('expert') systems

Intelligent knowledge-based systems under development include:

Corrosion Applications
ACHILLES Club

A number of expert systems which use corrosion information from an extensive database are being developed by the Metals Technology Centre at Harwell and the National Corrosion Service at the National Physical Laboratory with the assistance of industry. Two prototype expert systems for corrosion have been used to provide interactive advice and have met with an enthusiastic response from potential users. Consequently a 'Club' is being set up to develop over a three-year period a set of expert systems which will incorporate a substantial digest of corrosion information and give appropriate recommendations.



Fundamental research is being carried out on the design and performance of cathodic protection systems.

Chemical Plant Design

A prototype expert system for the selection of solid-liquid separation equipment is now used by the member companies to the Harwell and Warren Spring Laboratory's Separation Processes Service (see Chapter 7 – Engineering Science and Process Technology). The system advises on the selection of sedimentation, filtration and electrical and magnetic separation equipment.

DECISION SUPPORT SYSTEMS

Decision support systems are planning tools, to provide the manager with an integrated set of sub-models in order to gain a fuller understanding of the planning process. With these tools the planner may examine each aspect of his problem, test the sensitivity of subjective assumptions and evaluate the impact of a wide variety of scenarios. Recent projects include:

Solid Waste Management

A computer model originally developed to assist the Hong Kong Government to determine future policy on waste management is now being developed further to meet the needs of waste management planners worldwide.

Uranium Enrichment Market Assessment

A system of programs has been developed as planning aids for a uranium enrichment consortium. The capabilities of these programs include:

- exploration of demand for, and availability of, enriched uranium on a worldwide scale
- scenario generation of demand and cash flow arising from the consortium's long-term contracts

The Cray computer, one of Harwell's most advanced computer facilities.

SOFTWARE ENGINEERING

Software engineering tackles vital problems in the development of software that is reliable, manageable and meets specifications. Specific requirements are to:

- improve the quality of design
- facilitate software production and maintenance
- support project management
- minimise software life cycle costs

The Computer Science and Systems Division develops and markets software packages for this purpose. One example is the 'Program Development Facility' (PDF). This is an advanced tool for the generation and maintenance of computer programs, using the widely accepted Jackson Structured Programming method. Structure diagrams and text are prepared and edited at the computer terminal prior to the automatic generation of the code. When requirements change, structure diagrams are modified with PDF, thereby removing the need to maintain programs. PDF offers code generation in a number of high level languages.

Harwell is collaborating with GEC-Marconi and Imperial College in an Alvey Directorate project. The aim is to develop rigorous methods and to produce supporting program tools which assist in formulating precise customer requirement specifications and aid the task of designing and writing complex computer software.

COMPUTER SERVICES

Powerful computing facilities are important for much of Harwell's work and the Computer Science and Systems Division has the responsibility of providing the main service, which is currently based on IBM and Cray mainframe computers, together with various peripherals to handle communications and special facilities. There are about 700 terminals and minicomputers on the Harwell site linked to the mainframes. In addition, there are a further 150 terminals from the other establishments of the United Kingdom Atomic Energy Authority. Authorised users from outside Harwell may access these facilities by various methods including dial up, direct leased lines, Kilostream and Megastream services and Packet Switch Stream (PSS) connections. The central services are available commercially to external organisations who have specific requirements to use Harwell's advanced facilities.

Other resources include VAX-11 and PDP11 computers and a variety of microcomputers.

Research at Harwell into software engineering and development has led to a number of computer packages. Many of the programs written for the Laboratory's own use are available commercially. The emphasis is on ease of use and adaption to meet customer requirements. Licenses to use these packages are made available either directly from Harwell or through franchise holders.

Commercial programs developed by Harwell

Facsimile Flow and chemistry simulator for solving differential equations.

FS & P Fleet scheduling and planning program for the movement of fleets of cargo ships.

Harwell Subroutine Library A collection of about 200 subroutines for numerical and mathematical methods.

HVRP Vehicle routeing program for scheduling road transport fleets.

MicroMESH For communications between distributed computers and terminals.

PDF Program development facility for the generation and maintenance of software.

PORES For the simulation of oil/gas reservoirs (available from Energy Resource Consultants Limited).

SNAPI Systems Network Architecture Performance Indicator for efficient use of computer terminals.

STATUS Free text information storage and retrieval system.

SWAP Small works allocation package for scheduling single strings of operations against fixed capacity facilities.

TSSD Typesetting for scientific documents including the reproduction of mathematical formulae.

WASP Workshop analysis and scheduling package for small batch manufacturing and 'made to order' work.

Waste Management Model For determining future waste management policies, including transportation, treatment and disposal.

WUDCUT For minimising waste in cutting wood panels, printed circuit boards, sheet metal and glass.

XN11 IBM-DEC link via Systems Network Architecture (available as 'SUPERGATE' from Scicon Limited).

ZIP A zero-one integer program for solving large scale set-covering and set-partitioning problems arising in scheduling applications.

MARINE TECHNOLOGY

- **Silt and Seabed Movement**
- **Dredging, Surveying, Hydrography**
- **In-well Photography** (gas wells)
- **Oil Reservoir Modelling**
- **Well and Borehole Logging**
- **Offshore, Structures**
  – design, inspection, testing, materials, corrosion advice
- **Pipeline Inspection**
- **Computer Programs to Aid Management**
- **Multi-phase Flow in Pipes**
- **Expert Systems for Corrosion Control**
- **Scale Deposition in Reservoirs and Equipment**

Harwell's first involvement in seabed investigations was in the use of radioactive tracers to follow the movement of silt in the Thames and Forth estuaries, work which has led to dramatic savings in dredging costs.

Radioactive tracer techniques were extended to follow seabed movement offshore, coastal erosion and the distribution of sewage and industrial effluents in the sea. They have recently been further extended to monitoring the movement of waters in oil fields in order to improve the understanding and efficiency of water flood Enhanced Oil Recovery Schemes.

Marine technology R&D is now well established at Harwell in a number of specialist areas. Examples of some of Harwell's work are as follows:

WIND, WAVES AND CURRENTS

The North Sea is one of the most hostile environments in the world for recovering oil and gas. Production platforms must be designed to withstand the onslaught of the sea: failure could be catastrophic, over-design expensive.

The UK Offshore Operators' Association (UKOOA) and the Department of Energy are funding several organisations to collect wind, wave and current data from offshore platforms, weather ships and data buoys in the present and potential oil bearing areas. These activities are co-ordinated by the Marine Technology Support Unit (MaTSU) at Harwell, (see Chapter 10 – Government Support Services). One of the instruments used in this work, for measuring the speed and direction of sea currents, is Harwell's ultrasonic flow-meter. Absence of moving parts, quick response and accuracy result in outstanding reliability. It is also almost unaffected by corrosion or marine fouling. It out-performs the conventional propeller-type meters which were, until recently, the standard instruments.

RESERVOIR MANAGEMENT

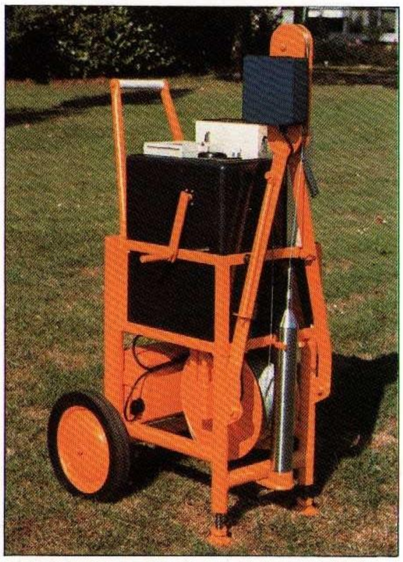
Water Injection Studies

Water injection is used to maintain reservoir pressure and thereby maximise oil recovery. Harwell has developed radioactive tracer techniques to provide detailed information on water flow paths within oil field reservoirs. This service is now offered as a joint venture activity with Oil Plus of Newbury. The service has so far been carried out on a number of North Sea and Middle East fields.

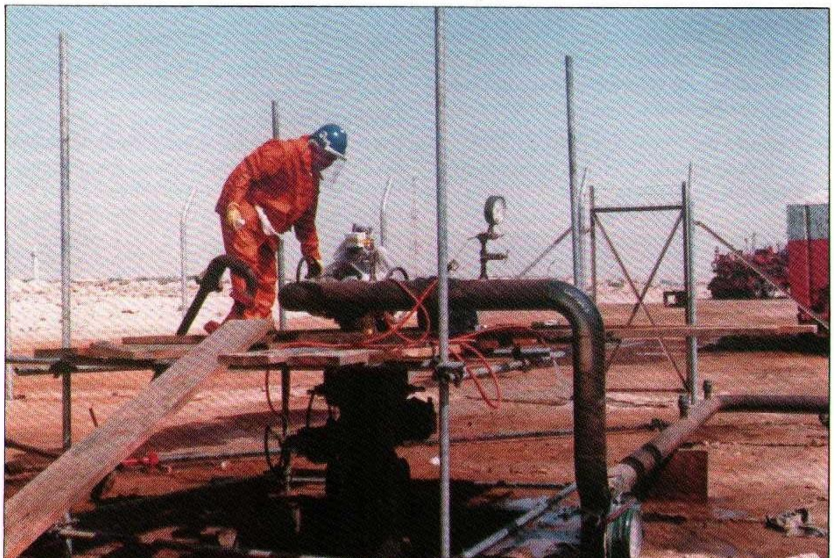
The sea water used for water injection must be free of suspended particles to avoid congesting the porous rock in the reservoir. Conventional filter systems make excessive space demands on offshore platforms. A novel lightweight micro-filter has been developed for this application.

Oilwell Borehole Logging

Information on the porosity of rocks around an oil well and the position of the oil/water interface is essential to the efficient operation of a reservoir. The most direct way of measuring these parameters is by nuclear probes, lowered inside the well. A range of probes for oil-well logging has been developed, particularly to provide more reliable interpretation of the measurements in non-homogenous rock formations. Computer modelling, based on 'Monte Carlo' programs used in nuclear energy work, has been successsfully developed. Companies from the oil and coal industries are supporting this work. For example, a multi-client club, MIDAS, provides an R&D service in this field for companies such as BP, Britoil, Shell, Chevron and Dresser Atlas.



Borehole logging equipment.



Injection of radioactive tracers on a middle-east oilfield.

CHAPTER 9

MARINE TECHNOLOGY

OFFSHORE STRUCTURES

Design and Materials Problems

A major hazard to offshore structures is failure by metal fatigue aggravated by marine corrosion. Toughness, fatigue resistance and tensile strength are prime considerations in the selection of materials for constructing North Sea production platforms. A national Offshore Steels Research programme was launched in 1973 to provide information on the performance of steel under operating conditions in the North Sea. Harwell's contribution to this programme has been to determine the influence of environmental factors such as the wave loading spectrum on the growth of cracks in offshore structural steels.

Reinforced Concrete

A national research programme, funded jointly by Government and industry, is investigating the effectiveness of protection offered by concrete to steel reinforcement in offshore structures. Harwell has:

- monitored the behaviour of reinforced concrete test specimens;
- studied the influence of cracks and other factors on corrosion and also the effectiveness of concrete containing pulverised fly ash in protecting the reinforcement;
- developed instruments for assessing the strength of set concrete on site (in collaboration with the Cement and Concrete Association).

Piles and Grouting

An offshore steel platform has to be anchored with piles driven deep into the sea bed. These are grouted, both into the foundation rock and into sleeves of the main structure. For strength, all spaces must be completely filled with cement. In 1977, when the 'Thistle A' production platform was installed in the North Sea, a Harwell team was there to demonstrate a new nuclear-based technique for monitoring the grouting operation 160 metres under water.

Six further contracts for grout monitoring on offshore structures were completed. The technique has now been licensed to Wimpey Laboratories.

Grouting of new structures can now be accurately monitored using:

- ultrasonic techniques to show pressures of grout on the inside of a pile sleeve;
- neutron techniques to confirm complete filling between pile and sleeve.

Both are in use on offshore platforms.

UNDERWATER INSPECTION

The Offshore Inspection R & D Service

This is a multi-company sponsored project aimed to improve or develop new NDT inspection and monitoring systems. This includes the data transmission, handling and display systems as well as the actual inspection head. Current membership is 15 firms plus the Department of Energy. Programme underway include:

- **Defect Locating and Sizing**

  The particular technique chosen for this is the Time of Flight Diffraction (TOFD) technique developed at Harwell.

- **Eddy Current Technique Assessment**

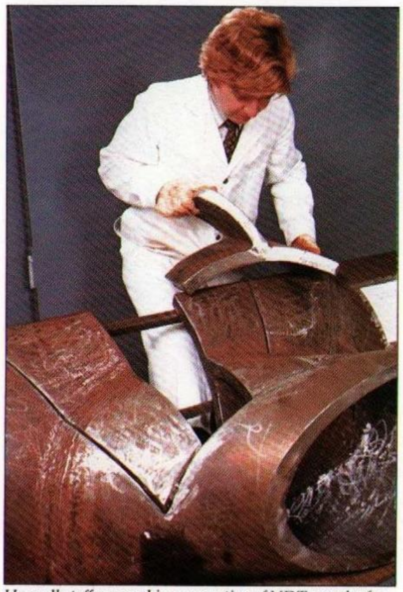
  This offers a considerable untapped potential for the detection and sizing of surface and subsurface defects in welds on offshore structures. Work has started on the development of a novel instrument for measurements both above and below the water line.

PRODUCT DELIVERY

Multiphase Flow

The design and operation of safe, efficient and economic oil and gas pipeline systems require the ability to predict accurately the behaviour of pipelines carrying mixtures of oil, water and gas. Present design practices are no longer acceptable for many gas-condensate and high gas to oil ratio fields. Experience at Harwell in the multiphase flow field (see Chapter 7 – Engineering Science and Process Technology) is being applied to these pipeline problems, under a multi-company sponsored project. A new large scale horizontal multi-phase flow test facility has been constructed at Harwell to improve understanding of multi-phase

Marine fouling: part of a gas platform removed from southern North Sea, with joints cleaned for weld inspection. Normally this is done underwater.



Harwell staff engaged in preparation of NDT samples for time of flight diffraction measurement.

flow regimes and to test pipeline components for industrial companies.

Tankers

The hulls of large tankers need regular inspection to ensure safety. A major need is to inspect the flat bottom, about the size of three football pitches, for damage or distortion without dry-docking.

For the Underwater Maintenance Company of Southampton, Harwell developed SCAN, a remotely controlled submersible. SCAN is a 1.5 metres diameter, saucer-shaped vehicle which can be man-handled by a diver. Its buoyancy can be adjusted so that its wheels press firmly against the tanker bottom. Once in place, it can be driven over the whole area using a remote control link, with closed-circuit television for guidance. A second television camera provides close-up pictures of chosen areas for detailed examinations. SCAN vehicles are used by the Underwater Maintenance Company and its agents in Las Palmas, Cape Town, Fujairah and Kuwait.

MARINE BOLTING MATERIALS

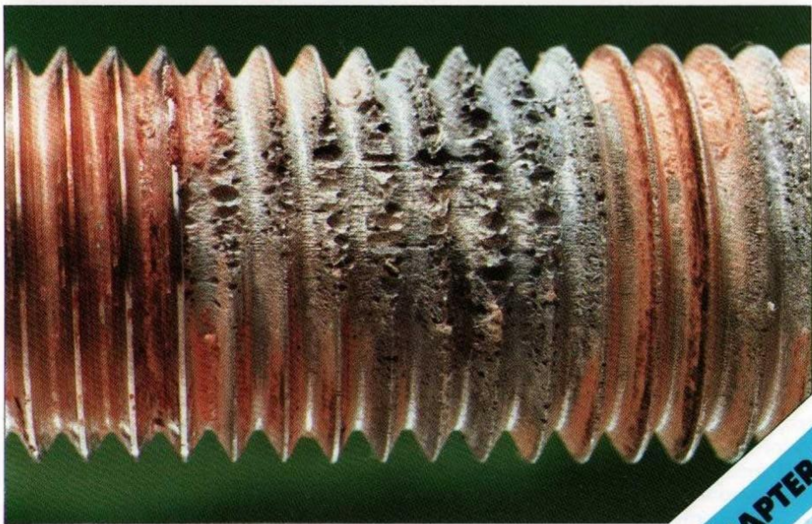
This is a multi-company sponsored research project. Bolts and threaded fasteners, often of relatively high strength materials, are used on a wide range of components on offshore structures, cranes, process plant, clamp repairs and subsea systems. A steady increase of failures is reported from the North Sea. Some can be ascribed to readily identifiable and easily rectifiable causes. However, growing concern is now being expressed by oil companies and manufacturers about the suitability of commonly-used offshore fastener materials and on the lack of understanding of the interplay between design, material characteristics and the environment.

In order to tackle these problems, a multi-client sponsored research and development project has been launched by Harwell and Wimpey Offshore Limited. The objectives of the project are:

- to provide improved engineering data on existing high strength fastener materials;
- to identify or develop alternative alloys with improved performance for specific applications;
- to learn more about the engineering aspects of fastener design and usage. For example: correct method of thread formation, the various type of loading methods, stress relaxation of fasteners; and how these factors affect bolt life.

Multiphase flow in a horizontal pipe.

SCAN-A remotely controlled submersible developed at Harwell.



An example of a failed high strength marine bolt.

CHAPTER 9

GOVERNMENT SUPPORT SERVICES

ENERGY TECHNOLOGY SUPPORT UNIT
- **Energy Efficiency**
- **Renewable Energy Sources**
  - wind, tides, biomass, geothermal, solar
- **Building Design**
- **Energy Assessments**

MARINE TECHNOLOGY SUPPORT UNIT
- **Offshore Supplies Office Support**
  - steels and concrete research
  - underwater welding
  - underwater electrical safety
  - oil and gas production
- **Petroleum Engineering Division Support**
  - environmental data gathering
  - offshore structures and pipe lines
  - oceanography programme

ENERGY TECHNOLOGY SUPPORT UNIT (ETSU)

This unit was established at Harwell in 1974 to support the Department of Energy in

- formulating and managing research, development and demonstration programmes on the efficient use of energy and on the renewable energy sources, and
- carrying out assessment work related to policy formulation in wider areas of energy technology.

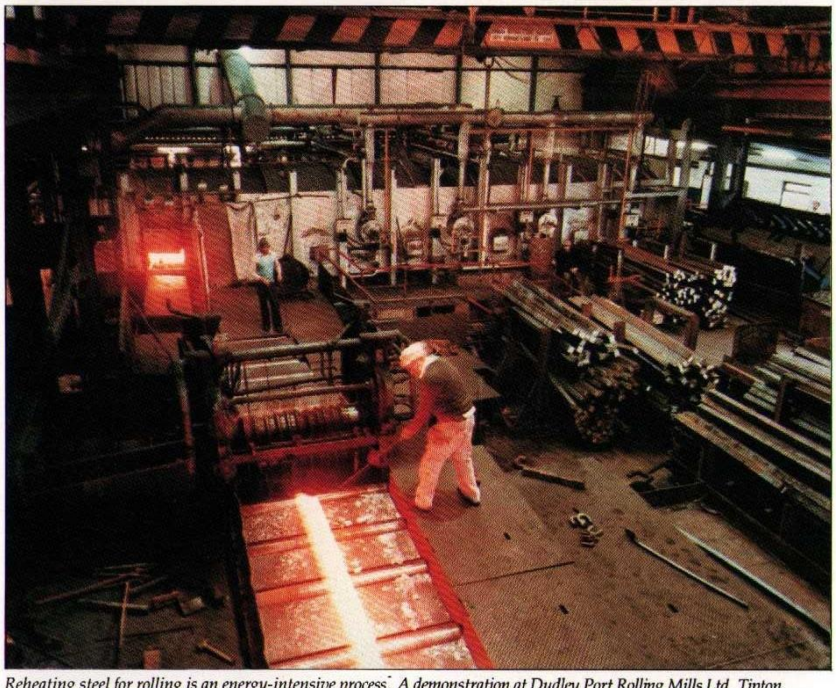
It has grown in response to the Department's needs, and in 1985 it employed about 100 staff, of whom over 50 are qualified scientists and engineers. The current size of the management function is illustrated by the value of the work in progress, over £100M, through nearly 600 contracts.

Energy Efficiency

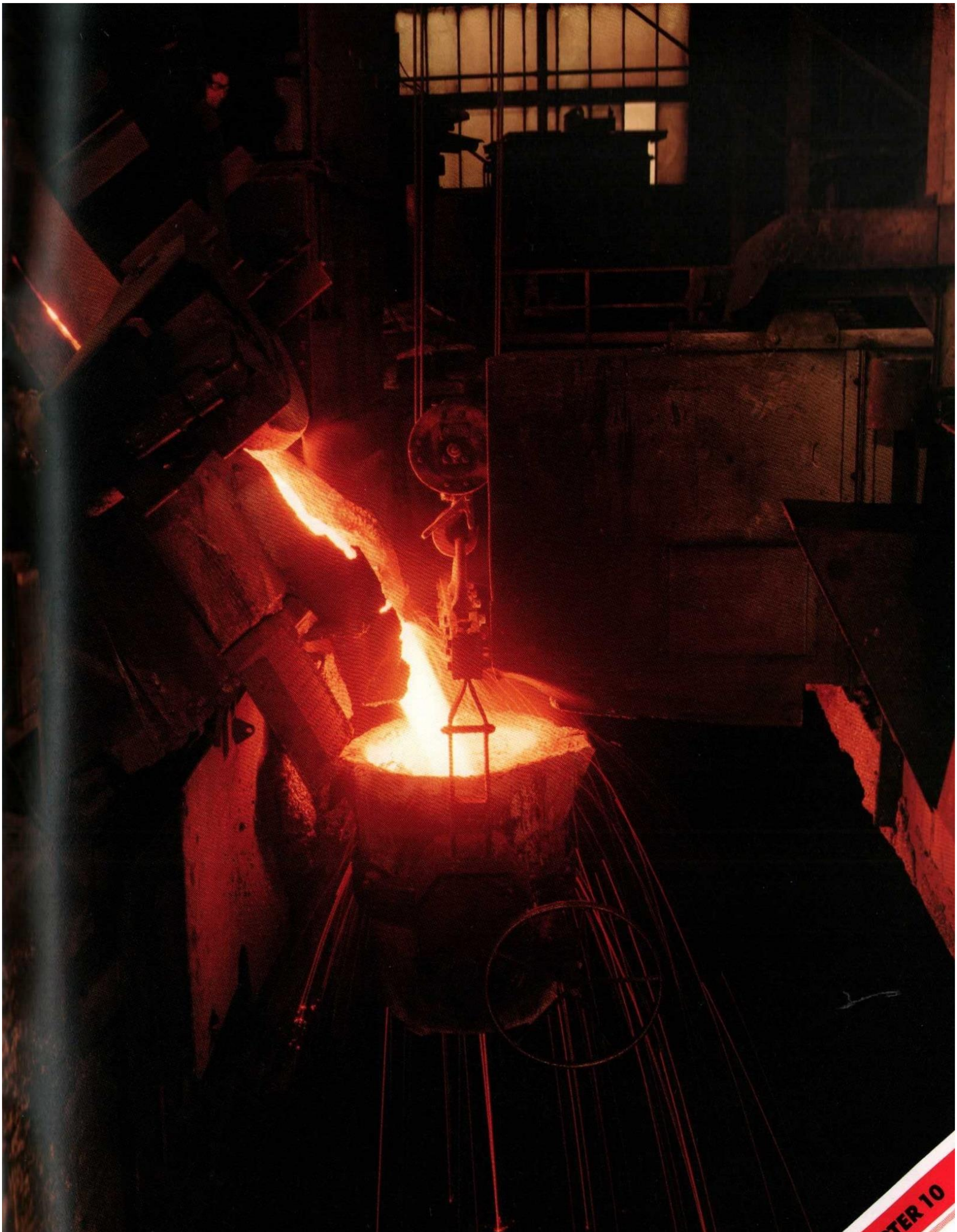
The Unit's largest team serves the Energy Efficiency Office (EEO), the primary aim of the work being to accelerate the adoption of new or improved techniques for using energy more efficiently. By the middle of 1985 about 220 commercial demonstration projects were under way. These were mainly in industrial applications, but with an increasing number in buildings, in collaboration with the Building Research Establishment. Nearly one million tonnes of coal equivalent per year (Mtce/y) of cost-effective energy savings have been achieved: the long term target is 10 Mtce/y by the early 1990s.

As part of its assessment role the Unit has completed a major study of the prospects for cost-effective improvement in the use of energy by UK manufacturing industry to the year 2000. The study, which was published by the EEC, showed that a substantial and cost-effective improvement in energy efficiency (up to 25%) should be attainable.

The adoption of a fast firing system introduced at James Sadler & Sons Ltd, Burslem (the UK's largest manufacturer of teapots) under the Energy Efficiency Demonstration Scheme has shown up to 65% energy saving.



Reheating steel for rolling is an energy-intensive process. A demonstration at Dudley Port Rolling Mills Ltd, Tipton, showed that the installation of recuperative gas burners in a reheating furnace could reduce the energy costs.



CHAPTER 10

GOVERNMENT SUPPORT SERVICES

Renewable Energy Sources

ETSU's activities cover wave, wind, tides, biomass, geothermal and solar energy sources. A short selection only is given here.

The two largest projects, in financial terms, for which ETSU has management responsibility are:

Wind
The construction of a 60m diameter, 3MW aerogenerator on Orkney – expected to produce power in 1986.

Geothermal
The hot rock project in Cornwall (cost of present phase £20M), which is examining the technical feasibility of recovering useful heat from the earth's crust. The next phase, at 6km depth, could become an international project.

'Passive' solar design of buildings – making the best use of solar energy in building design without recourse to expensive collecting panels – has been studied in some depth. Practical measurements on over 100 houses combined with a series of house design studies, involving 20 architectural practices, a computing centre and quantity surveyors, have shown that the encouragement of passive solar design in buildings could lead to worthwhile national energy savings. Ways of providing this encouragement are now being planned and developed.

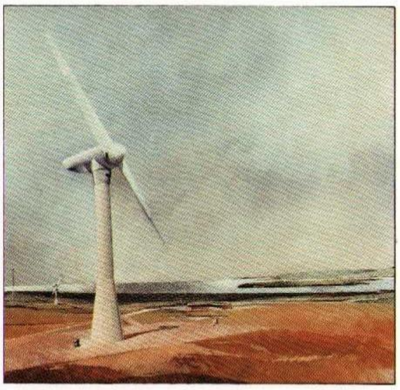
The use of combustible wastes from industry, commercial operations, households, agriculture and forestry as fuels is both practical and economic now, and is being promoted through the Energy Efficiency Demonstration Scheme. Both passive solar design and the use of wastes as fuel are subjects on which formal collaboration with parallel programmes in the USA is being developed under an agreement initiated by the UK and US Energy Departments in 1984.

Major reports summarising the findings of the R&D programmes in Wave Power and Active Solar Heating were published in 1985.

General Assessment Work

The Unit carries out technical and economic assessments across the broad spectrum of energy technology at the request of the Department, to assist in the formulation of R&D policy. Recently completed studies include:

- Low energy futures.
- A comparative assessment of the future economic prospects for the renewable energy technologies.
- A review of the state of knowledge of acidity in the environment (the 'acid rain' problem).
- A survey of the options available for the future supply of liquid fuels for transport.
- A study of the target costs of load management in the electricity supply industry and opportunities for increased electrical load management in the domestic, commercial and industrial sectors.



3MW rated 60m diameter wind turbine generator being built at Burgar Hill Orkney by Wind Energy Group for the North of Scotland Hydro-Electric Board and the Department of Energy under the wind energy R&D programme.

Geothermal Energy Research at Rosemanowes Quarry, Cornwall. (Camborne School of Mines).

MARINE TECHNOLOGY SUPPORT UNIT (MaTSU)

MaTSU provides support to the Department of Energy on its offshore oil and gas responsibilities. It acts as the Department's executive arm for the management of research and development undertaken with two objectives:

- to improve the competitiveness of the UK marine and offshore industries in the context of offshore energy supplies;
- to enable the Department to discharge its responsibility for ensuring the safety of offshore personnel and structures, and to protect the UK offshore investment, income and environment.

The Unit supervises over 400 projects, with a total annual expenditure (including industrial contributions) of about £20M, acting in support of the Offshore Supplies Office (OSO), and the Petroleum Engineering Division (PED).

Offshore Supplies Office

The R&D programme sponsored by OSO on offshore technology R&D is aimed at assisting and encouraging the UK offshore supplies industry. It covers a very wide range of projects which are normally financed by OSO and industry on a shared-funding basis. However, the programme also includes a number of fully funded projects especially in the area of underwater technology.

Among recent developments in this programme has been a significant expansion in its activity directed towards the development of subsea production systems. In the first instance studies are being undertaken to identify possible solutions to the problems of subsea production; to identify the R&D necessary to implement the solutions; and to identify possible UK consortia which could provide the system capability.

An example of a successful shared-funded project has been the development by British Underwater Engineering Limited of the hydraulically formed pile/sleeve connection, Hydro-Lok. Following a successful programme of development trials this simple, inexpensive and rapid technique has been successfully used in place of grouted piles to secure underwater structures to their foundations in the Balmoral and Forties fields in the North Sea. There are firm indications that Hydro-Lok will now become a favoured method of subsea template installation.

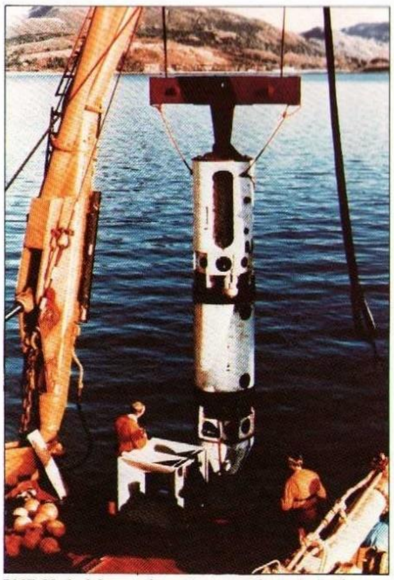
Petroleum Engineering Division

PED is responsible for the R&D required to ensure the safe and effective exploitation of UK oil and gas resources offshore. Except in the areas of geology, reservoir simulation and enhanced oil recovery, the R&D contracts related to this task are largely monitored by MaTSU. The technical range of this work covers the gathering of environmental data for design and planning purposes, the design, installation, inspection and repair of offshore structures and pipelines and a multiplicity of operational problems such as diver support, fire protection and emergency evacuation. The immediate output of this R&D is normally a research report, but MaTSU is also involved in the subsequent utilisation of the research results, for example in the formulation of the Department of Energy's "Guidance on the Design and Construction of Offshore Installations."

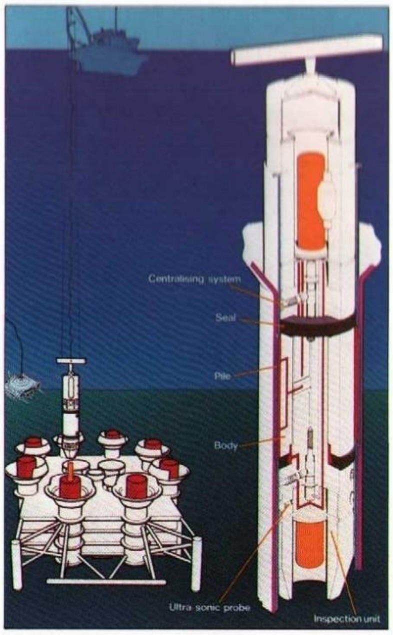
Areas in which PED is currently active include:

- The development of techniques for the assessment of extreme oceanographic parameters over large sea areas, including computer modelling of wave climates from known meteorological conditions, and remote sensing of currents by means of HF Radar.
- The measurement of the vibrations of pipeline spans induced by currents near the sea bed.
- The application of probabilistic methods to the design of offshore structures and to the assessment of risks offshore.

It should be emphasised that MaTSU activities are undertaken under the auspices of the Department of Energy: R&D contracts carried out at Harwell, under its Marine Technology programme, are separate activites.



BUE-Hydrolok — underwater connections. A simple, inexpensive and rapid method of making tubular connections for securing structures to the seabed.



A test rig for measuring vibrations of pipeline spans induced by currents near the sea bed. The rig, at Shepperdine in the Severn Estuary, is shown at low tide when it was accessible for setting-up, adjustment and maintenance. The instrumented fifty metre length of 500m diameter pipeline was submerged beneath a maximum of six metres of fast flowing water at the high tide condition.

CHAPTER 10

HARWELL MANAGEMENT

HARWELL DIRECTORATE

Director	Dr L E J Roberts CBE FRS (Dr G G E Low from 1 April 1986)
Deputy Director and Underlying Projects	Dr J Williams
Research Directors	
● Energy (Non Nuclear)	Dr P Iredale
● Environment	Dr V S Crocker
● Industry	Dr R G Sowden
● Nuclear Power	Dr R S Nelson

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, Process Technology & Safety, NPDE, Risley	Mr R H Allardice
Authority Fuel Processing Director, Harwell	Dr R H Flowers

Its Chairman is the Director of Harwell and its Secretary, Dr R D Worswick.

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 administrative central units provide services to the site as a whole.

Financial Department
Head: Mr J T Wright
- Costs & Revenue Control
- Finance and Accounts
- Contracts and Stores

Marketing and Sales
Head: Mr D F Jephcott
- Business Development
- Commercial Office
- Patents
- Public Relations
- Photographic
- Publicity Services

Personnel and Administration
Head: Mr A J H Wall
- Education and Training
- Personnel
- Site Manager
- Security & General Services

Research Planning and Information
Head: Dr R D Worswick
- Research Planning
- Information
- Library
- Market Intelligence
- Overseas Relations
- Publications

Chemical Engineering
Head: Dr P Hawtin
- Biochemistry
- Industrial Chemistry
- Liquid Processes
- Materials Processing
- Radioactive Waste Management

Chemistry
Head: Dr R L Nelson
- Actinide Chemistry and Analysis
- Actinide Metallurgy and Ceramics
- Waste Disposal Studies
- Reactor Chemistry
- Reactor Materials and Radiation Chemistry
- Radiation Chemistry Separation Processes

Energy Technology
Head: Dr J K Dawson
- Energy Conservation
- Engineering Group
- Renewable Energy Sources
- Offshore Supplies
- Petroleum Engineering
- Ship and Marine Technology

Computer Science and Systems
Head: Dr A E Taylor
- Computing and Information Services
- Information Systems
- Mathematics
- Networks
- Numerical Analysis
- Operations Research
- Systems Design and Development

Engineering Design and Manufacture
Head: Mr J Phillpott
- Engineering Support
- Production, Quality and Services
- Work Study

Engineering Projects
Head: Mr S L Nayler
- Project Engineering and Development
- Active Facilities and New Work
- Project Support and Design

Engineering Sciences
Head: Dr P Hutchinson
- Applied Chemistry
- Energy Efficiency
- Fluid Phenomena
- Process Engineering
- Transfer Processes

Environmental and Medical Sciences
Head: Mr H I Shalgosky
- Medical Services
- Atmospheric Pollution and Radiological Protection Research
- Radiological Sciences
- Chemical Analysis
- Environmental Safety

Instrumentation and Applied Physics
Head: Dr A W Penn
- Analogue Circuits and Signal Processing
- Analytical Chemistry/ARDU
- Detection and Physics
- Environmental Instrumentation
- Harwell Modular Electronic Equipment
- Materials Instrumentation Systems

Materials Development
Head: Dr R Bullough
- Applied Electrochemistry
- Ceramic Technology
- Coatings and Interface Technology
- Corrosion
- Polymers and Composite Materials
- Materials and Surface Chemistry

Materials Physics and Metallurgy
Head: Dr A E Hughes
- Centrifuge and Laser Enrichment
- Computer and Reactor Physics
- Image Analysis
- Instrumentation
- Neutron Beam Applications
- Neutron Diffraction
- Neutron Physics
- Neutron Scattering
- Nondestructive Testing Centre
- Optics and Acoustics
- Special Technology
- Advanced Systems
- Metals Fabrication
- Fast Reactor Fuels
- Fracture Studies
- High Voltage Microscope
- Radiation Damage
- Core Components and Structural Materials

Nuclear Physics
Head: Dr A T G Ferguson
- Applied Nuclear Geophysics
- Geophysical Tracers
- Electron Linear Accelerator
- High Voltage Laboratories
- Ion Crystal Interaction
- Mossbauer Effect
- Neutron Systems
- Nuclear Applications

Research Reactors
Head: Mr D B Halliday
- Design Services
- Reactor Services

Theoretical Physics
Head: Dr A B Lidiard
- Radiation Damage and Theoretical Metallurgy
- Nuclear Atomic and Molecular Physics
- Nuclear Power Applications
- Theory of Fluids
- Theory of Solid State Materials

Thermal Hydraulics
Head: Dr G F Hewitt
- Heat Transfer and Cryogenics
- Multi-Phase Systems
- Thermal Engineering

MARCH 1986

HARWELL

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